How well does satellite data quantify fire and enhance biomass burning emissions estimates?

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Abstract
Biomass burning is a major contributor of particulate matter and other pollutants to the atmosphere, and it is one of the most poorly documented of all sources. 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. Currently, the United States does not have a standard methodology to track fire occurrence or area burned, which are essential components to estimating fire emissions. One problem is the ownership and management of the land belongs to multiple organizations and private individuals, so there is not one organization that is responsible for thoroughly monitoring fire. Satellite imagery is available almost instantaneously, which would be valuable to warning the public about potential health concerns. Additionally, satellite data provides the opportunity to consistently sense fire across boundaries. The goal of this investigation is to define the ability of satellite-based fire products to detect active fire and quantify area burned in an effort to enhance existing area burned databases and emissions estimates. Three satellite-based fire products are compared temporally and spatially to ground-based data from Oregon, Arizona and Alaska. The best results are from MODIS Terra, which quantified 130% of the total area burned in Oregon in July 2002 and 100% in of the total area burned in Arizona in August and September 2002, and HMS-based Terra and Aqua data, which identified 112% of the total area burned in Alaska 2004. Satellite-based fire data could be used to increase the timeliness of emission estimates, augment existing fire databases to enhance emissions estimates, and to estimate emissions when detailed ground-based fire data are not available.

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 [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, 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 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 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 $PM_{2.5}$ - 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 $PM_{2.5}$, consequently regional haze, and it is poorly defined. 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 capture 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. 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 method, 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 [2].

The goal of this research is to assess the ability of satellite data to accurately identify fire events and to quantify area burned in order to enhance biomass burning emissions 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. In this investigation, satellite data are compared to reliable ground-based fire datasets to evaluate the ability of satellite data to fully describe fire.

2.0 Methods

Validation of satellite data is only as good as the dataset against which it is validated. For this investigation, a detailed quality checked ground-based fire dataset is available from the WRAP, and fire perimeter data is provided by the Alaskan Fire Service. Data from two satellites are used to quantify the number of fires and estimate area burned in Oregon in July 2002 and in Arizona in August and September 2002. Additionally, an extreme fire season in Alaska 2004 is similarly examined. Because fire perimeter data is available from Alaska, the ability of the satellite data to track the movement of fire across a landscape is also investigated.

2.1 Oregon 2002

Satellite–derived fire products are compared temporally and spatially to a ground-based fire dataset from Oregon July 2002. Two satellite-derived products are considered in this analysis, Geostationary Operational Environmental Satellite (GOES) Automated Biomass Burning Algorithm (ABBA) and the MODerate Resolution Imaging Spectroradiometer (MODIS) thermal anomaly data. The reason for comparing two satellite products is to take advantage of the unique temporal resolution of GOES (15 minute data, 16 km^2 nadir resolution) and the unique spatial resolution of MODIS (twice daily, 1 km^2 nadir resolution).

Both MODIS and GOES ABBA products have demonstrated their ability to detect biomass burning in numerous ecosystems [3-7]. 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. Then, to account for the spatial resolution and the Point Response Function (PRF)[8] of the instrument, the instantaneous fire size is surrounded by a 5 km radius buffer. This provides for a realistic temporal and spatial assessment of the GOES ABBA fire data. 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. The buffered regions are used only to establish coincidence in fire events, not to calculate area burned.

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 has a detection confidence of less than 20% is excluded. An area burned estimate is not included in these data. For this reason and in consideration of the instruments 1 km^2 spatial resolution, the MODIS data points are surrounded (buffered) with a 0.5 km radius in GIS. Then to account for the PRF, the area is buffered with an additional 1.0 km radius. Similar to the GOES data, these buffered regions are used only to establish coincidence in fire events, not to calculate area burned. For this analysis, MODIS area burned is assumed to be equal to the approximate nadir pixel size (1 active-fire detection = 1 km^2).

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, etc.). These data were checked, geolocated and quality control reviewed by Air Sciences Inc. in preparation for the 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. With the exception of total area burned consideration, this analysis is focused on the wildfire, wildland fire use, and prescribed burning in wildlands data. The reasons for this are fourfold: there are no agricultural fires in Arizona during the time period analyzed; no coincidence exists in rangeland fires in Arizona; there are no rangeland fires in Oregon during the time period analyzed; and the dates in the Oregon agricultural data are inaccurate.

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, similar to the GOES and MODIS satellite data. Then, the number of coincident fires and the coincidence in area burned are analyzed. Coincident fire events are defined as those that occur in the same space and time. If satellite and ground-based data are coincident in time, then spatial coincidence occurs when the buffers overlap, as shown in figure 1. As long as one buffer touches another and the dates are coincident, then the fire is considered coincident. Every dataset (ground, GOES and MODIS) is projected to USA Contiguous Albers Equal Area Conic for a consistent analysis.

2.2 Alaska 2004

MODIS fire data are compared to Alaskan fire data from the extreme 2004 fire season to analyze the spatial and temporal coincidence in the data. Analysis includes the coincidence in the number of fire events, the amount of area burned and the spatial patterns of fire scars. The MODIS data used for this analysis are downloaded from the NOAA Hazard Mapping System (HMS) for June, July, and August 2004. Both the daylight and evening overpasses from the Terra and Aqua satellites are downloaded and duplicate detections are screened. For ease of calculation, each pixel is assumed to be 1 km^2. The ground fire dataset are provided by the Bureau of Land Management, Alaska Fire Service, and include 14 fire management zones under the jurisdiction of the Bureau of Land Management, the State of Alaska, and the Forest Service (http://agdc.usgs.gov/data/blm/fire/index.html). Unlike the WRAP data, these data include fire perimeters, as well as area burned, for fires greater than 100 acres (0.4 km^2), as reported in the fire incident reports. Complete fire perimeters will allow for an examination of how well MODIS fire detection data define the perimeters of fire scars as they burn across a landscape over time, which was not possible using the WRAP data.

3.0 Results

This analysis is possible because a high degree of confidence exists in the ground fire databases that allow for a developed investigation of the capability of satellite data to accurately quantify fire. Overall, the satellite data define fire well in Oregon, Arizona and Alaska, particularly in terms of area burned. The satellite data competently identify large fire events and the areas burned within large fires but the relationship is not as strong with small fires. Additionally, the spatial dimensions of the fire scars are accurately captured.

3.1 Limitations of the imagery

In order to understand and accurately assess the satellite-derived data products, one must consider the limitations of the satellite instruments. For one, cloud cover prevents the instruments from detecting active fires, so when thick persistent clouds are overhead, active fires are missed. Also, 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 instance, when an instrument detects fire, the position of the fire within a pixel is not known. Additionally, 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)] [8]. 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 edge overlap). Consequently, fires that burn between satellite overpasses are excluded, although a fire line is not typically1 km^2, thus it is anticipated that the resultant area burned is balanced. The GOES instrument is in a geostationary orbit and is constantly viewing North America. However, considering the GOES PRF, nadir spatial resolution, and the position of a fire within a pixel, the geolocation of a fire event could be off by maximum of about 10 km (0.05 degrees). Each of the instruments capture fires that the other instrument does not, but generally they capture the same fires and occasionally both instruments capture fires that are not described in the ground fire datasets.

3.2 Oregon and Arizona data coincidence

Maps of Oregon and Arizona showing regions of coincidence are provided in figure 2. Throughout this analysis, the WRAP dataset is considered to be "truth", and the authors regard this database as the best available ground fire data for the western region. In Oregon, during the month of July 2002, 101 unique fires (296 records) are recorded in the WRAP ground fire database (table 1). The combined satellite data distinguish 40% of the number of fires, and 90% of the representative area burned. Representative area burned is the area quantified in the WRAP dataset of the 40% coincident fires identified. Because the largest fires are consistently identified, even though the number of fires identified is often less than 50%, area burned approaches 100%. Overall, ignoring coincidence, GOES instantaneous area data accounts for 38% of the total area burned defined in the WRAP July 2002 Oregon data. Terra describes 130% and Aqua 67% of the total WRAP area burned (all MODIS 197%). This demonstrates that if 1 km^2 detections are assumed, then only 1 MODIS instrument is necessary to define area burned in fire regimes similar to Oregon July 2002.

In general, most of the fires that are identified by satellite in Oregon are identified by both the GOES and MODIS instruments (28 of 40, 68%). The GOES instrument identified 5 fires that MODIS did not distinguish, and MODIS identified 9 fires that GOES did not distinguish. MODIS identified are smaller fires (17 acres) than GOES detected (28 acres) in Oregon, which might be expected considering the spatial resolution of the instruments. GOES detected more large fires, so the area that is represented in the ground fire database as identified by GOES (not GOES instantaneous area calculation) is slightly larger (89.5%) than the area represented by MODIS (85.7%). There are also fires that are identified by both the GOES and MODIS instruments that are not recorded in the ground fire database, one of which is pictured in figure 3. Also, it appears that several coincident fires are missed due to differences in dates and geographic coordinates.

In Arizona, during August and September 2002, 165 unique fires (201 records) are recorded in the WRAP ground fire database (table 2). The combined satellite data distinguish 15% of the number of fires, and 58% of the representative area burned. Overall, ignoring coincidence, GOES instantaneous area data accounts for 22% of the total area burned defined in the WRAP data. Terra describes 100% and Aqua 97% of the total WRAP area burned (all MODIS 197%).

Because the background temperature in Arizona is high and much of the geologic material is highly reflective, satellites have a difficult time distinguishing fire in this ecoregion. For instance, in this ecoregion in August and September 2002, GOES classified 85% of the fires as low probability flag 5 data, as compared with GOES July data from Oregon that classified 14% of the fires as low probability flag 5 data. Both instruments identified 6 fires and MODIS identified an additional 19. Another reason for these differences between states is the mean fire size in Arizona is 79% smaller than that in Oregon. Additionally, there are numerous fires that are identified by both the GOES and MODIS instruments that are not temporally coincident with the ground fire database (offset by 1-2 days), which could have skewed the results (see figure 3).

Area burned within individual fire events is directly compared to satellite data, and this comparison is shown in figure 4. In Oregon, both the GOES (R^2 = 0.85) and MODIS (Terra and Aqua R^2 = 0.78) area burned products compare well to the WRAP fire data. GOES data generally underestimate area burned, which is reasonable considering that GOES data are estimating instantaneous fire size. Nonetheless, the GOES/WRAP area burned relationship is stronger than the relationship between the MODIS/WRAP data in this example. In this case, MODIS overestimates one large fire by 45% and underestimates a medium-sized fire by 450%. However, if these 2 outliers are deleted, the R^2 value increases from 0.78 to 0.95. In Arizona, the relationship between the WRAP and GOES data (R^2 = 0.48) is not as strong as the relationship between the WRAP and MODIS (Terra R^2 = 0.95; Aqua R^2 = 0.99) area burned products.

3.3 Alaskan data coincidence

The HMS MODIS data compare successfully to the Alaskan large ground fire database as shown in figures 4 and 5. The fires that burned during the 2004 Alaskan fire season are shown in figure 4a, and figures 4b through 4f show the outline of random fire scars and the MODIS detections. The MODIS data are capable of defining the spatial extent of the fire scars over time, as shown in figure 4. This in not possible using the EPA ground-based data, however the additional spatial domain could greatly improve the spatial domain of biomass burning emissions. For example, referring to the zoomed image shown in figure 1, one can picture the spatial domain captured by MODIS but not captured in the WRAP data.

MODIS fire detections identify 86% of the number of fires and account for 112% of the total area burned during the Alaskan fire season. In this ecoregion, the combined Terra and Aqua data did not substantially overestimate area burned. Potential reasons for this improvement could be due to the rigor of the HMS algorithm and/or satellite data are better at defining the large fire scars that are typical of this ecosystem. Fire scars that are not detected by the MODIS instrument are generally less than 1 km^2 (largest undetected scar 4.56 km^2). In figure 5, a linear relationship between the fire scars and MODIS data is shown, demonstrating that the relationship between MODIS data and area burned is strong overall (r^2 = 0.94) and when defining large scars (r^2 = 0.92). The relationship between small fire scars (< 6 km^2) and MODIS data is not as strong (r^2 = 0.04).

Commission errors are false positive detections or where the satellite data identified a fire and none was reported on the ground. In the Alaskan data, commission errors are remarkably low, 6.78% of the number of fire scars and 0.31% of the area burned. Furthermore, the commission error is likely to be less than the reported value because several fire scars are also identified in alternative imagery [Advanced Very High Resolution Radiometer (AVHRR)] in regions where the MODIS instruments detected fires but the ground fire database did not report fires. The MODIS instruments omitted 14% of the fire scars identified in the ground data (omissions error), which equates to 0.08% of the area burned, supporting the argument that small scars are generally omitted and most of the area burned can be adequately quantified with satellite data.

4.0 Discussion

In this investigation, satellite data are shown to be able to accurately identify large fires, to quantify the largest percentage of the area burned and to emulate the spatial pattern of fire across landscapes. One of the major goals of this research is to accurately quantify emissions by accurately defining the amount of area burned that can be quantified by satellite data. Because area burned amounts to easily half of the emissions equation[9,10], it is important to assign error to satellite estimates of area burned before emission estimates can be viewed with confidence.

Satellite data identified 90% of the representative area burned in Oregon and 58% of the representative area burned in Arizona. Even though the number of fires identified is often less than 50%, area burned is generally well described. This is because most of the area burned can be defined by the largest fire events, and these are the events that satellite data accurately define. In Oregon, 80% of the area burned can be defined with the largest 10% of the fires, and in Arizona, 74% of the area can be defined with the largest 10% of the fires. The ground data from Alaska is only a large fire database, so a similar analysis is not possible. However, long-term Alaskan fire records (since 1950) show that 96% of the area burned is by large fires (> 20 km^2)[11]. The same relationship holds in Canada and Russia [12,13]. For this reason, the greatest percentage of area burned and emissions can be identified and quantified using satellite data. Consequently, these data can be used to estimate the largest fires and the largest biomass emissions, which result in the 20% worst air quality days[14,15]. These are the days that constitute the greatest health risk to the public and push the limits of air quality attainment.

At this time, 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 define an accurate perimeter of fires as they progress across a landscape, which is valuable to estimating the locational source and transport of biomass burning emissions. Considering that firefighters are generally concerned with controlling fire, not area mapping for emissions, this adds enhanced value to satellite data. Additionally, relatively 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.

5.0 Conclusions

This paper is the result of an initial investigation that explores the capability of satellite data to detect active fires and quantify area burned in Oregon July 2002, in Arizona August and September 2002 and in an extreme fire season in Alaska 2004. Due to the resolution of the satellite instruments, the data poorly define the number of fires and small fire events. However satellite data are able to proficiently identify large fires, which accurately characterizes the amount of area burned and the spatial pattern of fire. However, in order to move satellite-based emissions fire science forward, a 1 km^2 fire scar (area burned) product is essential due to the inherent inaccuracies of fire detection (thermal anomaly) data. A burning fire line is rarely, if ever, 1 km^2. Also, a reliable validation dataset is crucial to accurately validating satellite data. For this reason, because an accurate 2002 ground-based fire dataset exist, a key year for a validation exercise would be 2002.

Ground and satellite data provide unique views of patterns of fire in Oregon, Arizona and Alaska, and this investigation demonstrates that a more rigorous examination of the data is warranted. In the future, we intend to expand this analysis to include several additional ecoregions (WRAP states, Georgia, Virginia and Florida) over a longer period of time to enhance error estimates, which are inherent to specific ecosystems and at particular times of the year. These types of investigations are limited by the availability of accurate ground fire data.

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 near-real-time biomass burning emissions inventory system that contains accurate error assessments.

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Table 1. Coincidence in Oregon ground- and satellite-based fire data for July 2002. The coincidence analysis is based on wildfire, wildland fire use, and prescribed burning in wildland inventories. Percent area burned includes all available ground data (shown in red).

Data source	Number of records	Acres burned (range)	Percent area burned of ground data	Percent number of fires coincident	Percent representative area coincident
GOES ABBA	1996	197,655 (1.16 – 806.66)	38% (Instantaneous)	31%	89.5%
MODIS Terra	2761	682,268 (from detections)	130% (detect = 1km^2)	33%	85.7%
MODIS Aqua	1419	350,643 (from detections)	67% (detect = 1km^2)	27%	80.7%
Oregon ground data, 101 fires	296	**500,555** (1.98 – 54400.5) **mean 1691 acres**		Combined satellite 40%	Combined satellite 90.1%
Oregon agricultural burning	312	**21,569** (0.30 – 469) **mean 69 acres**			

Table 2. Coincidence in Arizona ground- and satellite-based fire data for August and September 2002. The coincidence analysis is based on wildfire, wildland fire use, and prescribed burning in wildland inventories. Percent area burned includes all available ground data (shown in red).

Data source	Number of records	Acres burned (range)	Percent area burned of ground data (all satellite data)	Percent number of ground fires coincident	Percent representative ground area coincident
GOES ABBA	169	9,491 (1.23 - 442)	22% (Instantaneous)	3%	44.8%
MODIS Terra	168	41,514 (from detections)	100% (1km^2 detection)	10%	51.4%
MODIS Aqua	162	40,031 (from detections)	97% (1km^2 detection)	9%	51.1%
Arizona ground fire data, 165 fires	201	**22,612** (0.50 – 1,598) **mean 113 acres**		Combined satellite 12%	Combined satellite 58%
Arizona Non-federal rangeland burning	34	**18,750** (124 – 1,100) **mean 552 acres**			

Figure 1. Buffer overlap. In this example, there are many WRAP ground fires shown in red, surrounded by area burned in rose. Note the varying sizes of the GOES instantaneous area data. Also, there is a spatial pattern formed with the MODIS data that is not available with the point-based ground data. All of the buffered pixels that are overlapping are considered coincident, as long as they are within the date range of the overlapping WRAP data. In this view, if the satellite dates are within the WRAP fire date range, then there are 16 coincident fire events and several of the WRAP fires are defined by more than 1 record.

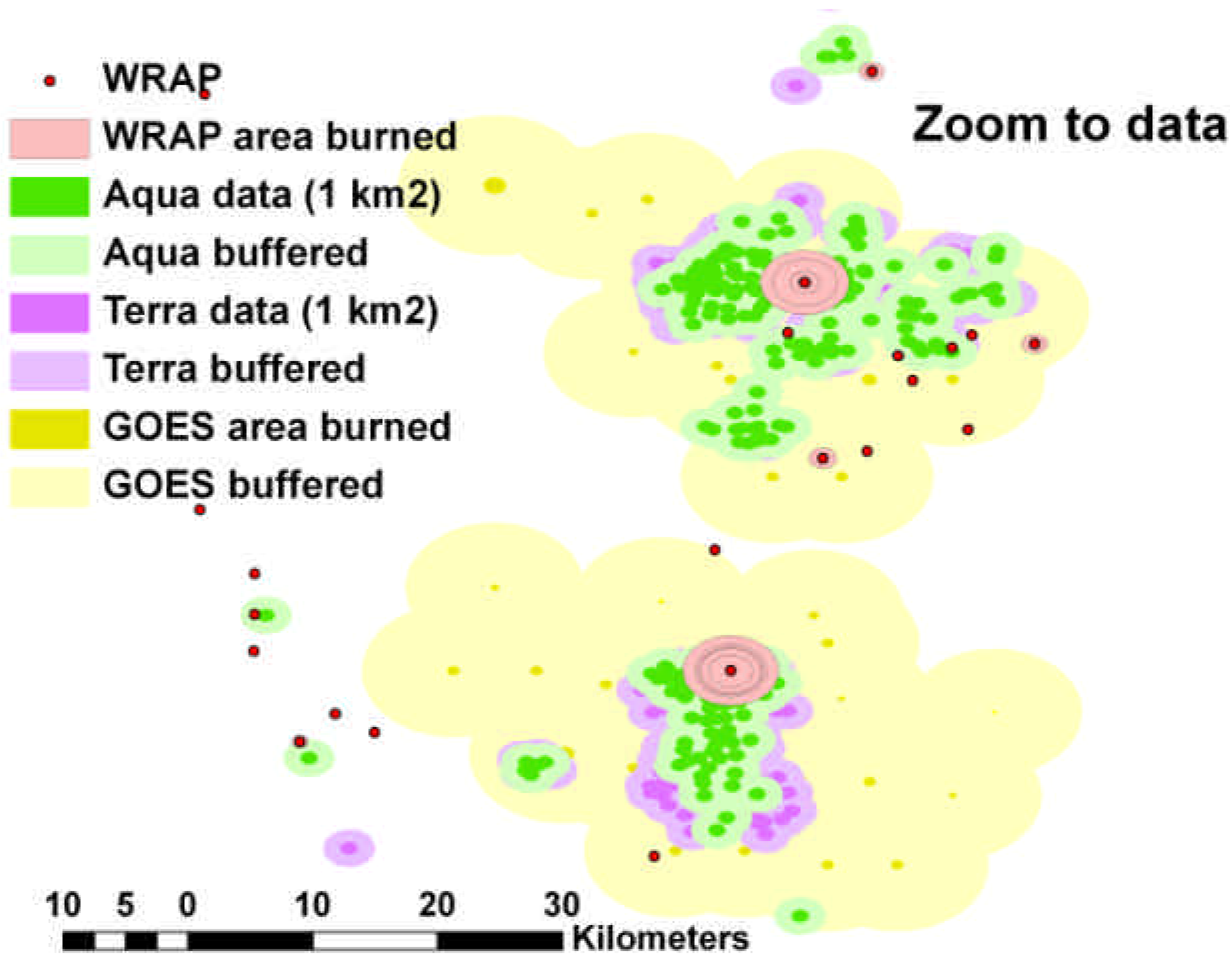
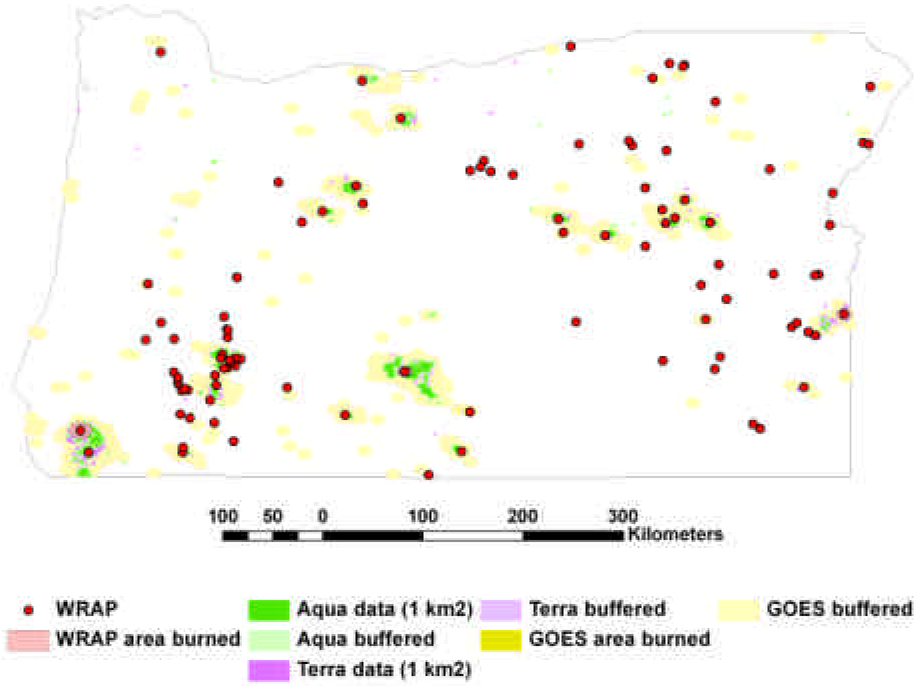
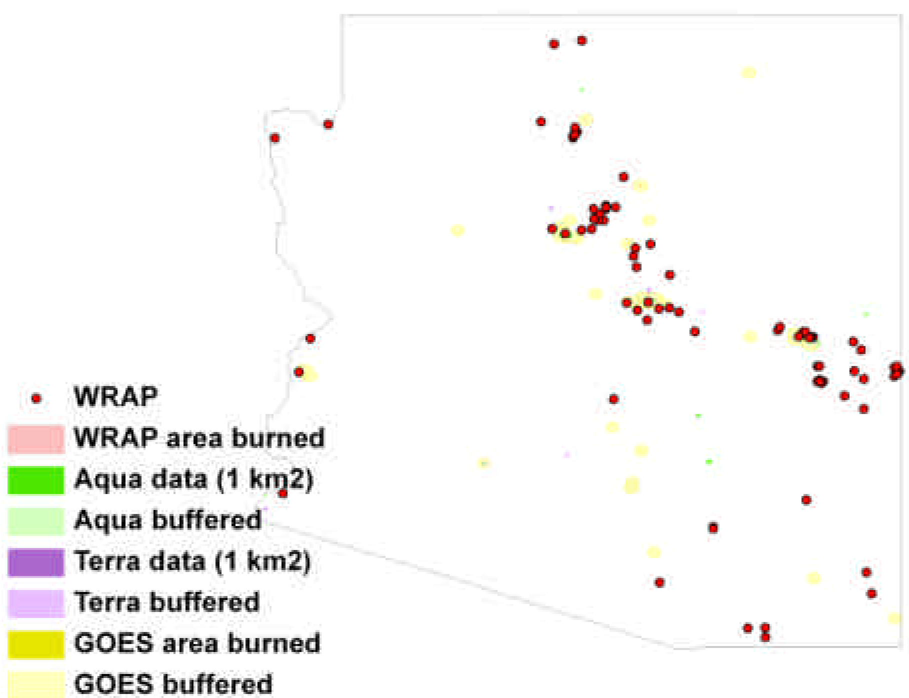


Figure 2. Spatial coincidence in satellite- and ground-based fire data.

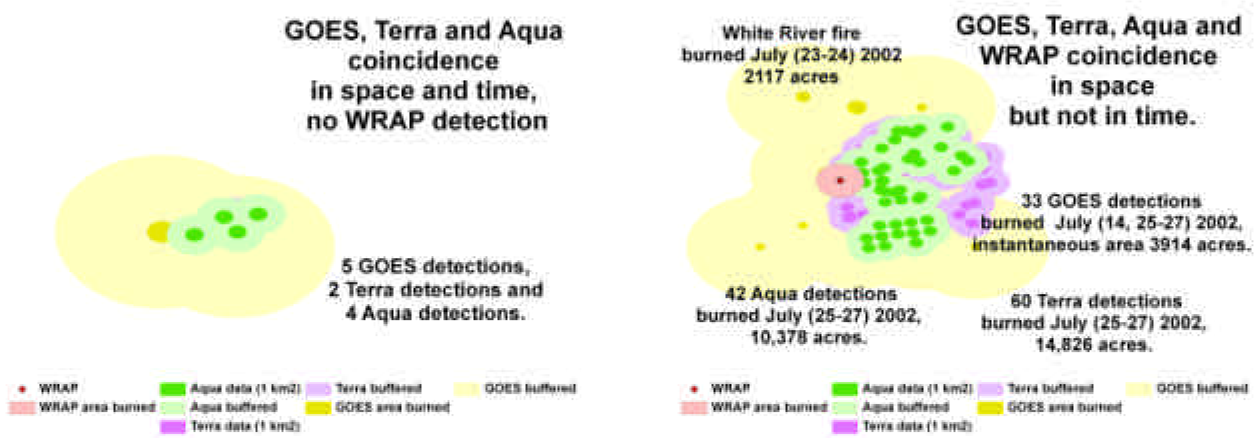


a. Oregon, July 2002

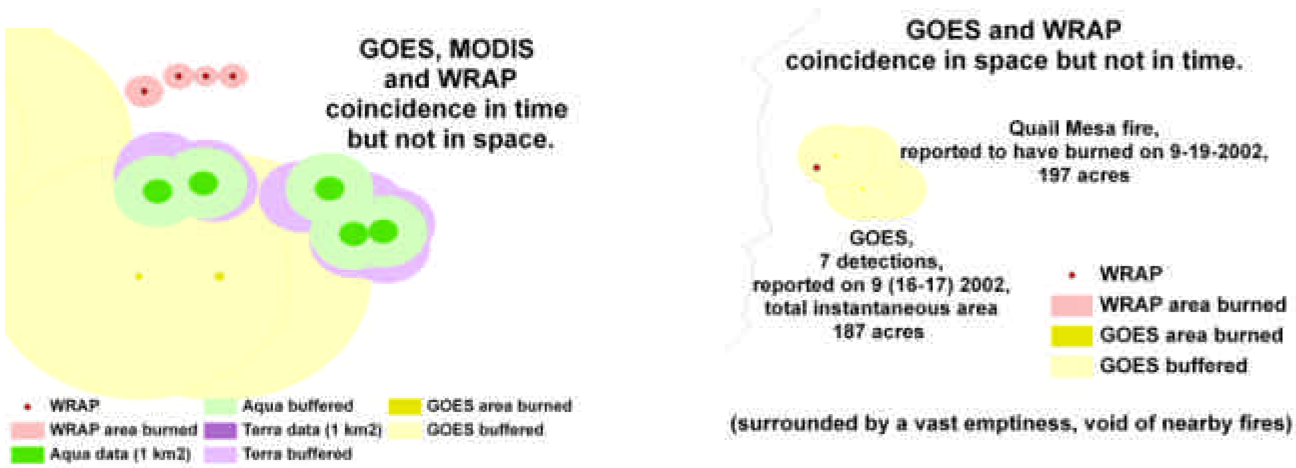


b. Arizona, August and September 2002

Figure 3. Examples of potential error in time and space.

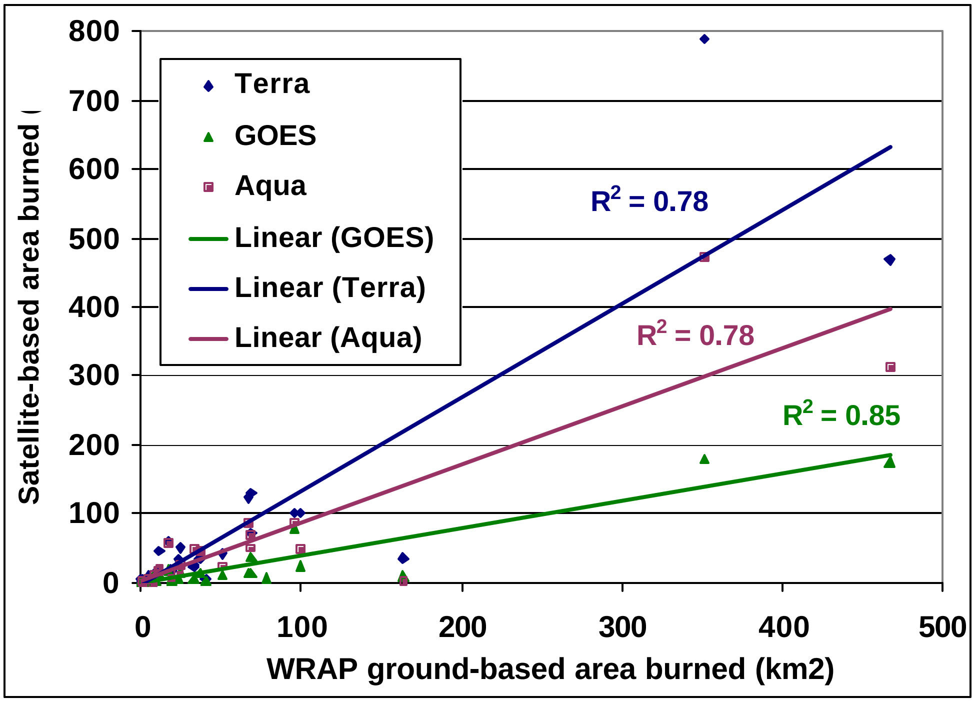


a. Examples taken from Oregon.

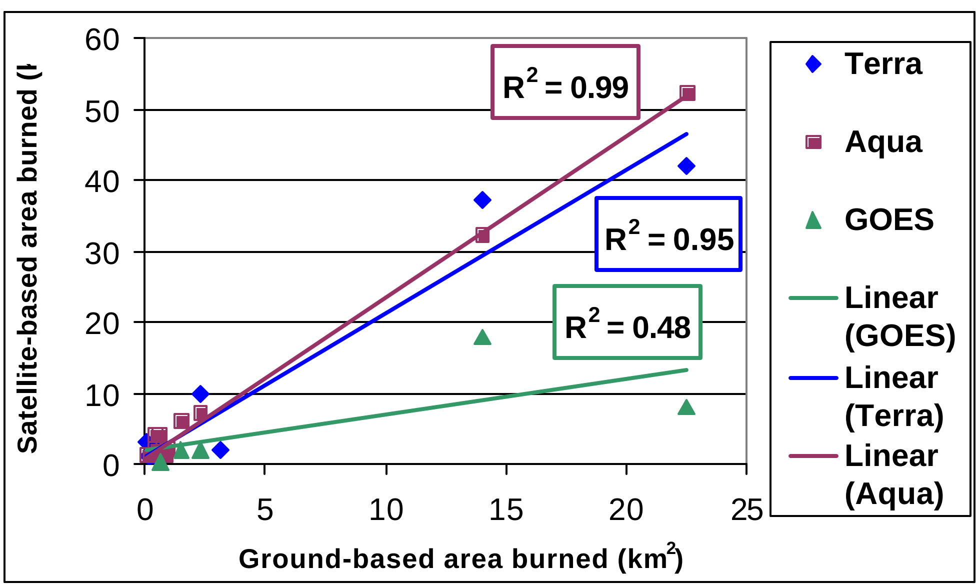


b. Examples taken from Arizona.

Figure 4. Comparison of satellite-based area burned (km^2) to ground-based data (km^2). GOES area burned is the sum of the instantaneous fire sizes that are spatially and temporally coincident with the WRAP data. Each active-fire MODIS pixel is considered to be fully burned (1 km^2), and the sum of the pixels that are spatially and temporally coincident with the WRAP data are evaluated.



a. Oregon, July 2002



b. Arizona, August and September 2002

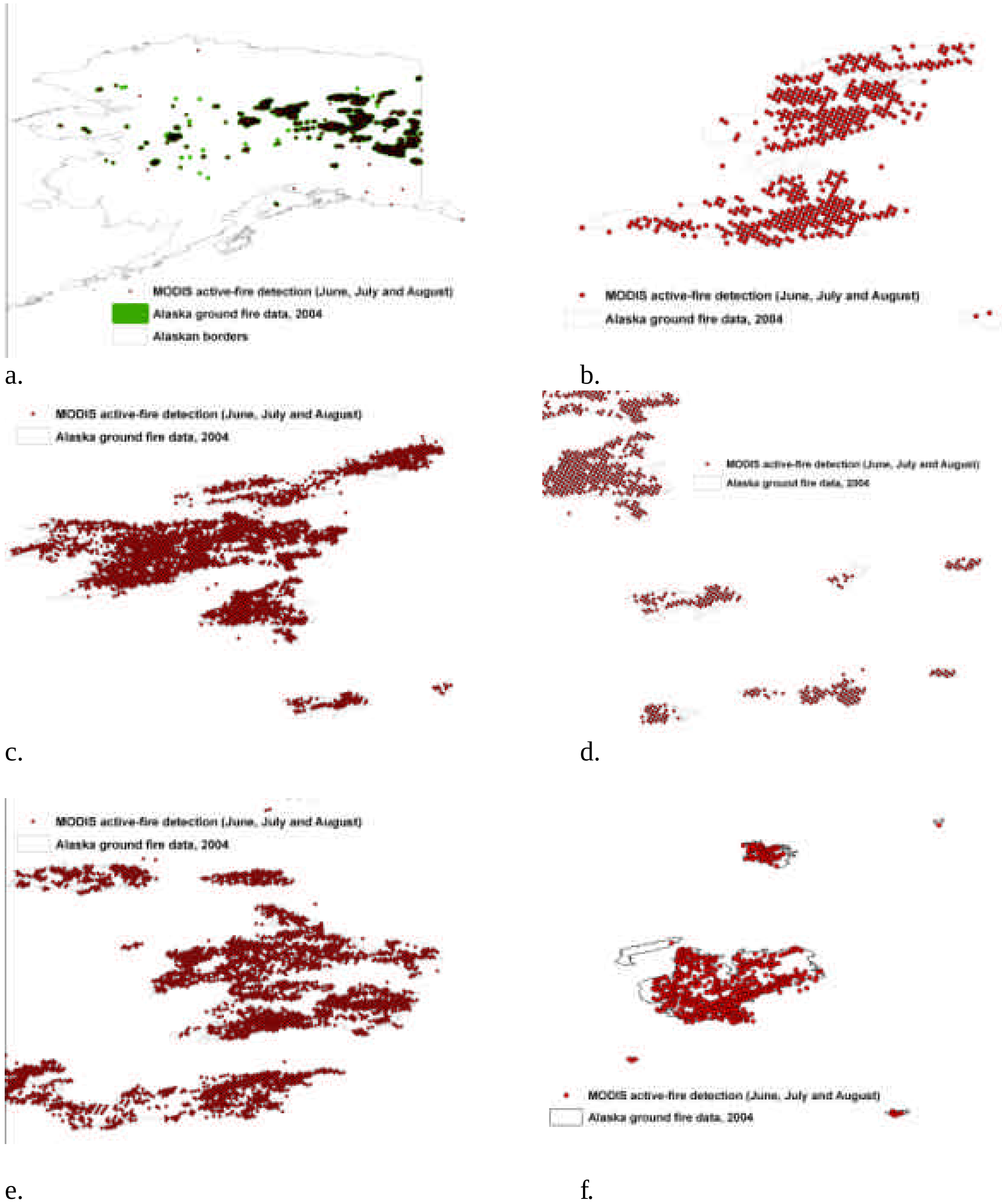
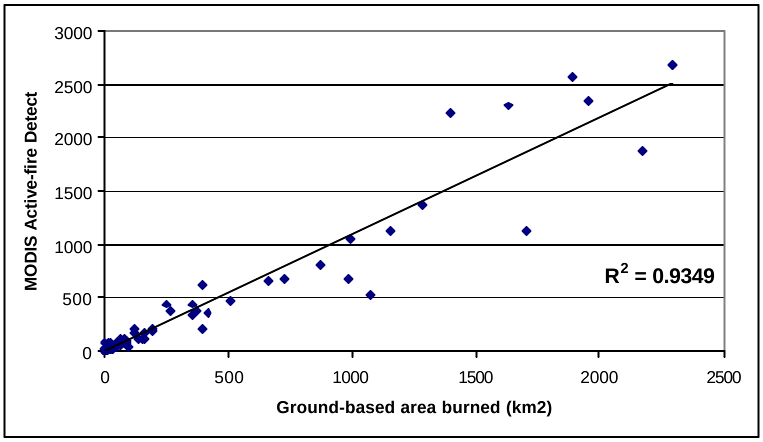
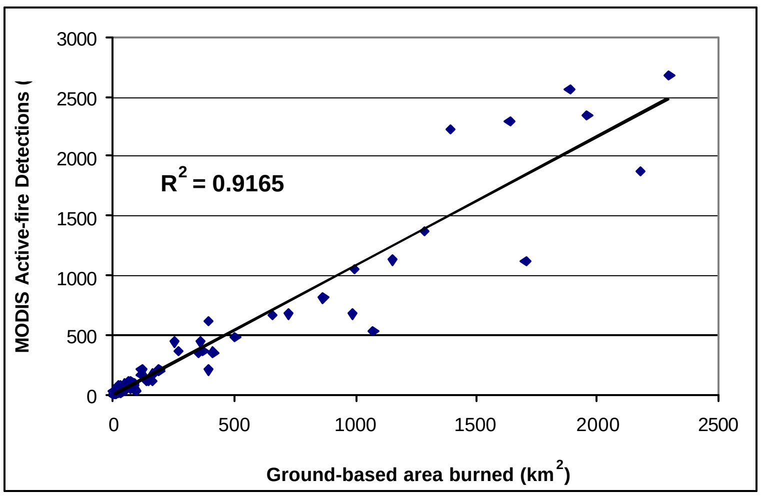


Figure 4. Fire scars from the 2004 Alaskan fire season and MODIS data from June, July and August, 2004. MODIS thermal anomaly data are overlaid on a fire perimeter database showing the spatial coincidence in the MODIS data and the fire scars over time. In most cases, the MODIS data fall within the fire perimeters demonstrating the ability of MODIS data to outline the spatial movement of fire over time. The MODIS data are able to detect most scars (86% of the number of fires and 99.9% of the area).

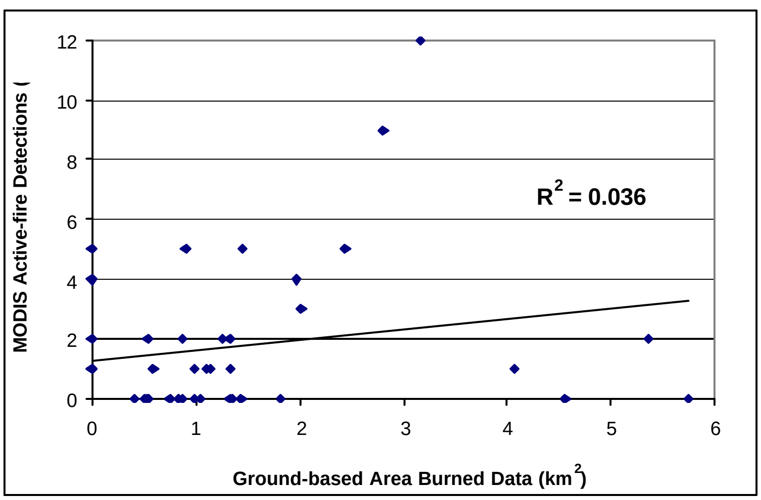
Figure 5. Comparison of area burned during the extreme 2004 fire season in Alaska. MODIS data are taken from June, July and August 2004 when the fires are most active and the fire scars sizes are reported for the entire fire season. The linear relationship show that MODIS data are able to accurately estimate the amount of area burned, particularly for large fires.



a. All data



b. Large fire data only (ground fires > 6 km^2).



c. Small fire only (ground fires < 6 km2)