

**A methodology for estimating area burned  
using satellite-based data in Near-Real-Time  
in Oregon and Arizona.**

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## Abstract

Biomass burning is significant to emission estimates because: (1) it is a major contributor of particulate matter and other pollutants to the atmosphere; (2) it is one of the most poorly documented of all sources; and (3) it can adversely affect human health. 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. However, satellite imagery is available almost instantaneously and has great potential to enhance emission estimates and their timeliness. Over the last years, we have worked to statistically define the amount of area burned that could be defined by satellite-derived data in Near-Real-Time. Without this background information, potential error can not be assigned to area burned estimates and confidence in satellite-based emission estimates is limited.

This investigation: (1) demonstrates the ability of satellite-derived fire products to quantify ground-based area burned estimates; and (2) suggests a methodology to improve area burned estimates in an effort to enhance existing emission estimates, particularly in large-scale models (i.e. National Emissions Inventory). First, statistical analyses comparing 2002 ground-based area burned data to satellite-based data [MODIS (Terra and Aqua) thermal anomaly and GOES] are provided. These analyses demonstrate that MODIS detects most of the area burned by wildfires, and GOES shows an enhanced ability to detect agricultural fires. Then a methodology is presented that combines satellite data to produce a product that captures 81 to 92% of the total area burned by wildfire, prescribed, agricultural and rangeland burning.

### 1.0 Introduction

In 1990, Congress amended the Clean Air Act (CAA) to require the United States Environmental Protection Agency (EPA) 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<sup>1</sup>. 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, and other interested parties, to develop and implement State Implementation Plans (SIPs) to reduce the pollution that causes visibility impairment. Additional information concerning the regional haze program can be found at the EPA's website: <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 United States 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 by December 17, 2007, must include 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<sub>2.5</sub> - 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<sub>2.5</sub> 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<sub>2.5</sub>, consequently regional haze, and it is poorly quantified. In particular, biomass burning is often influential on the top 20% worst air quality days, which is a significant parameter to monitor for the regional Clean Air Act. The inability to adequately define biomass emissions is due to the fact that the United States does not have a standard database of fire events or area burned for any year. Several organizations [i.e. U.S. Forest Service, 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 often fail to capture agricultural burning (e.g., sugar cane, wheat/rice stubble, and grasses).

Current 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 1885-1998 obtained from the U.S. Department of Interior and the U.S. Forest Service 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 can often lead to large errors and inaccuracies when comparing where emissions were shown to occur and where actual biomass burning occurred<sup>2</sup>. The EPA focuses on producing a substantial National Emission Inventory (NEI) every 3 years, so the next years of concentration are 2002 and 2005. The focus of this work is on 2002, because the EPA and the RPOs committed a substantial amount of support to build an intensive ground-based area burned inventory for 2002.

The main goal of this investigation is to completely assess the ability of satellite data to quantify fire in an effort to enhance biomass burning emission estimates. Without an understanding of the capability of satellite data to describe fire and the error associated with these data, emission estimates using these data are uncertain. This work builds on previous work (<http://www.epa.gov/ttn/chief/conference/ei15/index.html> and <http://www.epa.gov/ttn/chief/conference/ei14/index.html>) to provide enhanced results. First, the ability of satellite data to quantify fire is statistically analyzed by (1) comparing ground and satellite data to identify coincident fire events; and (2) by quantifying the amount of area burned that can be identified by satellite. Then, we will use lessons learned to define a methodology that best captures all fires, from small agricultural fires to large wildfires. 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.

## **2.0 Methods**

Satellite data are compared to reliable ground-based fire datasets to evaluate the ability of satellite data to fully describe fire. Data from three satellites are used to quantify the number of fires and estimate area burned in Oregon (July 2002) and in Arizona (August and September 2002). We focus on these distinct ecoregions because Oregon is defined by a cool, dark vegetation-filled background that typically enhances the 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 United States, or/and emissions are time sensitive and must rely on active fire detections.

## 2.1 Satellite data, 2002

Satellite-derived fire products are compared temporally and spatially to ground-based fire datasets from Oregon and Arizona. Two satellite-derived products are considered in this analysis, one based on Geostationary Operational Environmental Satellite (GOES) Automated Biomass Burning Algorithm (ABBA) data and the other on 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 (15 minute data, 16 km<sup>2</sup> nadir resolution) and the unique spatial resolution of MODIS (twice daily, 1 km<sup>2</sup> nadir resolution).

Both MODIS and GOES ABBA products have demonstrated their ability to detect biomass burning in numerous ecosystems<sup>3-7</sup>. The GOES ABBA algorithm uses GOES visible, shortwave 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.

Historic filtered GOES ABBA data are provided by Elaine Prins and Chris Schmidt, who originally developed the fire algorithms and are still heavily involved in their evolution. The historic ABBA data can be 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). Fire flags range from 0 to 5 and correspond to 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 processed data contain the estimated instantaneous size of a fire. Therefore, because we are interested in area burned, the instantaneous fire size is assumed to be consistent within ecoregions. The mean instantaneous fire size is calculated using the processed data within an ecoregion, and this mean fire size is assigned to fires in flag categories 1 through 4. Instantaneous fire size is computed as a circle (polygon) around the latitude and longitude point locations in GIS. GOES area burned during a fire event is defined as the sum of the instantaneous fire sizes that are spatially and temporally consistent with that event.

Next, GOES instantaneous area is buffered to realistically assess the coincidence in these data and ground-based data. The instantaneous fire size is surrounded by a 10 km radius buffer (~ 0.05 degrees) to account for: (1) the spatial resolution of the instrument; (2) the Point Response Function (PRF)<sup>8</sup> of the instrument; and (3) spatial error in the ground-based data (buffer example, see Figure 1). 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 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 MODLand 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. An area burned estimate is not included in these data. For this reason and in consideration of the instruments 1 km<sup>2</sup> nadir spatial resolution, the MODIS data points are surrounded (buffered) with a 0.5 km radius in GIS, which is equivalent to an area of 0.79 km<sup>2</sup>. Then, to account for the PRF and inconsistencies in ground-based data, the area is buffered with an additional 3.0 km radius. 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, 2002**

The Western Regional Air Partnership (WRAP) provided the ground-based “truth” fire data for Oregon and Arizona. The WRAP data include natural and prescribed burns and are collected from every available fire data source (209 reports, NIFMD/USFS, SACS/1202, DEQs etc.). These data were checked, geolocated and quality control reviewed by Air Sciences Inc. in preparation for the intensive 2002 EPA emissions inventory (<http://www.wrapair.org/>). The fire data include 5 categories: wildfire; wildland fire use; prescribed burning in wildlands; non-federal rangeland fires; and agricultural burning. Even though these data are the most comprehensive and reliable ground-based dataset generated in the United States, words of caution are useful. Agricultural fires do not consistently burn within the space and time reported, and this is often dependent on the reporting state or county. Also, while the amount of area burned in non-federal rangelands is considered correct, the temporal and spatial domains recorded are typically incorrect. Hence, non-federal rangelands are not suitable for spatial coincidence analyses, only area burned analyses. Even though these fire types are problematic, they are not ignored in this analysis because agricultural fires are significant to the EPA, and during some portions of the year, agricultural fires can account for the majority of emissions at that time. Additionally, in Arizona (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.

The WRAP data are altered from a GIS point database by assigning polygons equal to the amount of area burned around the point location of the fires (typically ignition points), similar to the GOES and MODIS satellite data. 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 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 analysis, 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<sup>2</sup>) in a day, however satellites often detect this burning. Also, agencies report area burned at the ignition location of the fire, and satellite data record the fire as it moves over space and time (Figure 2).

For these reasons, a fire is considered coincident if:

- ❖ the WRAP and satellite data coincide in space and time or
- ❖ the WRAP data and overlapping satellite buffered space coincide in space and time (Figures 1 and 2) 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 or
- ❖ the WRAP and satellite data are coincident in space, as defined above, and the satellite data fall within 3 days of the beginning or end of the date range of a WRAP fire event.

### 3.0 Results and discussion

In general, each of the instruments is able to capture a large portion of the representative area burned and the spatial domain of the fires, which is not captured in current ground-based data. Representative area is the area reported burned in the WRAP data that each satellite identifies. The combined satellite data capture 69% of the representative area burned in Arizona and 97% of the representative area burned in Oregon. This demonstrates that the satellite data competently identify large fire events, but the relationship is not as strong for small fires. Additionally, MODIS data are more likely to capture area burned by medium to large wildfires, and GOES data are more likely to detect small, short-lived agricultural fires.

#### 3.1 Oregon analyses

Statistics are provided in Table 1, and Figure 3 shows the overall spatial coincidence of the fires that burned in July, 2002. MODIS instruments aboard Terra and Aqua are capable of detecting 37 and 43% of the number of non-agricultural fires, respectively. However if one considers a fire detection equivalent to 1 km<sup>2</sup>, Terra and Aqua detect 131 and 98% of the total area burned by these fires, respectively. In contrast, GOES is able to detect 34% of the number of non-agricultural fires but only 32% of the area burned.

GOES is able to detect 34% of the total number of agricultural fires and 20% of the area burned. In contrast, Terra and Aqua both detect < 2% of the total number of agricultural fires and if a fire detection is considered equivalent to 1 km<sup>2</sup>, 10% of the agricultural area burned. In essence, MODIS does not capture agricultural fires well and then severely overestimates the size of the fires it does capture. Agricultural fires are typically small, so this explains the MODIS area overestimate. Then MODIS instruments capture a limited number of agricultural fires, because the timeframe Aqua and Terra are overhead is limited and often not when the agricultural fires are burning. Even though GOES substantially underestimates area burned by agricultural fires, the instruments accurately capture the spatial and temporal domain of agricultural fires.

Overall, Terra and Aqua are able to detect 10 and 12%, respectively of the total number of fires in Oregon in July, 2002. These numbers are low, because agricultural fires are included in this count. Again, if one considers a fire detection equivalent to 1 km<sup>2</sup>, Terra and Aqua detect 126 and 94% of the total area burned by all fires, respectively. Conversely, GOES captures 34% of the number of all fires but only 37% of the total area burned. It should also be noted that on several occasions, either all satellites or two satellites identified fires that are not reported in the WRAP, so one might anticipate that the coincident event percentages reported here are slightly low. Coincident fires are compared in Figure 4 (satellite area to WRAP area), and each satellite instrument correlates well with the WRAP data. However if one considers a straight area to area comparison (X in Figure 4), each MODIS instrument generally overestimates area burned and substantially overestimates area burned if Terra and Aqua detections are combined. In contrast, GOES generally underestimates area burned.

In combination, all the satellites are able to detect 53% of the total number of fires and 181% of the area burned by all fires (MODIS detect = 1 km<sup>2</sup>). The combined satellite products are able to

detect 97% of the representative area burned (from 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 (<http://www.epa.gov/ttn/chief/conference/ei14/index.html>), 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<sup>9</sup>, and in Alaska, the long-term fire records (since 1950) show that 96% of the area burned is by large fires (> 20 km<sup>2</sup>)<sup>10</sup>. This relationship is also consistent for Russia fires<sup>11</sup>. Consequently, the largest fires present the greatest health risk to the public and push the limits of air quality attainment.

### 3.2 Arizona analyses

The overall spatial coincidence of the fires that burned in September and August, 2002 is shown in Figure 5, 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. For example, GOES classified 85% of the fires as low probability flag 5 data 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, coincidence analyses are impossible, but area burned is compared.

GOES identifies only 5% of the total number of fires and 18% of the total area burned. Terra and Aqua identify 14 and 12% of the total number of fires, respectively, but 77 and 76% of the total area burned (MODIS detect = 1 km<sup>2</sup>), respectively. Of the fires that are coincident in the satellite and WRAP data, these correlate well, as shown in Figure 6. However, if strictly comparing area to area (X in Figure 6), each MODIS instrument generally overestimates area burned and substantially overestimates if the instrument detections are combined. Again, GOES generally underestimates area burned.

All satellites combined are able to detect 20% of the total number of fires that burned in this region. Nonetheless, combining all satellite data (MODIS detect = 1 km<sup>2</sup>) results in an overestimate of the total area burned (171%). The total representative area burned by all satellite data is 40%, however this area increases to 69% if non-federal rangeland data is excluded. This is because non-federal rangelands represent a large portion (45%) of the total area burned, but it is not coincident in space and time, so it is not part of the coincident representative area. The satellites are able to capture most of the largest fires in Arizona (69%), and as previously stated, this accounts for most of the area burned and biomass emissions. Specifically for Arizona, the largest 10% of the fires represent 74% of the total area burned.

### 3.3 Limitations of the 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 prevents the instruments from detecting active fires, so when thick persistent clouds are overhead, active fires are missed. Then again, the weather that is conducive to fire (dry, high pressure dominated) is often not conducive to cloud cover (low pressure). Additionally, each instrument is limited in its ability to detect and geolocate fire by its spatial resolution (GOES 16 km<sup>2</sup>; MODIS 1 km<sup>2</sup>). For example, when an instrument detects fire, the position of the fire within a 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 from 1.42 km (MODIS) and 5.68 km (GOES), for ~99% of the energy 2.47 km (MODIS)]<sup>8</sup>. 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<sup>2</sup> (perhaps 50 x 250 m or 0.0125 km<sup>2</sup>) can often activate numerous MODIS 1 km<sup>2</sup> fire detections. In addition, the MODIS instrument is in a sun-synchronous orbit and is limited by two overpasses per day (2 satellites Aqua and Terra, 4 overpasses with some latitude-dependent edge overlap). Consequently, fires that burn between satellite overpasses are excluded. These analyses demonstrate that in the ecosystems analyzed here, the pixels sensed during fires overcompensate for the occasions when fires are missed (cloud cover or time of fire). One exception is small fires that burn briefly (i.e. agricultural or pile burning).

Remarkably, even though the GOES instrument has a larger spatial resolution, the instrument captures a greater number of small agricultural fires. This seems a bit counter intuitive until one remembers the GOES instrument is in a geostationary orbit and is constantly viewing North America, enabling the instruments to sense fires every 15 minutes. However, the geolocation of a GOES fire event could be off by maximum of about 10 km (0.05 degrees) due to its PRF, nadir spatial resolution and the position of a fire within a pixel. 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 Methodology to accurately assessment of fire**

As shown in Figures 4 and 6, area burned from each satellite instrument correlates well with coincident data. However, both MODIS instruments overestimate area burned, and GOES instantaneous area underestimates area burned. The conundrum is that to accurately capture all fires, one must use all the instruments. Terra and Aqua capture unique fires because of unique overpass times and GOES captures small agricultural fires that are not likely to be burning at MODIS overpass times. However, when combining the instruments, area burned is severely overestimated.

To address this problem using lessons learned from this and previous work, we generated a cumulative satellite product that takes input from Terra, Aqua and GOES. First, Terra and Aqua are buffered with a 0.50 km diameter (0.79 km<sup>2</sup>). Then the MODIS instruments are combined into one aggregated MODIS data product, eliminating detection overlap. An example of the resulting product is shown in Figure 7. Comparing this result from the Biscuit fire (July 2002 burning only) to that shown in Figure 2 illustrates the improvement in the area burned estimate for this fire. MODIS fire detections overestimate area burned by 256%, and GOES cumulated instantaneous area estimates only 51% of the area burned. In contrast, the buffered MODIS area overestimates the area burned in this fire by only 6%. 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, GOES agricultural area burned is increased 5 times. 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 Near-Real-Time (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 in NRT.

#### **4.0 Conclusions**

This investigation focused on two distinct ecoregions in Arizona and Oregon to quantify the amount of area 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 instantaneous area, Terra and Aqua detections) are able to identify 97% of the representative coincident area burned in Oregon and 69% of the representative coincident area burned in Arizona. However, if all the satellite data is considered (not solely coincident), Terra and Aqua substantially overestimate total area and GOES underestimates area burned. Both MODIS instruments accurately define the spatial pattern of fire as it moves across a landscape, which is information that is not available in current ground-based data. GOES demonstrates an enhanced ability to detect agricultural fires, which is a result of its geostationary orbit (spatial resolution large-scale).

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 m diameter) to 0.79 km<sup>2</sup>, combined and aggregated to eliminate pixel area overlap. Then, GOES data is adjusted (5 times) to quantify area burned in agricultural regions. 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) in Oregon. In Arizona, the aggregated MODIS product defines 81% of the total area burned. The derived product is based on satellite data that is 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.

Currently, the EPA depends on rigorous ground-truthed fire data to estimate area burned and emissions, which is costly and takes years to prepare. However, even this type of data can miss some fires, and the area burned is necessarily determined after the fact. In addition, most ground-based data is not of this quality. 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. Moreover, satellite data accurately define fire perimeters as they progress across a landscape, which is valuable to defining the source location to accurately transport biomass burning emissions. Considering that firefighters are generally concerned with controlling fire, not area mapping for emissions, satellite data adds 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 only collects detailed ground fire data every 3 years, satellite data can be used to estimate emissions in the years where the detailed ground fire inventory data are not available. Considering the cost of a detailed analysis (~ 1 million dollars, 24-36 months), this is a substantial benefit.

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) enhancing and improving estimates during times when detailed ground inventories are not available; and (3) enhancing and improving estimates in regions where temporal and/or spatial ground-based data is imprecise. Our ultimate goal is to work towards establishing a national, automated Remote Sensing-based NRT biomass burning emissions inventory system that contains accurate ecosystem-dependent error assessments.

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**Key Words**

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GOES ABBA

Active fire detection

PM 2.5

Haze

Air quality

Particulate matter

United States

North America

Area burned

Oregon

Arizona

**Acknowledgement**

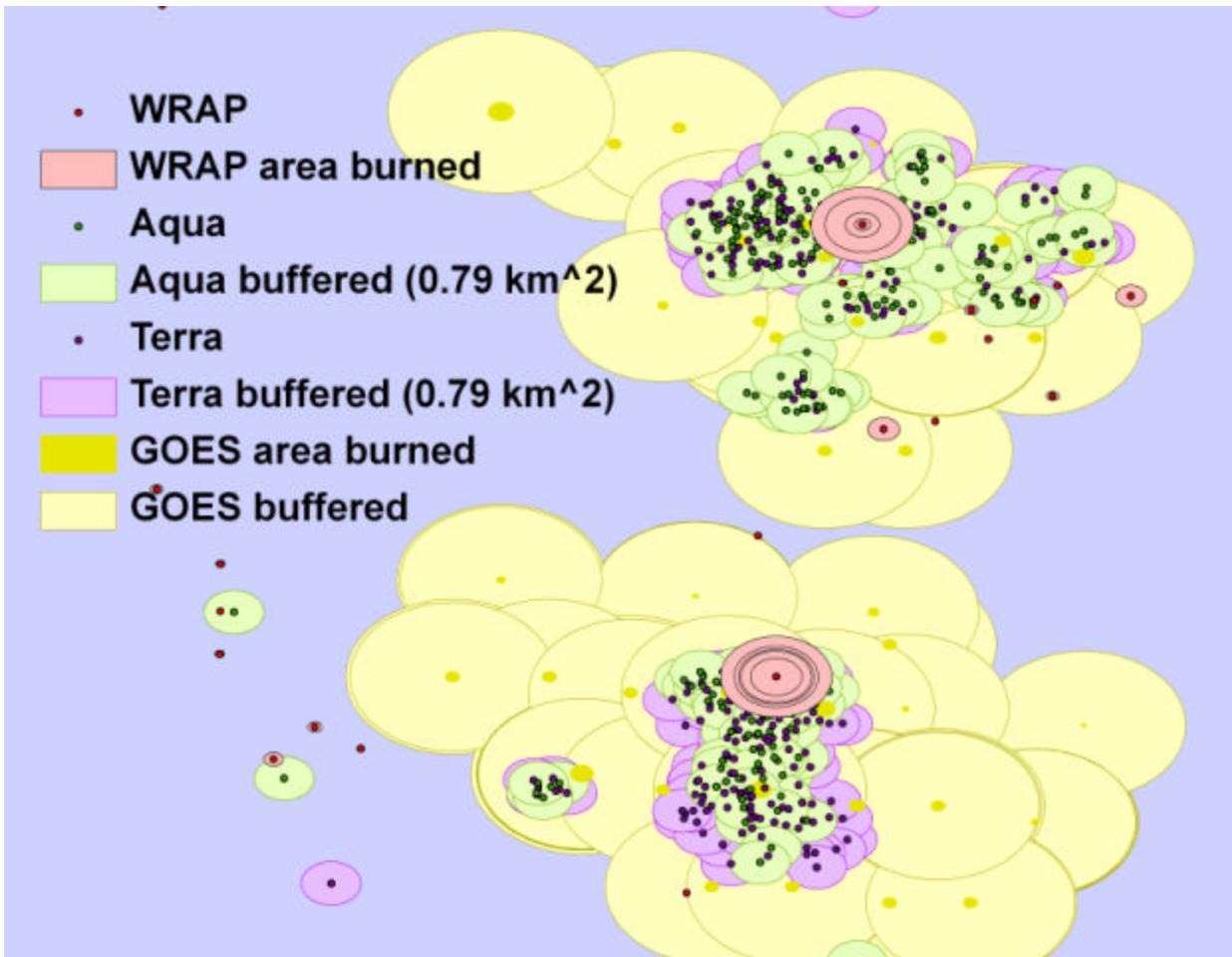
We would like to gratefully acknowledge Elaine Prins and Chris Schmidt who were instrumental in providing information and advice throughout this process. We would also like to thank the Western Region Air Partnership and the Environmental Protection Agency for providing data and support, without which this work would not have been possible.

Data source	Number of records	Non – Agricultural acres burned (range) [Agric. Acres ]	Percent area burned, all ground data Percent area non-Agric. [Percent area Agric.]	Percent number of all fires coincident Percent number non-Agric. [Percent number Agric.]
GOES ABBA [Agric. Fires]	1996	197,655 (1.16 – 806.66)	37%, 32% (Instantaneous) [20% Ag area]	34 % 34 % [ 34 % ]
MODIS Terra [Agric. Fires]	2761	682,268 (from detections)	126%, 131% (detect = 1 km <sup>2</sup> ) [10% Ag area]	10 % 37 % [ < 2 % ]
MODIS Aqua [Agric. Fires]	1984	350,643 (from detections)	94%, 98% (detect = 1 km <sup>2</sup> ) [10% Ag area]	12 % 43 % [ < 2 % ]
Oregon ground, 101 fires, mean 1691 acres [Agric. Fires] [mean 69 acres]	296 [312]	500,555 (1.98 – 54400.5) [ 21570 Agric. Acres ]	All sat., all area 181% All sat., non-ag 312% Combined <u>representative area,</u> all satellite 97%	Combined satellite, all fires 53 % [ 41 % ]

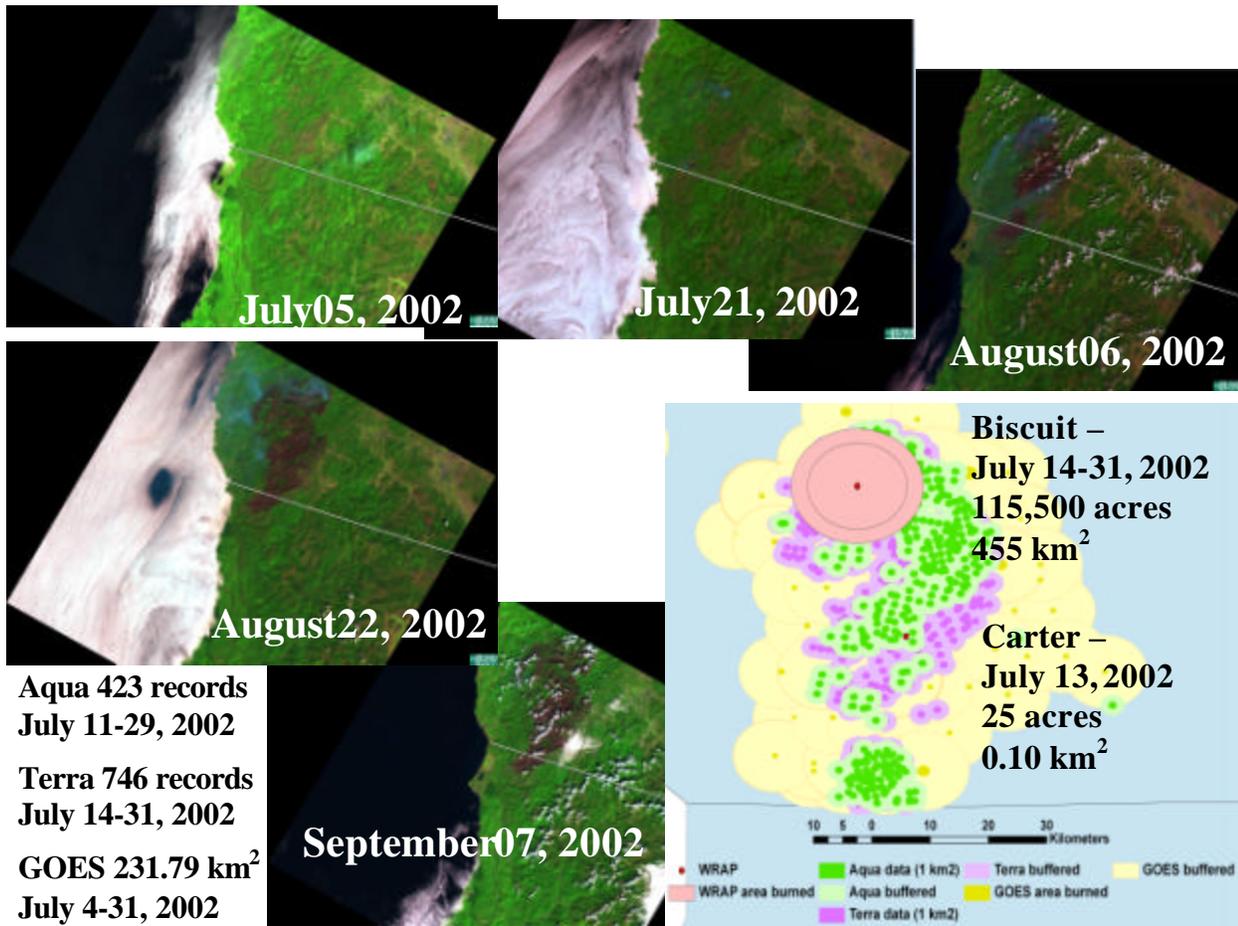
Table 1. Oregon fire statistics from July 2002.

Data source	Number of records	Acres burned <b>Non-federal rangeland</b>	Percent area burned, all data	Percent number of all fires coincident <b>[Percent number without rangeland]</b>
GOES ABBA	169	7358 acres	18 % all (Instantaneous)	5%, <b>5%</b>
MODIS Terra	168	31,877 acres (from detections)	77 % all (detect = 1 km <sup>2</sup> )	14%, <b>15%</b>
MODIS Aqua	162	31,382 acres (from detections)	76 % all (detect = 1 km <sup>2</sup> )	12%, <b>12%</b>
Arizona ground fire data, <b>Non-federal rangeland</b>	165 fires 201 records <b>34 non-fed range</b>	22,613 acres mean 113 acres, range (0.5 - 1598) <b>18,750 acres</b>	<b>All sat. 171 %</b> Combined <u>representative</u> satellite area 40% <b>Without non-fed rangeland, 69%</b>	Combined satellite 20%

**Table 2.** Arizona fire statistics for August and September, 2002.



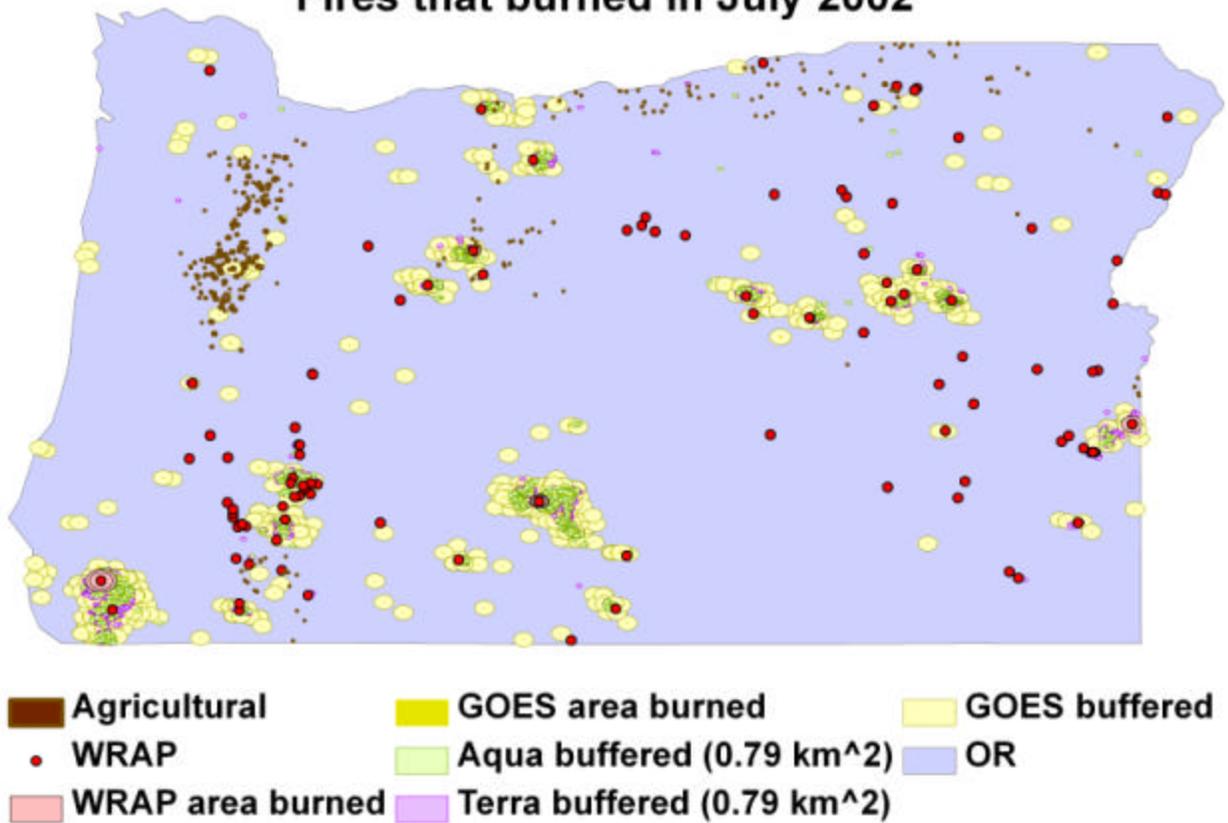
**Figure 1.** Buffer overlap. WRAP fire locations are pictured in red, and WRAP area burned data are shown in rose, emanating from the point of ignition. For this reason, satellite data, particularly MODIS data, better define the actual shape of fire scars (see Figure 2). MODIS (Terra and Aqua) data are buffered, showing the area of buffered pixel overlap. Note the varying sizes of GOES instantaneous area and the buffers surrounding these regions, shown in yellows. 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 at least 15 coincident fire events and several of the WRAP fires are defined by more than 1 record.



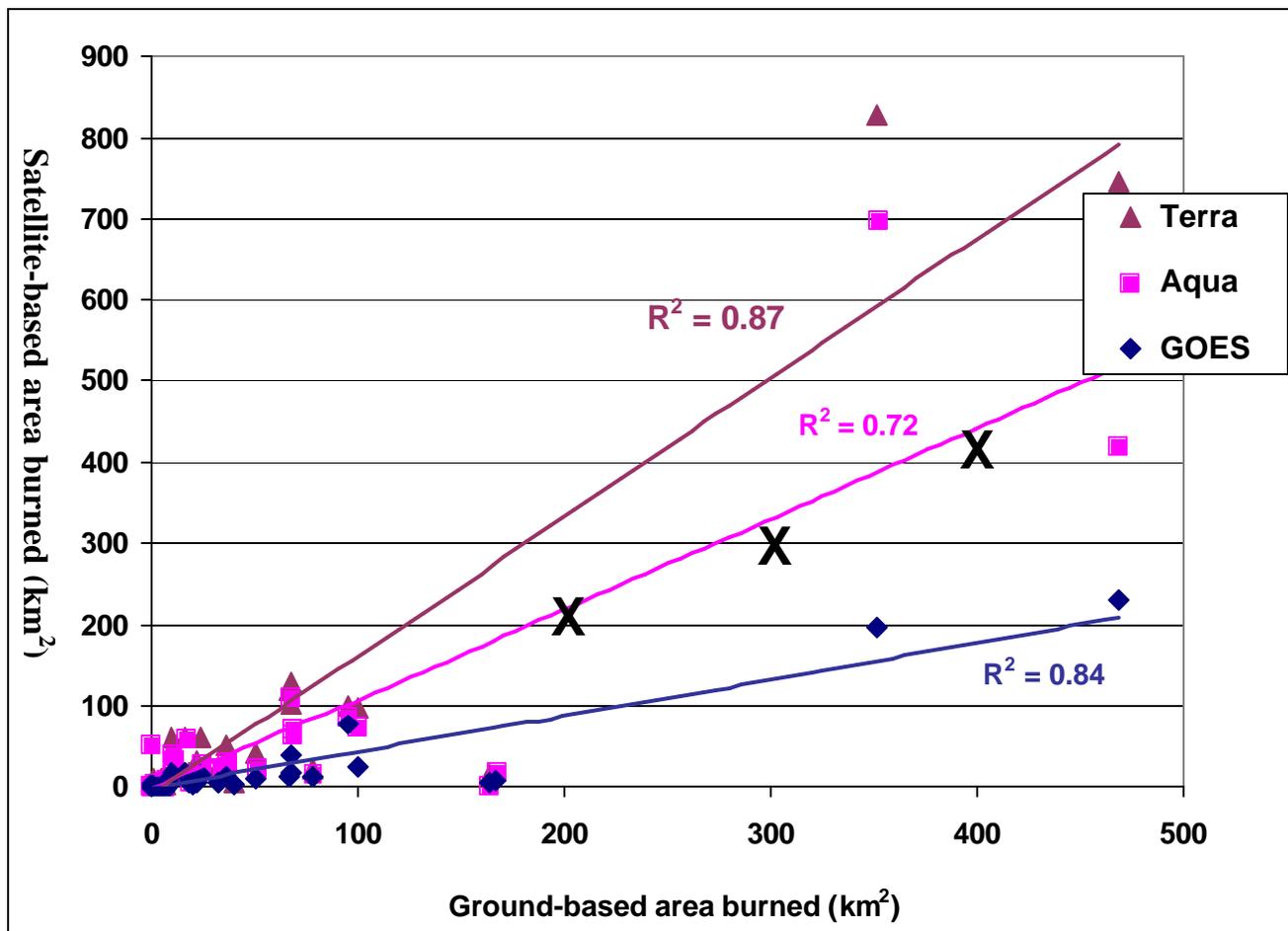
**Figure 2.** Evolution of the Biscuit fire over time. Enhanced Thematic Mapper pictures are provided to show the shape of the fire scar. Satellite and WRAP fire records represent only those recorded in July, 2002, not the entire area burned during the Biscuit fire.

# Oregon

## Fires that burned in July 2002



**Figure 3.** Geographic coincidence in fire (Oregon July 2002). There are no non-federal rangeland fires burning in Oregon during the time period analyzed.



**Figure 4.** Comparison of coincident satellite and ground-based area burned data for Oregon, July 2002. The data show good correlation, however one must note the differences in the axes. Even though the data positively correlate, GOES data underestimate area burned, and both Terra and Aqua (detections) overestimate area burned, substantially when the instrument detections are combined.

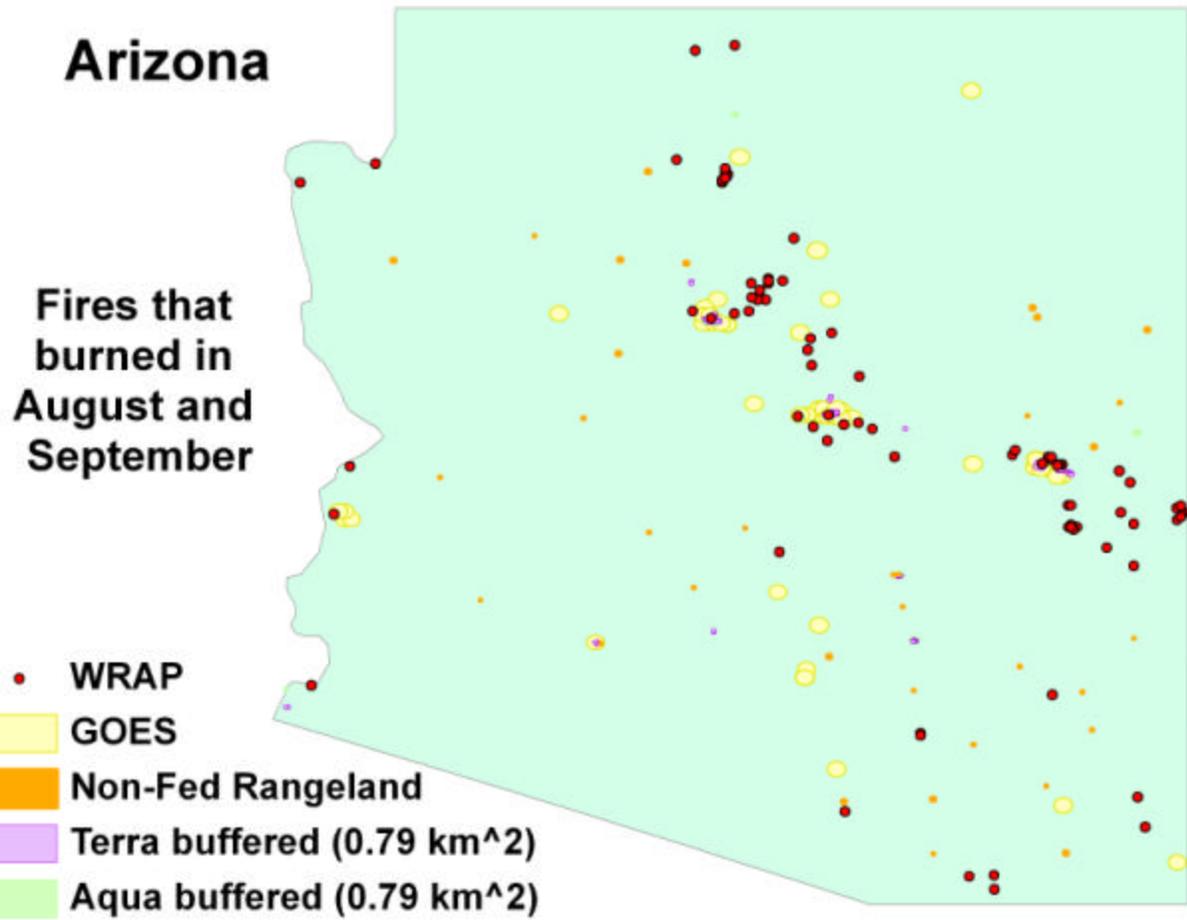
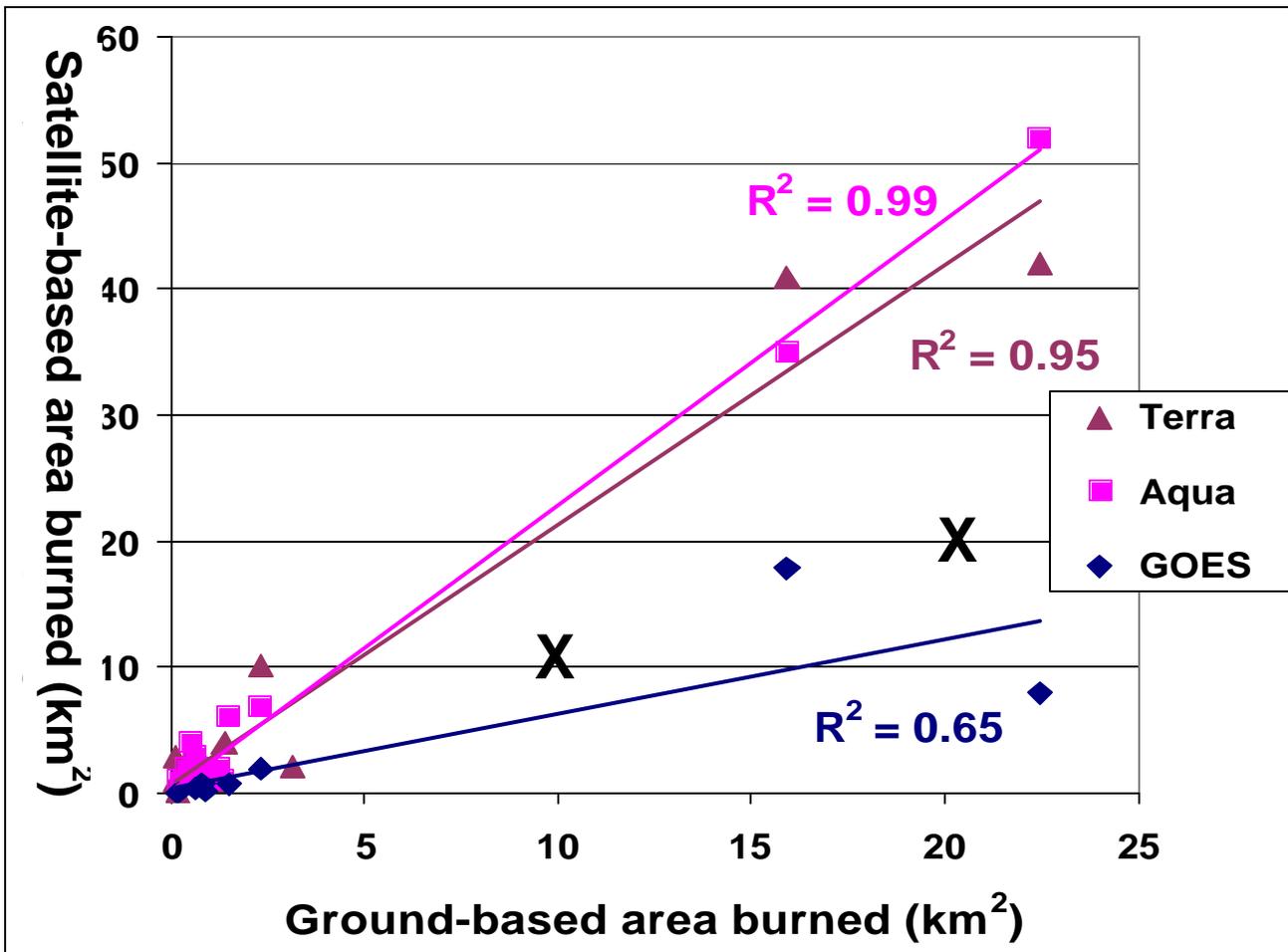
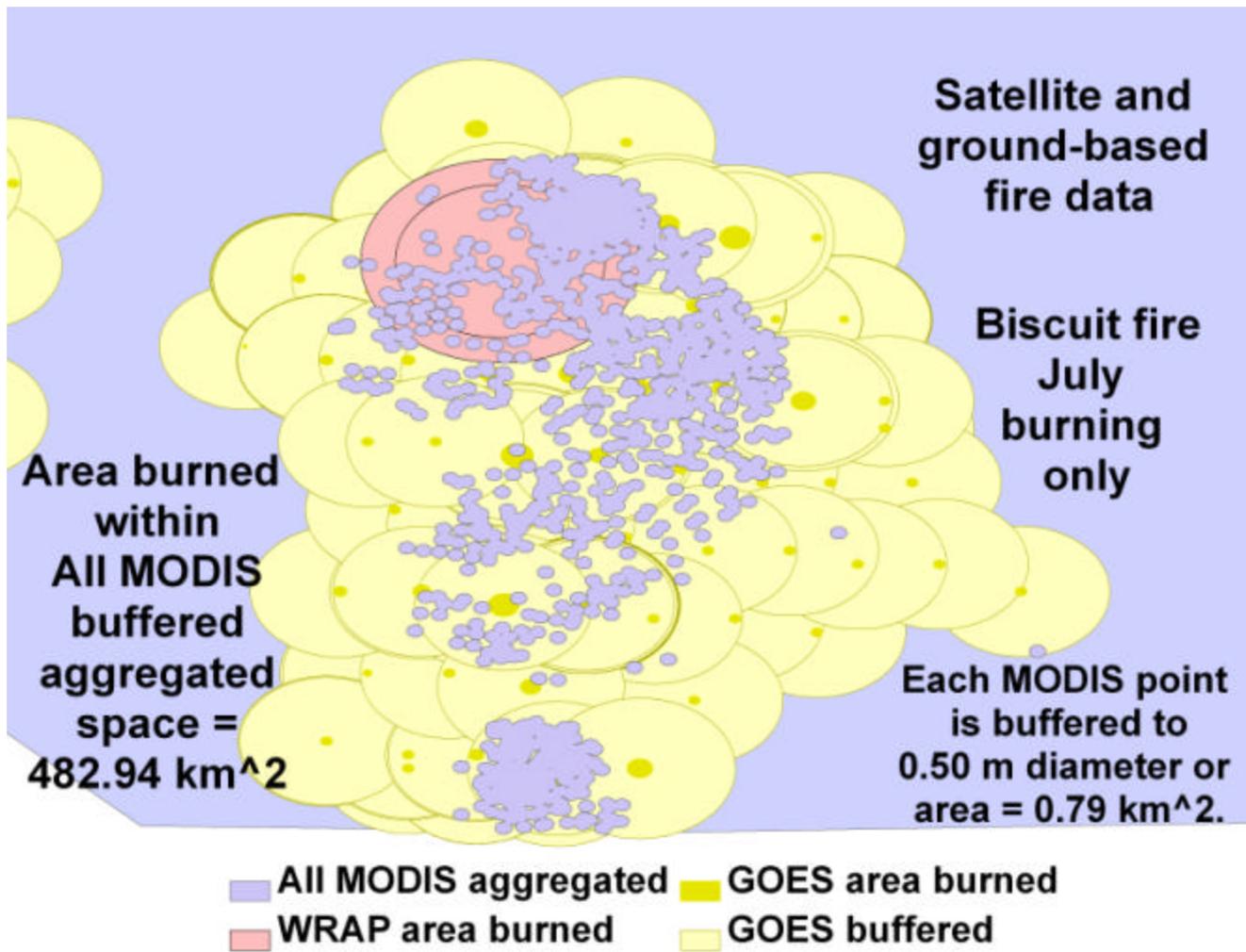


Figure 5. Geographic fire coincidence (Arizona August and September, 2002).



**Figure 6.** Comparison of coincident satellite and ground-based area burned data for Arizona (August and September 2002). Again, the data show good correlation, however one must note the differences in the axes. Even though the data positively correlate, GOES data underestimates area burned, and both Terra and Aqua (detections) individually overestimate area burned, severely if detections are combined.



**Figure 7.** Buffered and aggregated MODIS (Terra and Aqua) data product. Total area burned within the buffered space for the Biscuit fire in July is 483 km<sup>2</sup>, which is only 6% greater than that reported (see Figure 2).