AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE
10.1029/2017JD028217

Key Points:
- Comparisons between permit record data sets and two satellite-derived data sets show that satellite products underestimate the burned areas
- Satellite-derived products can capture a cluster of fires better than isolated fires but may misinterpret them as one big fire
- Considering the deficiencies of satellite-derived products, and the missing data caused by cloudy days, we trust the permit records more

Supporting Information:
- Supporting Information S1

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Citation:
Huang, R., Zhang, X., Chan, D., Kondragunta, S., Russell, A. G., & Odman, M. T. (2018). Burned area comparisons between prescribed burning permits in southeastern United States and two satellite-derived products. *Journal of Geophysical Research: Atmospheres*, *123*, 4746–4757. https://doi.org/10.1029/2017JD028217

Received 19 DEC 2017
Accepted 9 APR 2018
Accepted article online 16 APR 2018
Published online 7 MAY 2018

Burned Area Comparisons Between Prescribed Burning Permits in Southeastern United States and Two Satellite-Derived Products

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Abstract Prescribed burning (PB) is one of the most prominent sources of $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) in the southeastern United States. The PB emissions estimates may have significant uncertainty because they are based on the burned areas reported to the state agencies when burners apply for burn permits. When no permit records are available, satellite-derived products could be used as a substitute tool to provide burned area data. In order to evaluate burned areas from satellite-derived products, we conducted a comparison between PB permit records and two satellite-derived products, Blended Polar Geo Biomass Burning Emissions Product and Global Fire Emissions Database, in Georgia and Florida. The comparison results indicate that both satellite-derived products underestimate seriously the burned areas compared to permit record data. They can capture a cluster of fires better than isolated fires but may misinterpret those small fires together as one big fire. Overall, current satellite-derived products have limitations in estimating the burned areas of small fires and still need improvements.

Plain Language Summary Prescribed burning is a preferred land management tool but also a prominent source of air pollution in the United States, and exposure to fire smoke is a growing health concern. Burned area is a direct input to the estimation of smoke emissions; therefore, it is critical to have accurate burned area data to be able to conduct reliable assessments of exposure to smoke. While some states like Florida and Georgia keep extensive prescribed burn records through permitting programs, other states may not even have a permitting system in place. In the absence of permit data, satellite products are the only recourse to obtaining burned area data. Previous studies have attempted to evaluate the uncertainty of burned areas by comparing different satellite products. In this study, we compared burned areas from prescribed burning permit records and two satellite products in Florida and Georgia during the 2015 and 2016 burning seasons. Burned areas in permit records are only preburn estimates, but a survey we conducted suggests that they are within 15% of the actual burned areas. Our comparison results show that current satellite products generally underestimate the burned areas of small fires and need several improvements for detection of prescribed burns.

1. Introduction

Biomass burning (BB) is the burning of land covering vegetation for a wide range of purposes ranging from land clearing to restoring nutrients to the soil. Emissions from BB could interact with the atmosphere and climate systems; change carbon balances and atmospheric chemistry components; and affect clouds and precipitation (Liu, 2005), permafrost structure, and surface albedo (Natarajan et al., 2012; Randerson et al., 2006; Sokolik et al., 2010). BB is also an important global source of aerosols such as $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) and black carbon (Andreae & Merlet, 2001), which can affect human health, and smoke, which can reduce visibility and paralyze highway transportation. Considering the potential impacts of BB, the estimation of those emissions is crucial. Typically, emissions are calculated by the amount of burned area, biomass present in the ecosystem, efficiency of combustion, and pollutants emitted per unit mass of fuel consumed, also known as emission factors (Seiler & Crutzen, 1980). Here we will focus on the burned area.

Prescribed burning (PB) is a type of BB employed as a land management tool since the 1930's to improve native vegetation and wildlife habitat, control insects and disease, and reduce wildfire risk in the United States (Leopold, 1987). The U.S. Environmental Protection Agency 2011 and 2014 National Emissions Inventories reported that 14.8% (2014) and 15.1% (2011) of $PM_{2.5}$ emissions in the United States are attributable to PB and 27% of $PM_{2.5}$ emissions from PB originate from the southeastern United States (U.S. Environmental Protection Agency, 2011, 2014). PB is one of the most prominent sources of $PM_{2.5}$ emissions in the southeastern United States (20% in 2011 and 24% in 2014) and will become an increasing source as other sources are controlled. According to the 2014 National Emissions Inventory, nearly 50% of all fire-related $PM_{2.5}$ emissions are from prescribed fires, while over 75% of those emissions come from prescribed fires in the southeastern states. These emissions estimates are based on the burned areas reported by the states, which may be subject to large uncertainty since not all states have reliable prescribed burn records. In some states, a permit is not necessary to conduct a burn. Some states keep records of the burns on state-owned and private lands, but federal land managers are not obligated to report burns to the state. Also, the permit records themselves have uncertainties since they contain values for areas intended to be burned and not actual burned areas. Finding another, more reliable way to estimate those prescribed burned areas is important for accurately estimating the emissions of PB and evaluating its impacts to air quality.

Several satellite-derived products such as Hotspot and Normalized Difference Vegetation Index Differencing Synergy (Fraser, Li, & Cihlar, 2000; Fraser, Li, & Landry, 2000), Global Burned Area – 2000 (Tansey et al., 2004), Global Wildland Fire Emission Model (Hoelzemann, 2004), Global Fire Emissions Database 3 (Giglio et al., 2010), MCD45A1 (Roy et al., 2008), L3JRC (Tansey, Beston, et al., 2008; Tansey, Grégoire, et al., 2008), GLOBSCAR (Simon et al., 2004), Global Burned Surfaces (Carmona-Moreno et al., 2005), Global Fire Emissions Database (GFED4s; Giglio et al., 2013) and Blended Polar Geo Biomass Burning Emissions Product (Blended-BBEP or BBEP in this paper) (Zhang & Kondragunta, 2008) have been developed for estimating the burned area of BB. Only GFED4s and BBEP continue to be available publicly at this time. Several evaluations (Boschetti et al., 2004; Chuvieco et al., 2016; Hoelzemann, 2004; Kukavskaya et al., 2013; Li, Nadon, & Cihlar, 2000; Li et al., 2003; Randerson et al., 2012; Zhu et al., 2017) have been conducted to examine the uncertainties of those products. Although these products are in good agreement with emission inventories reported by different countries in most regions around the globe, there are major disagreements in terms of burned area estimates, which could be caused by spatial, temporal, and spectral disparities, distinct algorithms, and instrument drift from different satellite products (Boschetti et al., 2004; Kukavskaya et al., 2013). For example, Global Wildland Fire Emission Model emissions are biased low in most regions compared to the Along Track Scanning Radiometer-scaled Model for Ozone and Related chemical Tracers inventory (Schultz, 2002), but the uncertainty is the largest in regions where small fires dominate (Hoelzemann, 2004). Those small fires may have a large impact on global BB carbon emissions (Randerson et al., 2012). Zhu et al. (2017) found large underestimation in croplands by comparing burned area from Moderate Resolution Imaging Spectroradiometer (MODIS) and other satellite products with higher resolution. Zeng et al. (2016) compared fire counts from MODIS with Visibility Improvement—State and Tribal Association of the Southeast fire inventory and reported improved model performance with the MODIS-updated fire emission inventory. Hu et al. (2016) performed a comparison between Hazard Mapping System fire product and permit records based on fire detection rate as a function of burned area. Up to now, uncertainty in satellite burned area estimates has been estimated only through comparison of different satellite products; there has been no comparison of satellite burned area estimates with ground-based burned area measurements or estimates.

In PB, fires are usually small to keep them under control. Satellite-derived products may have large uncertainty when used in estimating burned area of those small fires (Hoelzemann, 2004; Kukavskaya et al., 2013; Mouillot et al., 2014; Randerson et al., 2012). This is especially true for current operational geostationary satellites whose imagers have a spatial footprint of 4 km in nadir view and as large as 8–12 km at the edge of the scan. This can lead to missed detections if fire temperature is not too high compared to surrounding pixels as the algorithm uses surrounding pixels to obtain background temperature (Schroeder et al., 2010). In order to evaluate those satellite-derived products and assess whether they can be used in PB burned area estimation, we conducted a comparison between PB permit records and satellite-derived burned area. This paper will focus on the comparison of PB permit records in Georgia and Florida in the first 4 months of 2015 and 2016, which is the most active burn season in those two states, with two satellite-derived products: BBEP and GFED4s. The goal is to assess the uncertainty of those two products and to determine whether they can be used in follow-up research to forecast the PB impact on air quality.

2. Data

2.1. Burn Permit Data

2.1.1. Georgia Prescribed Burn Permit Record Data

Georgia is one of the most active states in applying PB in the United States. The Georgia Forestry Commission (GFC) is responsible for PB services in the state. It is necessary to obtain a burn permit from the local GFC office before burning woods, lands, marshes, or other flammable vegetation. Burn permits contain the contact information of the landowner, county of burn, location of the burn, acres to be burned, the start and end times of the burn, and the name/phone number of the person to contact during the burn in case additional information is needed according to Georgia Prescribed Burning Act (GA Code Ann. 12-6-145 to 12-6-149). The PB season for Georgia is from 1 October to 30 April. A burn ban goes into effect in 54 counties during the ozone season (1 May to 30 September). We obtained permit record data from GFC for the years 2015 and 2016. Considering the ozone season restriction and the relatively small number of burns during October–December, we focused our analysis on the first 4 months of each year. Some permits have latitude/longitude information of the burn, but most of them only have an address, which may be in a nonstandard format that is difficult to be geo-referenced.

2.1.2. Florida Open Burn Authorization Record Data

Florida, another high burn activity state in the United States, issues 120,000 authorizations allowing landowners and agencies to prescribe burn an average of over 800,000 ha (2 million acres) each year. Florida Forest Service (FFS), a division of Florida Department of Agriculture and Consumer Services, is in charge of managing prescribed fire in Florida. Landowners need to contact the local FFS office with their customer number and provide the location and size of their burn to get an authorization. A smoke plume model is executed before approving the burn request to make sure that there are no potential problems with the smoke from the burn. The dominant burn types in Florida are agricultural, land clearing, and silvicultural burns. We obtained open burn authorization (permit) data from FFS for the years 2015 and 2016 and conducted an analysis of the first 4 months of each year. Each open burn authorization in Florida has latitude and longitude information, which are either provided by a GPS device or from a digitized map during the authorization process.

2.1.3. Uncertainty of Permit Records

The permit records are considered to be accurate by the permit issuing agencies based on their experience and anecdotal evidence, but there is no scientific research to support this hypothesis. One of the strongest supports for their hypothesis is that the permits are issued on the day of the burn and, when a landowner calls for a permit, there is a strong intention to burn. However, weather may still play a role in whether a burn is conducted or not on that day after the permit is issued. If the weather onsite is not conducive to a successful burn, permit holders may choose not to exercise their right to burn.

Another source of inaccuracy may be the recorded size of the burn. The burned areas in permit records are not necessarily equal to the actual burned areas; they are simply estimates of areas planned to be burned. Even if the burn is conducted on the day the permit was issued for, the actual burned area may differ from the permitted area. Considering the difference between the fire weather forecast and actual field conditions during the burn, landowners may burn more or less land than they reported at the time of permit application. For example, landowners usually ask for a permit for the total area of their land but drainage areas are not burned and some sensitive ecosystem areas may be avoided.

Neither Georgia nor Florida follows up with the burners to find out the actual burned areas. We conducted a limited survey in Georgia to evaluate how well the burned area values in permit records represent the actual burned areas. We called a small subset of the landowners and asked them to report any differences between the actual burned areas and the areas on the permit records. Because of the difficulty many landowners had in retrieving older records, we surveyed burns from 2016 and 2017. Our initial selection of the burners aimed to be representative of the sizes and geographic locations of the burns throughout the state, but the respondents did not necessarily match these profiles.

2.2. Satellite-Derived Data

2.2.1. Blended Polar Geo Biomass Burning Emissions Product

The Blended-BBEP is a continuous product for North America of BB emissions with active fire data that are detected using WildFire Automated Biomass Burning Algorithm (WF-ABBA) from Geostationary

Operational Environmental Satellite (GOES; Prins & Menzel, 1992, 1994), Fire Identification, Mapping, and Modeling Algorithm from the Advanced Very High Resolution Radiometer (AVHRR) (He & Li, 2012; Li, Nadon, Cihlar, & Stocks, 2000), and an enhanced contextual fire detection algorithm from the MODIS (Giglio et al., 2003, 2016). The Blended-BBEP is produced by blending, every 6 hr, fires detected from GOES-East, GOES-West, MODIS on both the NASA Terra and Aqua satellites, and AVHRR on National Oceanic and Atmospheric Administration 15/17/18. The outputs include burned area and emissions of the following species: $PM_{2.5}$, CO, CH_4, CO_2, total nonmethane hydrocarbon, NH_3, N_2O, NO_X, and SO_2. The burned area is simulated using active fire observations from MODIS, AVHRR, and GOES for each GOES fire pixel (Zhang et al., 2011). Instantaneous fire size obtained from 30-min GOES observation using WF-ABBA is found to be an accurate representation of burned area for that time interval. The determination of fire size happens for approximately 20–30% of all WF-ABBA detected fires. For fires that are detected but not determined in size by the WF-ABBA algorithm, the size is simulated using climatological diurnal variation in fire size specific to biomass type where the fire is observed. If fire hot spots are detected only by polar-orbiting satellites, fire size is determined using a conversion factor that was derived by regressing fire hot spots with the burn scars detected from postfire Landsat Enhanced Thematic Mapper plus imagery. We downloaded the 2015 and 2016 BBEP data from the BBEP website (http://satepsanone.nesdis.noaa.gov/pub/FIRE/BBEP-geo/PREVIOUS_DAYS/).

2.2.2. Global Fire Emissions Database

GFED4s provides monthly burned area and fire emissions by combining satellite information on fire activity and vegetation productivity. The current version, Version 4, has a spatial resolution of 0.25°. GFED4s is the product including small fires, combining 1-km thermal anomalies (active fires) from Terra and Aqua and 500 m burned area observations from MODIS daily composition thermal anomaly/fire products (MOD14A1 and MYD14A1) (Randerson et al., 2012). Small-fire-burned area is estimated by computing the difference normalized burn ratio (dNBR) for these two sets (1 km and 500 m) of active fires and then combining these observations with other information such as efficacy of the burned area detection algorithm, the frequency of satellite overpasses, and the rate of movement of the fire front (Randerson et al., 2012). We obtained the monthly GFED4s data from Dr. James Randerson's group at the University of California, Irvine.

2.2.3. Burned Area Essential Climate Variable

To test the effect of finer spatial resolution, we used Burned Area Essential Climate Variable (BAECV) as an additional product. BAECV is the burned area product from Landsat satellite developed by the U.S. Geological Survey (USGS) (Hawbaker et al., 2017). Landsat has a repeat cycle of 16 days, and BAECV only has annual data over the contiguous United States with 30 m × 30 m resolution. BAECV uses a gradient boosted regression model to estimate the probability that pixel had burned, followed by a thresholding process to generate a binary burned or unburned classification. We downloaded the 2015 BAECV data from the USGS website (https://rmgsc.cr.usgs.gov/outgoing/baecv/BAECV_CONUS_v1_2017/).

2.3. Correlation Analyses

We conducted correlation analyses using Pearson and Spearman correction coefficients. Using daily state total burned areas from Georgia's permit records and BBEP, we performed a log transformation of the data to test if Pearson correlation coefficient is suitable for our analysis. Since BBEP data may have zero burned area on some days, which, when log transformed, would lead to negative infinity, we added 12 ha (which is approximately equal to BBEP's detection limit) to both permit record and BBEP burned areas. Then we took the common logarithms ($\log_{10}(x)$) of both permit and BBEP data and plotted their correlations. Finally, we calculated the residuals of both the untransformed and transformed data sets as $y_{obs} - y_{mod}$ where $y_{mod} = x \times \text{Slope} + \text{Intercept}$; y_{obs} is the BBEP data, and x is the permit data before or after the log transformations.

3. Results and Discussions

Prescribed burning includes controlled fires conducted for the maintenance and protection of commercial timber stands, land clearing, agriculture, reduction of vegetative fuels for wildfire prevention, and management of fire-dependent ecosystems. Here we considered all burn permits/authorizations with records of burned areas.

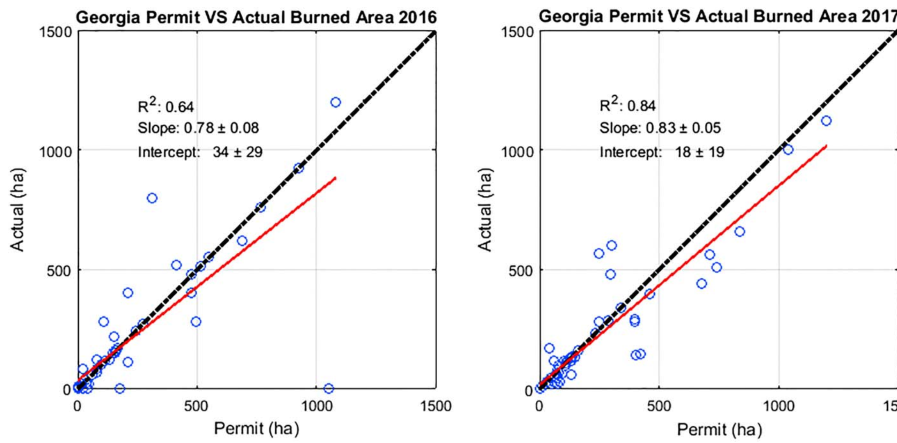

Figure 1. The results of a phone call survey comparing permitted and actual burned areas in Georgia for 2016 and 2017. The survey covered 346 small (less than 24 ha), 212 medium (24 to 54 ha), and 185 large (larger than 54 ha) burn permits for 2016 and 371 small, 228 medium, and 215 large permits for 2017.

3.1. Burn Permit Survey

The target sample size of our phone call survey was approximately 10% of the total area that got burned during the calendar year. There was a total of 96 respondents in our survey. Many respondents are from professional companies that have complete records of the burns they conducted. To those that did not have detailed records of their burns, we asked to report the total acreage of their land minus the known protected areas to get the approximate area they burned. The result shows good agreement between permitted and actual burned area with r^2 equal to 0.64 and 0.84 for 2016 and 2017, respectively (Figure 1). Each point on the plot represents the totals for one burner. The figures include 371 small (less than 24 ha), 228 medium (24 to 54 ha), and 215 large (larger than 54 ha) burn permits for 2017, and 346 small, 212 medium, and 185 large permits for 2016. The survey results suggest larger uncertainty in 2016 permit records than 2017 since the regression line deviates more from the 1:1 line with a slope of 0.78 versus 0.83 and an intercept of 85 versus 46. This may be simply due to better remembrance of the more recent year's burns.

The burned area data came from permit/authorization records. Actual burn areas are not tracked by the authorizing agencies (GFC and FFS), and the landowners are not required to call back and confirm or correct the burned areas. Our phone survey revealed that unburned areas within the plots such as drainages, deer camps, and structures are not always excluded. However, our survey also found that this constitutes a small part of the uncertainty. Unsuccessful burns remain in the records as permitted. GFC, which has evaluated this issue before, postulates that since almost all of their permits were issued on the day of the burn, after the landowner reviewed the fire weather forecast and assessed the fuel conditions, the landowner's estimate is reliable. However, our survey discovered that a few burns were called off after the attempts of ignition, because it became obvious that the objectives would not be achieved. Considering all these factors, we placed the uncertainty of the burned area in the permit records at 20%.

3.2. Comparison of State, District, and County Total Burned Areas

Almost 50% of the prescribed burns in Georgia have areas smaller than 2 ha according to the permit records, while, according to BBEP, nearly 80% of the fires have sizes ranging between 10 and 20 ha (supporting information Table S1a). This inconsistency of the dominant fire size between the two data sets may be due to the satellite detection limit. In Florida, about 25% of the authorized burns have sizes between 10 and 20 ha, with another 20% ranging between 20 and 40 ha (Table S1b). However, more than 45% of the fires BBEP captures are in the 10 to 20 ha size range, with less than 10% between 20 and 40 ha. BBEP does not capture any fires between 0 and 2 ha, while almost 20% of the burns in permit records are in this size range.

The comparison of state totals indicates that in Georgia, both BBEP and GFED4s underestimate the burned areas compared to the permit records (Figure 2). GFED4s only accounts for 7.6% and 11% of the burned areas in permit records, while BBEP accounts for 15% and 44% in the first 4 months of 2015 and 2016, respectively.

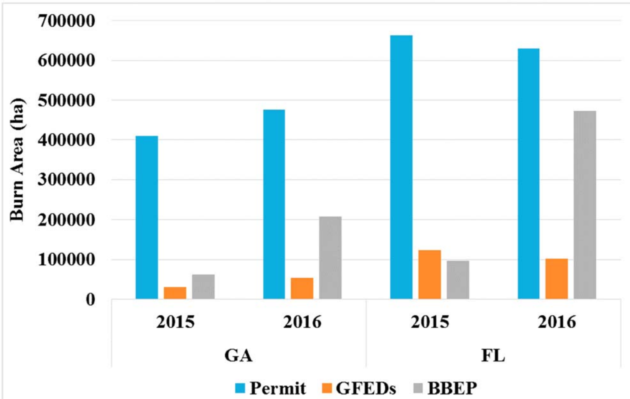

Figure 2. Comparison of state total burned areas from permit records, Biomass Burning Emissions Product (BBEP), and Global Fire Emissions Database (GFED4s) in Florida and Georgia for the first 4 months of 2015 and 2016.

All data sets show an increase in burned areas in Georgia from 2015 to 2016. In Florida, BBEP and GFED4s also underestimate the burned areas with respect to the permit records. GFED4s' state total burned areas are 19% and 16% of those in permit records in 2015 and 2016, respectively. BBEP's are 15% and 75% of burned areas in permit records. Permits and GFED4s show a decrease in burned area from 2015 to 2016, while BBEP shows a large increase.

Total burned areas in permit records of Georgia from January to April in 2015 and 2016 show that most of the burn activity takes place in the southwest portion of the state (Figure S1). The dominant burn types here are land clearing and hazard reduction burns. Neither GFED4s nor BBEP captures the level of burned area in permit records (the scale is 10 times larger for 2015 and 2016 permits in Figure S1). BBEP is in better agreement than GFED4s with the permits in terms of the burn locations. In Florida, the largest burned areas in permit records are in the panhandle and the south central counties (Figure S2, where the scale is 5 times larger for 2015 permits and 4 times larger for 2016 permits). The dominant burn type in Florida is agricultural burn. Compared to 2015 burned areas in permit records, most counties have a decrease in total burned area in the first 4 months of 2016. However, BBEP shows an increase of burned area in 2016 compared to 2015. Both GFED4s and BBEP underestimate the total burned areas for most counties. We also compared the fires between Hazard Mapping System Fire and Smoke Product (a product which shows the detected hot spots and smoke plumes indicating possible fire locations by combining human analysis with the satellite data) with BBEP and found some differences but nothing that might explain the large difference from the permit data. Prescribed burns are typically ignited around noon and put out before sundown. The flaming phases are typically very short (1–2 hr). If the sky is overcast by clouds during these periods, the satellites cannot detect the fires. Finally, we extracted the 2015 Georgia burned area data from BAECV and compared these with the permit records for the whole year (Figure S3). The results are similar to the other two satellite products: while BAECV captures the spatial patterns, it underestimates the total burned areas.

The potential uncertainty due to geolocation is reduced in our county-by-county analysis. While the uncertainty of geolocations is a concern (more so in Georgia where some nonstandard addresses could not be converted accurately to geolocations than in Florida where the coordinates were available for all the burns), the burn locations should be within the same county due to permitting requirements and practices. The discrepancies between the satellite and the permits in the countywise analysis are most likely due to the inability of the satellites to detect the burns. Prescribed fires in Georgia and Florida are usually both low intensity and under the tree canopy making satellite detection difficult. In addition, the frequent presence of clouds in the region during the active burn season further obscures the satellites' view (Connell et al., 2001; Gibson & Vonder Haar, 1990; Schreiner et al., 2001).

In addition, we compared the district total burned areas for 11 fire districts in Georgia (Figure S4a) and 15 fire districts in Florida (Figure S4b). For the first 4 months of 2015, BBEP is more correlated with permit record burned areas than GFED4s (Figure S5 and Figure S6). There is a strong correlation between BBEP and GFED4s burned areas because both of them use data from MODIS. The correlation is larger for district totals compared to the county totals in Georgia, but the opposite is true in Florida.

3.3. Comparison of BBEP Daily Total and GFED4s Monthly Total Burned Areas With Permit Data

The permit record and BBEP daily state total burned areas are correlated in the first 4 months of 2015 in Georgia and Florida with r^2 equal to 0.57 and 0.66, respectively (Figure 3). However, they are not correlated as strongly in 2016 (r^2 = 0.29 and 0.14), because of the days when BBEP state total burned areas are larger than those from permit records. The slope of all regression lines are smaller than 1.0, and in 2015, the year with good correlations between permit records and BBEP, the slopes are smallest with values equal to 0.17 and 0.15 for Georgia and Florida, respectively. These slope values and the scatterplots of Figure 3 show that BBEP may underestimate the burned area by more than 80%. Note that permit records only account for

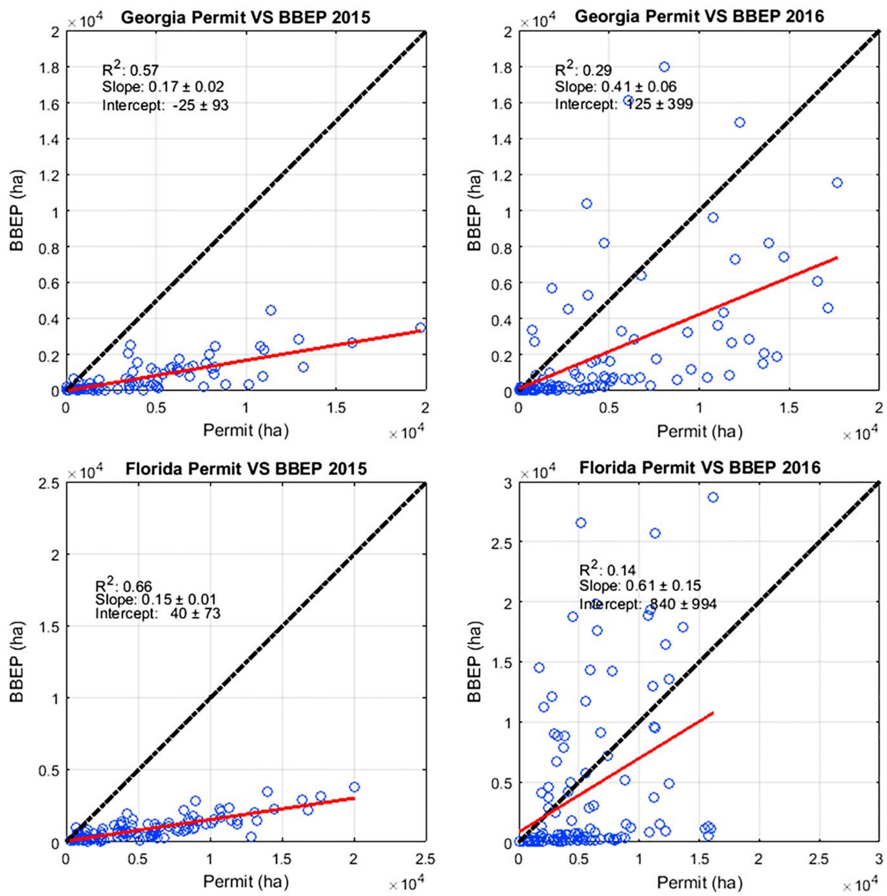

Figure 3. Comparison of daily state total burned areas for the first 4 months of 2015 and 2016 in Georgia (top row) and Florida (bottom row): Biomass Burning Emissions Product (BBEP) versus permit record data.

prescribed burns, while satellites cannot differentiate prescribed burns from wildfires. However, our investigations showed no major wildfire incidences on those days.

The correlation of log transformations is strong ($R^2 \geq 0.63$) in both years for a near-linear relationship between the permit and BBEP burned areas as implied by a slope close to unity (0.74 in 2015 and 0.88 in 2016, Figure S7). The similarity in the slopes and intercepts suggests a similar population for the two years. Therefore, the 2016 results are not really that different, though they are visually different because of the few times BBEP have values above the 1:1 line. When we plotted histograms of the residuals of both the untransformed and transformed data sets for comparison, we found that the log transformation residuals are more normally distributed than the untransformed residuals (Figure S8). In addition, we calculated the Spearman's R between permit records and BBEP for Georgia in 2015 and 2016. The Spearman's R is 0.81 and 0.84 for 2015 and 2016, respectively, while the p values are much less than 0.05.

Considering GFED4s only has the monthly total burned areas, there are only four points per year in the comparisons between permit records and GFED4s (Figure 4). There is strong correlation between GFED4s and permit record burned areas both in Georgia and Florida for 2015 ($r^2 = 0.61$ and 0.42) as well as 2016 ($r^2 = 0.53$ and 0.89).

3.4. Comparison of Daily Fire Counts Between Permit Record Data and BBEP

BBEP has difficulty detecting the prescribed burns according to the comparison of BBEP fire counts with the burn counts in permit records (Figure S9). In Georgia, although the correlations between the daily counts are good ($r = 0.71$ for 2015 and 0.73 for 2016), BBEP fire counts are only about one tenth (2015) and one twelfth (2016) of permit record burn counts. In Florida, the average daily number of burns from permit records, 120, is 4 times larger than the average daily number of fires from BBEP in 2015. In 2016, the average daily count from permit records, 132, is more than 4 times larger than that from BBEP.

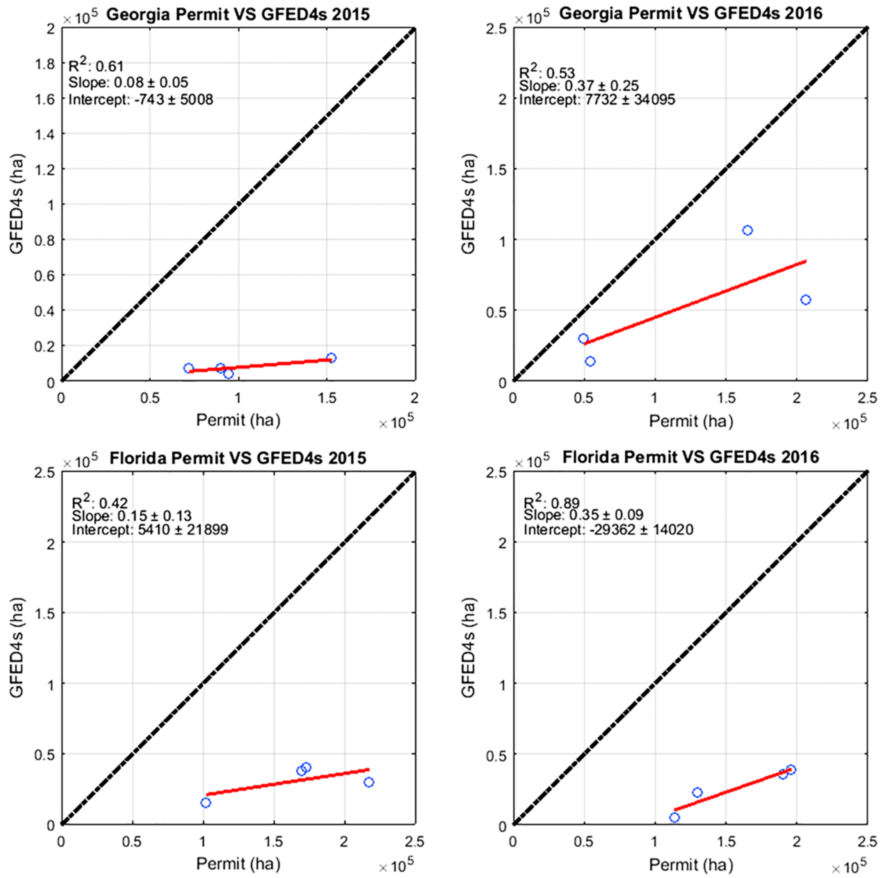

Figure 4. Comparison of monthly state total burned areas for the first 4 months of 2015 and 2016 in Georgia (top row) and Florida (bottom row): Global Fire Emissions Database (GFED4s) versus permit record data.

3.5. Special Days Analysis in Florida

Because Florida permit record data have latitude and longitude information for all the burns, we were able to perform spatial comparisons between permit record burns and BBEP fires. This analysis focused on special days. Uncertainties in this spatial analysis include possible human errors in converting the permit address to latitude and longitude and the limited resolution of the satellites.

For 17 March 2016, although state total BBEP and permit record burned areas are almost the same in Florida (~5700 ha), the locations of the fires are quite different (Figure 5). In particular, BBEP fires do not agree with the small burns permitted in South Florida; there are only a few small fires detected by the satellite, and their locations are different from those of the permitted burns. In addition, larger fires seen by the satellite in south central Florida are in different locations, even different counties.

For 18 March 2016, there is an overlap of permitted burns and BBEP-detected fire locations; however, BBEP detects one very large fire (~4000 ha) in south central Florida, while the permit database implies many small fires in that area (Figure 6). The county total burned area for the satellite-detected fires is much larger than the one for permitted burns in Charlotte County, Florida. BBEP may be interpreting several small fires as one big fire, as previously reported in the literature for other satellite products (Kukavskaya et al., 2013). This would lead to an overestimation by the satellites of the burned area for small fires such as prescribed burns.

3.6. Sugarcane Burn Comparison in Florida

The dominant burn type in Florida's Glades, Hendry, and Palm Beach Counties is agricultural sugarcane burn (Figure S10). Considering the high frequency of sugarcane burns and that they are conducted in open fields, satellites should be efficient in detecting this type of burns. Taking Palm Beach County as an example, there is

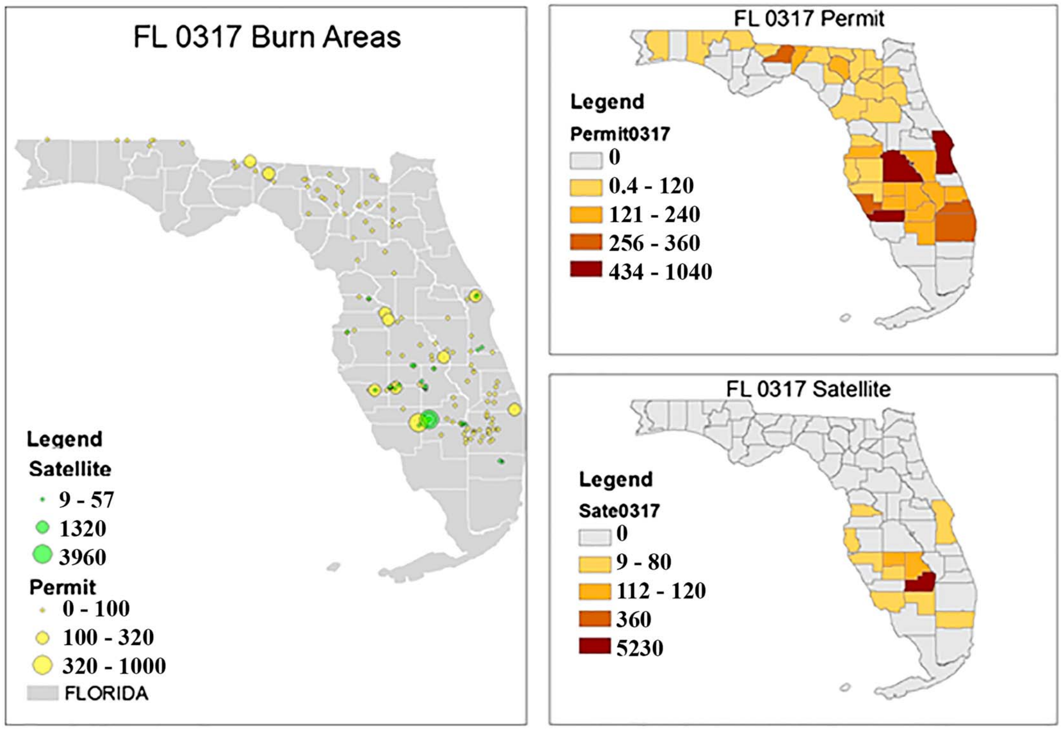

Figure 5. Spatial comparison between permitted burns and Biomass Burning Emissions Product-detected fires in Florida on 17 March 2016: Individual burned areas (left) and county total burned areas (right).

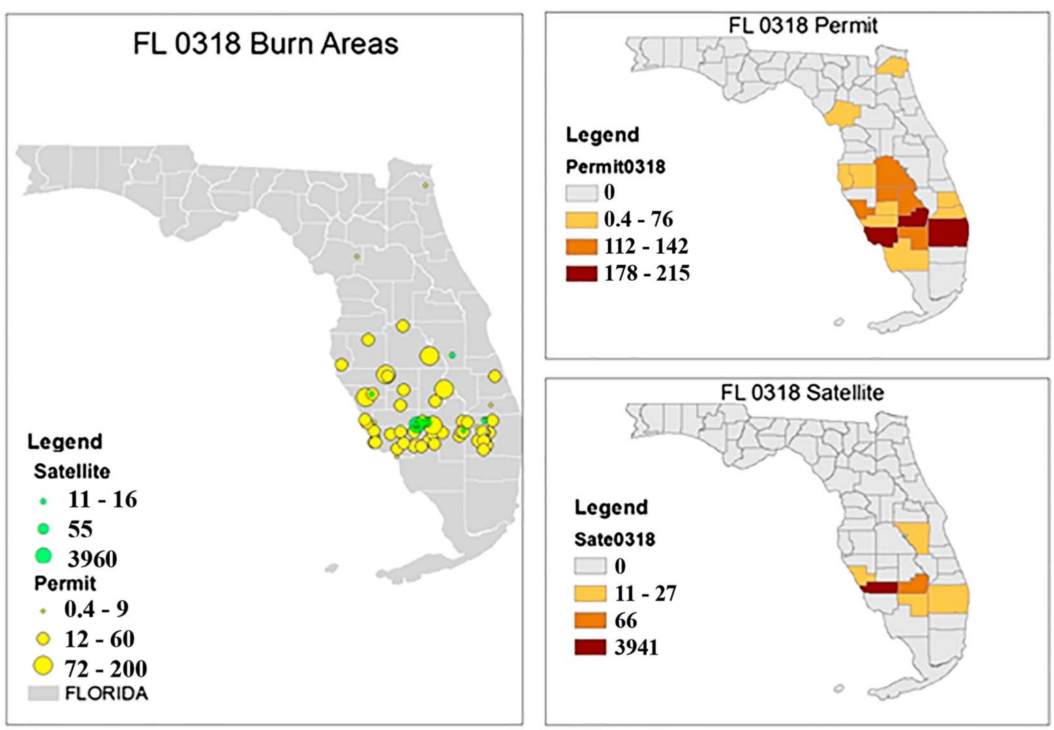

Figure 6. Spatial comparison between permitted burns and Biomass Burning Emissions Product-detected fires in Florida on 18 March 2016: Individual burned areas (left) and county total burned areas (right).

no correlation between the burned areas of permitted sugarcane burns and BBEP-detected fires in either 2015 or 2016 (Figure S11). However, the red dots in the comparisons of districtwise and countywise total burned areas in Figure S6 that represent District 18, which includes Palm Beach County, and Palm Beach County, respectively, show better than average agreement between the satellite products and permit records. This may be an indication that satellites can detect the sugarcane burns better than other types of burn.

The improvement in sugarcane burn detection is not as obvious according to the comparisons of BBEP fires with nonsugarcane burns (i.e., all burn types except sugarcane) in Florida (Figure S12). The r^2 of the 2015 comparison of daily state total burned areas between BBEP-detected fires in Florida and the permitted nonsugarcane burns is 0.69, slightly larger than that of the comparison with all permitted burns (0.66, Figure 3).

4. Conclusions

Current satellite-derived products have limitations in estimating the burned areas of small prescribed fires. Comparisons between permit record data sets and two satellite-derived data sets show that satellite products underestimate seriously the burned areas. The BBEP burned areas for 2016 are different from those for 2015, with no correlation between BBEP and permit record data in daily totals; on the other hand, GFED4s has good correlations with permit record data in monthly totals for both 2015 and 2016. Given the limited resolution of the satellite products, from coarser-resolution district level to finer-resolution county level, the correlation of the satellite burned areas with those of the permit records gets worse.

Satellite-derived products can capture a cluster of fires better than isolated fires but may misinterpret those small fires together as one big fire, as shown in our special day analyses in Florida. Sugarcane burn is the dominant burn type in three counties in southern Florida. Considering the openness and wide area of the sugarcane plantations, the high frequency of the burns, and the amount of heat produced, sugarcane burns should be detected more efficiently by the satellites. However, burned area comparisons of BBEP with permit records show only a slight improvement compared to other types of burn. The lack of convergence in sugarcane burns points to systemic problems such as relatively small sizes of those fields with respect to the resolution of geostationary satellites and short durations of the burns that are not in tune with the low frequency of overpasses for Earth-orbiting satellites.

Considering the deficiencies of satellite-derived products, and also the missing data caused by cloudy days, we trust the permit records more. We showed that satellite products vastly underestimated prescribed fire burned areas in the southeastern United States due to their small sizes. Therefore, emission inventories that use satellite-derived burned areas as input should be adjusted accordingly. On the other hand, satellite-derived products need to improve their accuracy in detecting small prescribed fires by taking advantage of new developments. For example, while the current GOES pixel resolution may be too coarse to resolve small fires, the newly launched GOES-16 Advanced Baseline Imager has 2-km spatial and 5-min temporal resolution; therefore, it should enable considerably better quality products for detecting and monitoring PB fires.

Acknowledgments
This publication was made possible in part by funding from NASA Applied Sciences Program under grants NNX11AI55G and NNX16AQ29G, U.S. EPA Science to Achieve Results Program under grant RD83521701, and the Joint Fire Science Program under grant 16-1-08-1. Its contents are solely the responsibility of the grantee and do not necessarily represent the official views of the supporting agencies. Further, The U.S. Government does not endorse the purchase of any commercial products or services mentioned in the publication. The prescribed fire permit records of Georgia and Florida are available from the Georgia Forestry Commission and Florida Forest Service separately upon request. The BBEP data were obtained from http://www.ospo.noaa.gov/Products/land/bbep2/. The GFED4s data are available from http://www.globalfiredata.org/data.html. We thank Mark Ruminski of NOAA/NESDIS Satellite Analysis Branch for HMS data, Yang Chen and James Randerson of UC Irvine for GFED4s data, John K. Fish of Florida Forest Service and his staff for Florida open burn authorization data, and Frank Sorrels of Georgia Forestry Commission for Georgia prescribed burn permit data.

References

Andreae, M. O., & Merlet, P. (2001). Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, *15*(4), 955–966. https://doi.org/10.1029/2000GB001382

Boschetti, L., Eva, H. D., Brivio, P. A., & Grégoire, J. M. (2004). Lessons to be learned from the comparison of three satellite-derived biomass burning products. *Geophysical Research Letters*, *31*, L21501. https://doi.org/10.1029/2004GL021229

Carmona-Moreno, C., Belward, A., Malingreau, J.-P., Hartley, A., Garcia-Alegre, M., Antonovskiy, M., et al. (2005). Characterizing interannual variations in global fire calendar using data from Earth observing satellites. *Global Change Biology*, *11*(9), 1537–1555. https://doi.org/10.1111/j.1365-2486.2005.01003.x

Chuvieco, E., Yue, C., Heil, A., Mouillot, F., Alonso-Canas, I., Padilla, M., et al. (2016). A new global burned area product for climate assessment of fire impacts. *Global Ecology and Biogeography*, *25*(5), 619–629. https://doi.org/10.1111/geb.12440

Connell, B. H., Gould, K. J., & Purdom, J. F. W. (2001). High-resolution GOES-8 visible and infrared cloud frequency composites over northern Florida during the summers 1996–99. *Weather and Forecasting*, *16*(6), 713–724. https://doi.org/10.1175/1520-0434(2001)016%3C0713:HRGVAI%3E2.0.CO;2

Fraser, R. H., Li, Z., & Cihlar, J. (2000). Hotspot and NDVI differencing synergy (HANDS): A new technique for burned area mapping over boreal forest. *Remote Sensing of Environment*, *74*(3), 362–376. https://doi.org/10.1016/S0034-4257(00)00078-X

Fraser, R. H., Li, Z., & Landry, R. (2000). SPOT VEGETATION for characterizing boreal forest fires. *International Journal of Remote Sensing*, *21*(18), 3525–3532. https://doi.org/10.1080/014311600750037534

Gibson, H. M., & Vonder Haar, T. H. (1990). Cloud and convection frequencies over the southeast United States as related to small-scale geographic features. *Monthly Weather Review*, *118*(10), 2215–2227. https://doi.org/10.1175/1520-0493(1990)118%3C2215:CACFOT%3E2.0.CO;2

Giglio, L., Descloitres, J., Justice, C. O., & Kaufman, Y. J. (2003). An enhanced contextual fire detection algorithm for MODIS. *Remote Sensing of Environment*, *87*(2–3), 273–282. https://doi.org/10.1016/S0034-4257(03)00184-6

Giglio, L., Randerson, J. T., & van der Werf, G. R. (2013). Analysis of daily, monthly, and annual burned area using the fourth-generation Global Fire Emissions Database (GFED4). *Journal of Geophysical Research: Biogeosciences*, *118*, 317–328. https://doi.org/10.1002/jgrg.20042

Giglio, L., Randerson, J. T., van der Werf, G. R., Kasibhatla, P. S., Collatz, G. J., Morton, D. C., & DeFries, R. S. (2010). Assessing variability and long-term trends in burned area by merging multiple satellite fire products. *Biogeosciences*, *7*(3), 1171–1186. https://doi.org/10.5194/bg-7-1171-2010

Giglio, L., Schroeder, W., & Justice, C. O. (2016). The collection 6 MODIS active fire detection algorithm and fire products. *Remote Sensing of Environment*, *178*, 31–41. https://doi.org/10.1016/J.RSE.2016.02.054

Hawbaker, T. J., Vanderhoof, M. K., Beal, Y. G., Takacs, J. D., Schmidt, G. L., Falgout, J. T., et al. (2017). Landsat burned area essential climate variable products for the conterminous United States (1984–2015). *U.S. Geological Survey Data Release*. https://doi.org/10.5066/F73B5X76

He, L., & Li, Z. (2012). Enhancement of a fire detection algorithm by eliminating solar reflection in the mid-IR band: Application to AVHRR data. *International Journal of Remote Sensing*, *33*(22), 7047–7059. https://doi.org/10.1080/2150704X.2012.699202

Hoelzemann, J. J. (2004). Global Wildland Fire Emission Model (GWEM): Evaluating the use of global area burnt satellite data. *Journal of Geophysical Research*, *109*, D14S04. https://doi.org/10.1029/2003JD003666

Hu, X., Yu, C., Tian, D., Ruminski, M., Robertson, K., Waller, L. A., & Liu, Y. (2016). Comparison of the Hazard Mapping System (HMS) fire product to ground-based fire records in Georgia, USA. *Journal of Geophysical Research: Atmospheres*, *121*, 2901–2910. https://doi.org/10.1002/2015JD024448

Kukavskaya, E. A., Soja, A. J., Petkov, A. P., Ponomarev, E. I., Ivanova, G. A., & Conard, S. G. (2013). Fire emissions estimates in Siberia: Evaluation of uncertainties in area burned, land cover, and fuel consumption. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, *43*(5), 493–506. https://doi.org/10.1139/cjfr-2012-0367

Leopold, A. (1987). Game management. Univ of Wisconsin Press. Retrieved from https://books.google.com/books?hl=en&lr=&id=p7aDQhy3J1AC&oi=fnd&pg=PR6&dq=game+management+Aldo+Leopold&ots=TER1lE8nr6&sig=F-h0sE7N7FX0NhO3NHHT_rWHS0#v=onepage&q=game management Aldo Leopold&f=false

Li, Z., Fraser, R., Jin, J., Abuelgasim, A. A., Csiszar, I., Gong, P., et al. (2003). Evaluation of algorithms for fire detection and mapping across North America from satellite. *Journal of Geophysical Research*, *108*(D2), 4076. https://doi.org/10.1029/2001JD001377

Li, Z., Nadon, S., & Cihlar, J. (2000). Satellite-based detection of Canadian boreal forest fires: Development and application of the algorithm. *International Journal of Remote Sensing*, *21*(16), 3057–3069. https://doi.org/10.1080/01431160050144956

Li, Z., Nadon, S., Cihlar, J., & Stocks, B. (2000). Satellite-based mapping of Canadian boreal forest fires: Evaluation and comparison of algorithms. *International Journal of Remote Sensing*, *21*(16), 3071–3082. https://doi.org/10.1080/01431160050144965

Liu, Y. (2005). Enhancement of the 1988 northern U.S. drought due to wildfires. *Geophysical Research Letters*, *32*, L10806. https://doi.org/10.1029/2005GL022411

Mouillot, F., Schultz, M. G., Yue, C., Cadule, P., Tansey, K., Ciais, P., & Chuvieco, E. (2014). Ten years of global burned area products from spaceborne remote sensing—A review: Analysis of user needs and recommendations for future developments. *International Journal of Applied Earth Observation and Geoinformation*, *26*(1), 64–79. https://doi.org/10.1016/j.jag.2013.05.014

Natarajan, M., Pierce, R. B., Schaack, T. K., Lenzen, A. J., Al-Saadi, J. A., Soja, A. J., et al. (2012). Radiative forcing due to enhancements in tropospheric ozone and carbonaceous aerosols caused by Asian fires during spring 2008. *Journal of Geophysical Research*, *117*, D06307. https://doi.org/10.1029/2011JD016584

Prins, E. M., & Menzel, W. P. (1992). Geostationary satellite detection of bio mass burning in South America. *International Journal of Remote Sensing*, *13*(15), 2783–2799. https://doi.org/10.1080/01431169208904081

Prins, E. M., & Menzel, W. P. (1994). Trends in South American biomass burning detected with the GOES visible infrared spin scan radiometer atmospheric sounder from 1983 to 1991. *Journal of Geophysical Research*, *99*(D8), 16719. https://doi.org/10.1029/94JD01208

Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M., & Morton, D. C. (2012). Global burned area and biomass burning emissions from small fires. *Journal of Geophysical Research*, *117*, G04012. https://doi.org/10.1029/2012JG002128

Randerson, J. T., Liu, H., Flanner, M. G., Chambers, S. D., Jin, Y., Hess, P. G., et al. (2006). The impact of boreal forest fire on climate warming. *Science*, *314*(5802). 1130–1132. https://doi.org/10.1126/science.1132075

Roy, D. P., Boschetti, L., Justice, C. O., & Ju, J. (2008). The collection 5 MODIS burned area product—Global evaluation by comparison with the MODIS active fire product. *Remote Sensing of Environment*, *112*(9), 3690–3707. https://doi.org/10.1016/j.rse.2008.05.013

Schreiner, A. J., Schmit, T. J., & Menzel, W. P. (2001). Observations and trends of clouds based on GOES sounder data. *Journal of Geophysical Research*, *106*(D17), 20,349–20,363. https://doi.org/10.1029/2001JD900213

Schroeder, W., Csiszar, I., Giglio, L., & Schmidt, C. C. (2010). On the use of fire radiative power, area, and temperature estimates to characterize biomass burning via moderate to coarse spatial resolution remote sensing data in the Brazilian Amazon. *Journal of Geophysical Research*, *115*, D21121. https://doi.org/10.1029/2009JD013769

Schultz, M. G. (2002). On the use of ATSR fire count data to estimate the seasonal and interannual variability of vegetation fire emissions. *Atmospheric Chemistry and Physics*, *2*(5), 387–395. https://doi.org/10.5194/acp-2-387-2002

Seiler, W., & Crutzen, P. J. (1980). Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change*, *2*(3), 207–247. https://doi.org/10.1007/BF00137988

Simon, M., Plummer, S., Fierens, F., Hoelzemann, J. J., & Arino, O. (2004). Burnt area detection at global scale using ATSR-2: The GLOBSCAR products and their qualification. *Journal of Geophysical Research*, *109*, D14S02. https://doi.org/10.1029/2003JD003622

Sokolik, I. N., Curry, J., & Radionov, V. (2010). Interactions of Arctic aerosols with land-cover and land-use changes in northern Eurasia and their role in the Arctic climate system. In *Eurasian Arctic land cover and land use in a changing climate* (pp. 237–268). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-90-481-9118-5_10

Tansey, K., Beston, J., Hoscilo, A., Page, S. E., & Paredes Hernández, C. U. (2008). Relationship between MODIS fire hot spot count and burned area in a degraded tropical peat swamp forest in Central Kalimantan, Indonesia. *Journal of Geophysical Research*, *113*, D23112. https://doi.org/10.1029/2008JD010717

Tansey, K., Grégoire, J.-M., Defourny, P., Leigh, R., Pekel, J.-F., van Bogaert, E., & Bartholomé, E. (2008). A new, global, multi-annual (2000–2007) burnt area product at 1 km resolution. *Geophysical Research Letters*, *35*, L01401. https://doi.org/10.1029/2007GL031567

Tansey, K., Grégoire, J., Stroppiana, D., Sousa, A., Silva, J., Pereira, J. M. C., et al. (2004). Vegetation burning in the year 2000: Global burned area estimates from SPOT VEGETATION data. *Journal of Geophysical Research*, *109*, D14S03. https://doi.org/10.1029/2003JD003598

U.S. Environmental Protection Agency (2011). 2011 National Emissions Inventory (NEI) Documentation. Retrieved from https://www.epa.gov/air-emissions-inventories/2011-national-emissions-inventory-nei-documentation

U.S. Environmental Protection Agency (2014). 2014 National Emissions Inventory (NEI) Documentation. Retrieved from https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-documentation

Zeng, T., Liu, Z., & Wang, Y. (2016). Large fire emissions in summer over the southeastern US: Satellite measurements and modeling analysis. *Atmospheric Environment*, *127*, 213–220. https://doi.org/10.1016/j.atmosenv.2015.12.025

Zhang, X., & Kondragunta, S. (2008). Temporal and spatial variability in biomass burned areas across the USA derived from the GOES fire product. *Remote Sensing of Environment*, *112*(6), 2886–2897. https://doi.org/10.1016/j.rse.2008.02.006

Zhang, X., Kondragunta, S., & Quayle, B. (2011). Estimation of biomass burned areas using multiple-satellite-observed active fires. *IEEE Transactions on Geoscience and Remote Sensing*, *49*(11), 4469–4482. https://doi.org/10.1109/TGRS.2011.2149535

Zhu, C., Kobayashi, H., Kanaya, Y., & Saito, M. (2017). Size-dependent validation of MODIS MCD64A1 burned area over six vegetation types in boreal Eurasia: Large underestimation in croplands. *Scientific Reports*, *7*(1), 4181. https://doi.org/10.1038/s41598-017-03739-0