NRCS CONSERVATION INNOVATION GRANT
Final reports

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Project Title: Developing a decision tool to assist management of prescribed fires in the Flint Hills region in order to reduce smoke impact on ambient ozone
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1. A summary of the project with main impacts

Prescribed burning is a long standing practice to maintain the ecosystem in the Flint Hills region. Approximately one third of the rangeland are burned each year, mostly in April. In 2019, a total of 2.6 million acres of rangeland were burned by more than 3000 prescribed fires.

Burning is ecologically and financially important to the rangeland communities. It is necessary because it enhances the nutritional value of the native grasses and reduces weeds and brush. However, the intensive burning in April impacts air quality, and constitutes public health concerns. Smoke from the fires contributes to violation of the ambient ozone (O_3) standard. Smoke from rangeland burning is unlike other pollutant sources that can use control devices. Reducing smoke impact relies on management and timing. However, current practices of prescribed burning are mainly based on experience. Many landowners lack scientific understanding of how burn and weather conditions affect smoke impact, and lack tools for better management and timing of prescribed fires. The current smoke management tools are not sufficient to prevent exceedance of the ambient O_3 standard.

The objective of this project was to develop a practical burning decision tool to assist management of prescribed fires in the Flint Hills region, which was based on combined analysis of historical data including O_3, weather variables, and daily burned area that were obtained from satellite observations for the first time through an innovative approach. The main findings of the project include:

- Both the annual burned percentage and the average sizes of one active fire varied at different part of the Flint Hills region. In the central part of the Flint Hills region, land owners tend to burn more frequently, and the fire sizes were generally larger. The annual average burned percentage ranged from 11% to 52% in different counties.
- Fire activities were highly concentrated in a few days in April that had desired weather and fuel conditions. In average, the burned area from fires between March 31st and April 30th accounted for 86% of the total burned area in the whole burning season. The maximum daily burned area in the Flint Hills region was around 0.5 million acres.
- The three most important weather variables that affected the daily burned area were solar radiation, cloud cover, and relative humidity (RH). The data indicated that, when weather conditions were acceptable for burning, many landowners chose to burn at lower cloud cover, higher solar radiation, lower RH, higher temperature, and lower wind velocity. About 94% of all the heavy-fire days had cloud cover <30%, which were not in the KDHE recommended range of optimum burning conditions (30~50%).
- The O_3 level was most sensitive to the O_3 level on the previous day, followed by the daily burned area, RH, and cloud cover. In average, for every 0.1 million increase of daily burned acres, the maximum O_3 level increased around 4 ppb.
- In order to reduce smoke impact on O_3, cloud cover and RH need to be considered when making burning decisions. The optimum conditions for burning is when cloud cover = 30~50%, and

under this condition, no O_3 exceedance has been observed. However, in average, there were only 8 days available in one spring burning season from March 8th to May 8th, with cloud cover = 30~50%, and other weather variables also in the acceptable ranges for burning (RH = 20~80%; wind speed = 1.3~8.0 m/s, air temperature = 4.2~25.8 ºC, precipitation < 2.38 mm).

- Another recommended weather conditions that are suitable for burning are when cloud cover = 10~30%, and RH = 40~80%. Generally, if the O_3 level on the previous day is at the average level (50.5 ± 10.9 ppb) or less, burning under these conditions will not likely result in O_3 exceedance. In average, there were 10 days available in one spring burning season from March 8th to May 8th, with these conditions and other weather variables also in the acceptable ranges for burning.
- When cloud cover = 10~30%, and RH = 20~40%, It is OK to burn but heavy fire is not recommended.
- When cloud cover = 0~10%, the O_3 background is generally higher, and O_3 is also most sensitive to fire activities, especially when RH is also low. Under these conditions, burning should be managed not to exceed the maximum daily burned area, which can be determined by the O_3 level on the previous day and the RH.

The detailed guidelines generated from this project can assist land managers to better plan their burning activities and enable the continuous practice of burning in a manner that minimize adverse air quality. It will not only help to reduce the impacts of smoke, but also increase capacity of land management by allowing more burning when conditions are favorable, and ultimately to transform the traditional prescribed burning into a safe, effective, and sustainable practice.

2. Background/rationale for the project

Prescribed burning is a long standing practice to maintain the ecosystem in the Flint Hills region, which extends throughout much of eastern Kansas, and contains 7 million acres of rangeland and the largest remaining area of unplowed tallgrass prairie in North America. Approximately one third of the rangeland are burned each year, mostly in April. Smoke from the fires causes elevated O_3 in ambient air, contributing to O_3 exceedances, and have affected several states downwind of Kansas. The smoke impact of rangeland burning has been subject to intense discussion and public debate.

For decades, O_3 has been the most persistent and perhaps the most dangerous air pollutants in the U.S. Exposure to O_3 can impair the breathing of healthy individuals, cause chest pain, headaches, respiratory problems such as pulmonary edema, and aggravation of asthma and arrhythmia (Lippmann, 1989). O_3 is usually formed through complex photochemical reactions between precursor species such as nitrogen oxides (NO_x) and volatile organic compounds (VOC) under influence of solar radiation (Mueller and Mallard, 2011). Both NO_x and VOC are commonly present in rangeland fire smoke. The production of O_3 occurs either in the original smoke plume or as a result of the smoke plume interacting with existing pollutants in the atmosphere (Dokas et al., 2007). There is a significant need for O_3 modeling in collaborative smoke management, especially after the national 8-hour O_3 standard was reduced from 75 to 70 ppb in 2015. The requirement on smoke management is growing as air quality standards become more stringent and other anthropogenic emissions have been better controlled.

Smoke from rangeland burning is unlike most other pollutant sources that can use control devices. Management is the key to reduce impact of smoke. The Kansas Department of Health and Environment (KDHE) adopted the Flint Hills smoke management plan (KDHE, 2010) in late December 2010 and started implementation of the plan in 2011. The plan recommended practices to reduce the air quality impacts of prescribed rangeland burning, and provided smoke modeling tools on www.ksfire.org to assist land managers and local fire officials in making burning decisions. The current smoke modeling tools focus on forecasting smoke contributions to PM (Particulate matter) based on dispersion models. They can assist land managers to redistribute the emissions by burning when dispersion is good, and when wind direction is favorable, so that the smoke impact on sensitive locations such as major cities can be reduced.

However, the contributions of burning activities to ambient O_3 mixing ratios have not been well documented. The current modeling tools are not capable to forecast smoke impact on O_3, and therefore the current smoke management plan is not sufficient to prevent exceedance of the O_3 standard.

Complex photochemical air quality modeling is usually needed to simulate both chemical and physical processes in order to model O_3 formation. Photochemical models simulate the changes of pollutant concentrations in the atmosphere using a set of mathematical equations characterizing the chemical and physical processes including chemistry, diffusion, advection, sedimentation (for particles), and deposition (both wet and dry) in the atmosphere. Most of current photochemical models adopt the three-dimensional Eulerian grid modeling. They solve a finite approximation by dividing the modeling region into a large number of cells, horizontally and vertically, which interact with each other to simulate the various processes that affect the evolution of pollutant concentrations. Input of emission and meteorological data are typically specified at hourly intervals for each computational cell in the modeling domain. Application of these photochemical models is generally expensive, and has significant requirements on model inputs and computational power. Results of several studies simulating impacts of prescribed fires suggested that the current module in photochemical models tend to underestimate O_3 production, indicating a lack of simulated photochemical production or a lack of precursors emitted from the burning (Hu et al., 2008). Accuracy of modeling results is affected by knowledge gaps in smoke evolution and photochemical mechanisms. In addition, accurate emission data with defined uncertainties for rangeland burning has not been available at the required space and time scales. Therefore, effort to apply photochemical modeling in smoke management is limited, and there is still a long way to go for a reliable and practical smoke management tool can be developed based on photochemical modeling.

The goal of this project is to establish practical forecasting models and a decision support system for smoke and air quality management in the Flint Hills region, which will encourage and enable the continuous practice of prescribed rangeland burning and maintenance of the ecosystem in a manner that minimize adverse air quality and social impacts. Specific objectives include:

- #1 Identify and model key meteorological and management factors that affect the timing of prescribed burning activities in the Flint Hills region;
- #2 Develop regression models to simulate O_3 contributions from prescribed burning using long term daily O_3 and daily burned-area data with random forest algorithms;
- #3 Develop a practical burning decision tool based on the regression models to assist collaborative management of prescribed fires in order to reduce smoke impact on ambient O_3, and disseminate the tool to land managers.

3. Methods

3.1 The study area

The Flint Hills region extends throughout much of eastern Kansas and northern Oklahoma, and contains 7 million acres of rangeland. Almost half of the rangeland are burned each year, and burning is done almost exclusively in the spring season due to economic and cultural factors (Baker et al., 2019; Weir & Scasta, 2017). A land use distribution map can be found in Scholtz et al. (2020) or Mohler & Goodin (2012ab). Our study area covers 17 counties in Kansas and Oklahoma (Figure 1), as they represent significant portion of the Flint Hills region, and we have access to consistent data in these counties from 2003 to 2019.

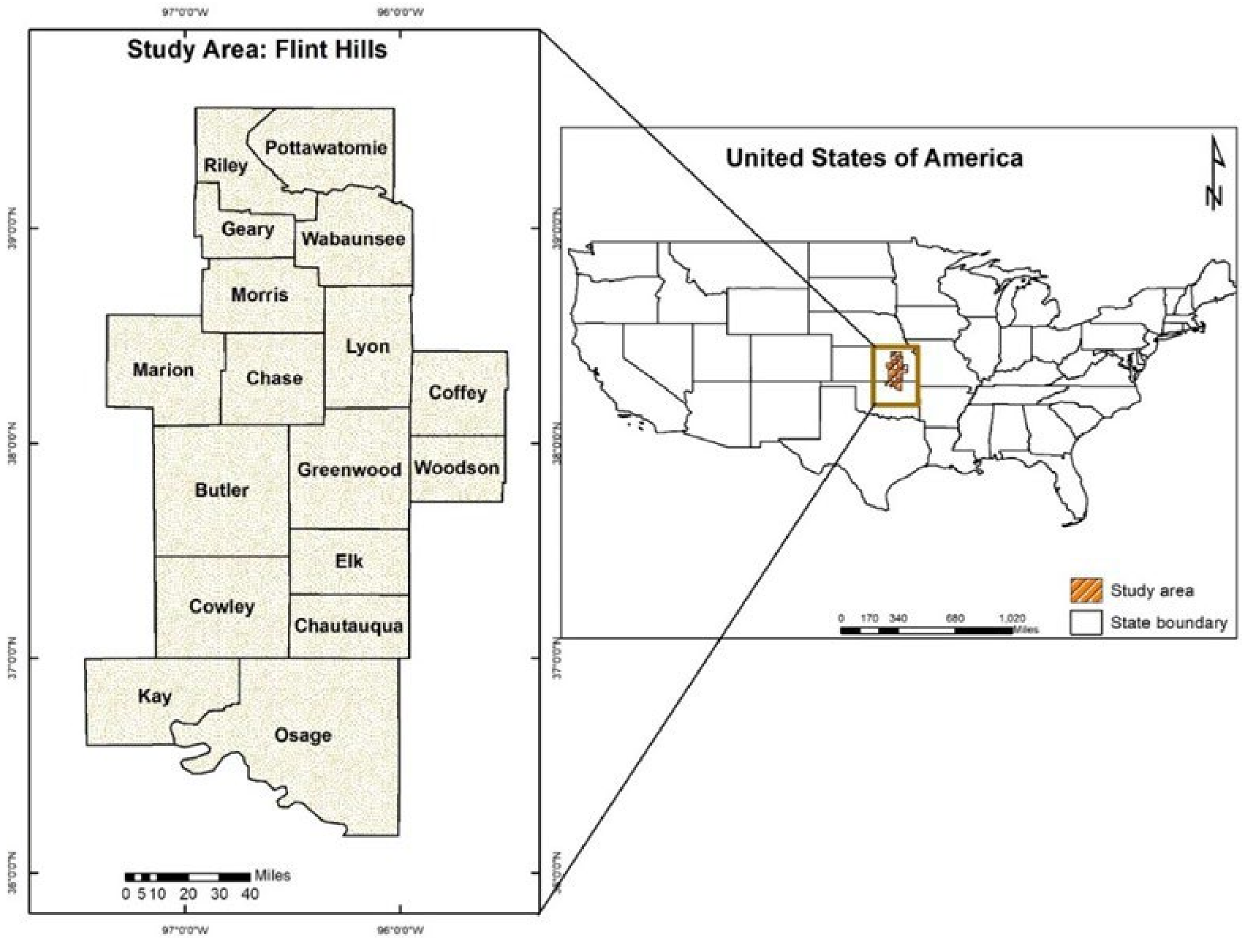


Figure 1. The 17-county of study area in Kansas and Oklahoma

3.2 Retrieve daily burned area data from combined satellite data

Remote sensing data are available for detection of burned-area and active fire, and fire emission inventories are often based on burned-area data from satellites accompanied by biogeochemical modeling of the available fuel load (Lentile et al., 2006; Langmann et al., 2009). In the Flint Hills region, the acres burned in each burning season have been estimated using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites since 2000 (Mohler and Goodin, 2012ab). Managers can keep track of fire activities through an annual reporting system using satellite products. However, the current method could not map daily burned area due to cloudy satellite imagery and quickly changing nature of burned and unburned areas amid rapid vegetation regeneration (Mohler & Goodin, 2010). Satellite active fire data provides information on the spatial and temporal distribution of fires. The algorithm to detect both day and nighttime active fires and other thermal anomalies was often based on the detection of the released elevated energy relative to the non-burning surroundings at middle-infrared to thermal wavelengths through MODIS Fire and Thermal Anomalies product (Schroeder et al., 2014; Chen et al., 2017). In this study, the combination of active fire data and burn scar detection algorithm as recommended by Urbanski et al. (2009) and Freeborn et.al. (2009) were used to produce daily burned area in the Flint Hills region.

The MODIS on NASA's Terra and Aqua satellites is making daily observations of the earth with 36 channels spanning the spectral range from 0.41 to 15 μm and representing three spatial resolutions: 250 m

(2 channels), 500 m (5 channels), and 1 km (29 channels) (Remer et al., 2005). The first MODIS instrument began transmitting data in 2000. Combination of band 1-red (620 - 670nm) and band 2- near-infrared (NIR) (841 - 876nm) at a spatial resolution of 250m was used because it offers the optimal combination of spatial, temporal, and spectral properties for this application as suggested by Mohler & Goodin (2012a). All 250m red and NIR Terra (MOD09GQ) and Aqua (MYD09GQ) images in March, April and May in each of the 17 years (2003 to 2019) were acquired from the Warehouse Inventory Search Tool of NASA. MODIStsp, a R package source code with graphical user interface (Busetto et.al., 2016) was used to perform downloading, mosaicking, reprojection and resize of raster derived from MODIS land products data. The downloaded images were converted from their native hierarchical data format (HDF) to tagged image file format (TIFF) using HDF-EOS to GeoTIFF conversion tool (HEG).

The TIFF format images were imported into ArcMap 10.7 to check for cloud or shadow cover through image metadata and visual examination. Images in cloud free day generally have lower reflectance with smaller standard deviation over a county. When clear images without cloud cover from both the Terra and Aqua platforms was available on the same date, the Aqua platform image was selected as it represents more burned areas from that day because the images were acquired during the evening pass. From 2000 to 2002, only one MODIS sensor on the Terra platform was in orbit, and these data were not included in our analysis.

The cloud cover was checked by visual examination of the downloaded MODIS images. Only the best cloud free images with classification accuracy of 90% and above were selected for mapping. Other images was considered cloudy to minimize false positives. The burns in cloudy images did not go unmapped, because they were visible in images from other dates close to the dates with the cloudy image.

Masked layers that contain the ground truth data from 2008 and 2010 (Mohler, 2011) were used to map out non-grassland from the selected cloudy free bi-spectral images using the ENVI 5.2 software. The stacked image masked files were obtained from the KDHE. These layers were prepared to permit the majority of each non-grassland land cover type such as actively growing crops, water and evergreen vegetation to be excluded from consideration.

Supervised minimum distance classification of the bi-spectral images were applied. The freshest burn scars were the darkest in color, and they fade to a lighter color as they get older (Mohler, 2011). Therefore, pixels from the most recent burned areas were selected as the training data to sustain the burned area estimation. Different training data were used for each day to prevent cloudy areas from being classified as burned areas. It was necessary in order to get good result due to the quickly changing nature of the burned areas and other variables like clouds and cloud shadows. The accuracy of classifications using this method has been estimated to be 90% or better by Mohler (2011).

The daily active fire data (2013-2019) in a point format at a 1 km resolution was collected from the MODIS Global Monthly Fire Location Product (MCD14ML), collection 6 product through the NASA's FIRMS website (https://firms.modaps.eosdis.nasa.gov/download/create.php). The information associated with each active fire count include coordinate location (latitude and longitude), date, time, confidence level and satellite type (Terra or Aqua). The acquired raw active fire points with a vegetation fire type and a non-zero confidence level were subset to the 17-county study area.

Correlations between the accumulated burned area and the active fire count observed at the same date were developed as a scale model. The scale model incorporates knowledge of point spread function when the acquired burn scar images are cloudy. Figure 2 presents a flowchart of the process for mapping daily burned area.

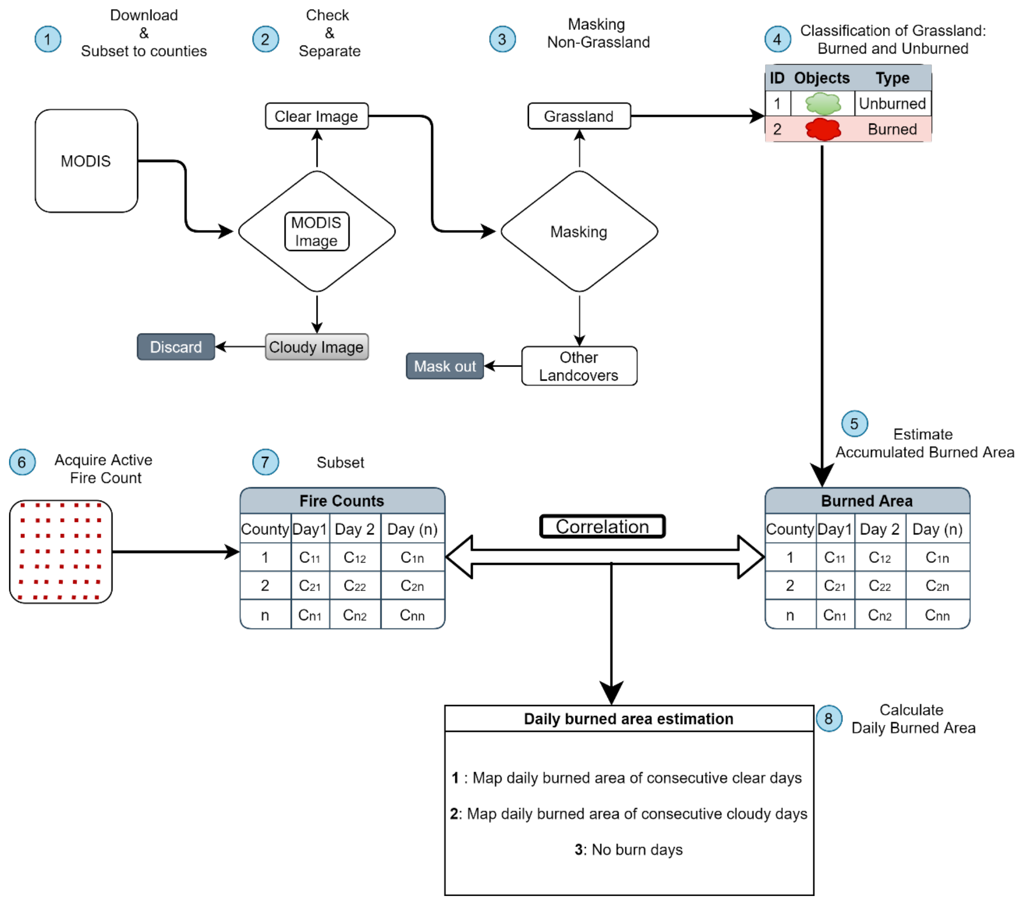


Figure 2. Flowchart of the process for mapping daily burned area

3.3 Classification of daily burned area

Clustering analysis was used to classify daily burned area into different categories by minimizing the distance between points in a cluster and maximizing the distance between clusters. A list for within-cluster sum of square (WCSS) was appended to the clusters using all the initial clusters. K-means algorithm is sensitive to the centroids' initialization or the mean points. A poor initialization of centroids could result in poor clustering. To overcome this drawback, K-means^{++} was used to ensure a smarter initialization of the centroids and improve the clustering quality (Kapoor & Singhal, 2017). The optimal number of clusters was determined to be four by using the elbow method on the plot of WCSS against number of clusters. All the days in the spring burning seasons from 2003 to 2019 were classified into the following four categories based on daily burned area, including no-fire days, light-fire days, medium-fire days, and heavy-fire days.

3.4 Processing of weather data

Hourly weather data from 2003 to 2019 in the Flint Hills region were obtained from Kansas State University weather data library and the Mesonet website (http://mesonet.k-state.edu/weather/historical). Since almost all the prescribed burning were conducted in day time, the average, maximum, and minimum hourly values of various weather variables in day time from 8am to 6pm were obtained and used in the following regression analysis. Cloud cover data was obtained from the Visual Crossing Weather (https://www.visualcrossing.com/resources/documentation/weather-data/where-can-i-find-historical-cloud-and-visibility-data/). Air stability classes were determined using the Pasquill-Gifford method based on solar radiation and wind speed as in Table 1.

Table 1. Modified Pasquill-Gifford stability classes (EPA Australia, 2012; Manju and Siddiqui, 1998)

Wind Speed (m/s)	Day-time incoming solar radiation (W/m^2)			
	Strong (>600)	Moderate (300-600)	Slight (175-300)	Overcast (<175)
<2	A	A	B	D
2 - 3	A	B	C	D
3 - 5	B	B	C	D
5 - 6	C	C	D	D
>6	C	D	D	D

Note: Very unstable = A, Moderately unstable = B, Slightly unstable= C, Neutral = D. For overcast conditions, regardless of wind speed, Class D is assumed.

The weather variables that were considered in the regression analysis included:

- Average cloud cover;
- Average solar radiation;
- Total precipitation in day time;
- Average, maximum and minimum air temperature;
- Average, maximum and minimum 4” soil temperature;
- Average, maximum and minimum RH;
- Average, maximum and minimum wind speed;
- Average wind direction;
- Air stability class.

3.5 Identifying weather conditions that affected the timing of prescribed rangeland burning

Statistics of weather conditions were summarized in the four fire categories (no-fire days, light-fire days, medium-fire days, and heavy-fire days) respectively. The weather conditions in the heavy-fire days were considered as acceptable burning conditions, and they were compared with the optimum burning conditions recommended in the Flint Hills smoke management plan (KDHE, 2010; RH = 30~50%; V = 5~15 mph, or 2.2~6.7 m/s; Mixing height >1800 ft; Cloud cover = 30~50%), in order to identify the potential area for improvement.

The importance of different weather variables as related to daily burned area were evaluated by the mutual information (MI) scores and the feature importance scores. The feature importance was computed for Random Forest algorithm by using SHAP values developed by Lundberg et al., (2017, 2018, 2020). The MI is a measurement of the reduction in uncertainty for one variable when the other variable's value is known. It measures the quantity of information a feature contributes to the correct classification decision of the dependent variable (Kraskov et. al., 2004). Classification and regression models were developed to simulate daily burned area in the whole Flint Hills region based on input of weather data, with an ensemble of decision trees using random forest algorithms, in order to identify key weather factors that had affected the timing of prescribed rangeland burning.

3.6 Normalizing daily burn area at the county level

Daily burned area in 4 counties (Riley and Geary in Kansas, Kay and Osage in Oklahoma) were normalized by dividing the maximum daily burned area in the county so that data from counties with different sizes become comparable. The local weather conditions when the normalized daily burned area in a county was larger than 0.5 were considered as the preferred weather conditions for prescribed fires, indicating most landowners in these counties preferred to burn under these conditions.

3.7 The O_3 monitoring sites

Current Kansas regulatory O_3 and $PM_{2.5}$ monitoring network includes nine sites throughout the state. Three sites are located around the Wichita area. One site is at Topeka. And one site is located at Cedar Bluff as the background site because it is not near any significant emission sources. The Chanute monitoring site is new and began operations in 2014. In addition, within the Flint Hills region, the Clean Air Status and Trends Network (CASTNET) has one site (Konza Prairie) that report O_3; the Interagency Monitoring of Protected Visual Environments (IMPROVE) program has one site (Tallgrass) that report speciated $PM_{2.5}$. The O_3 data from the nine regulatory monitoring sites were downloaded from https://www.epa.gov/outdoor-air-quality-data/download-daily-data. The O_3 data from the Konza Prairie site were downloaded from https://www.epa.gov/castnet. Location of the ten O_3 sites and the Tallgrass $PM_{2.5}$ site are illustrated in Figure 3.

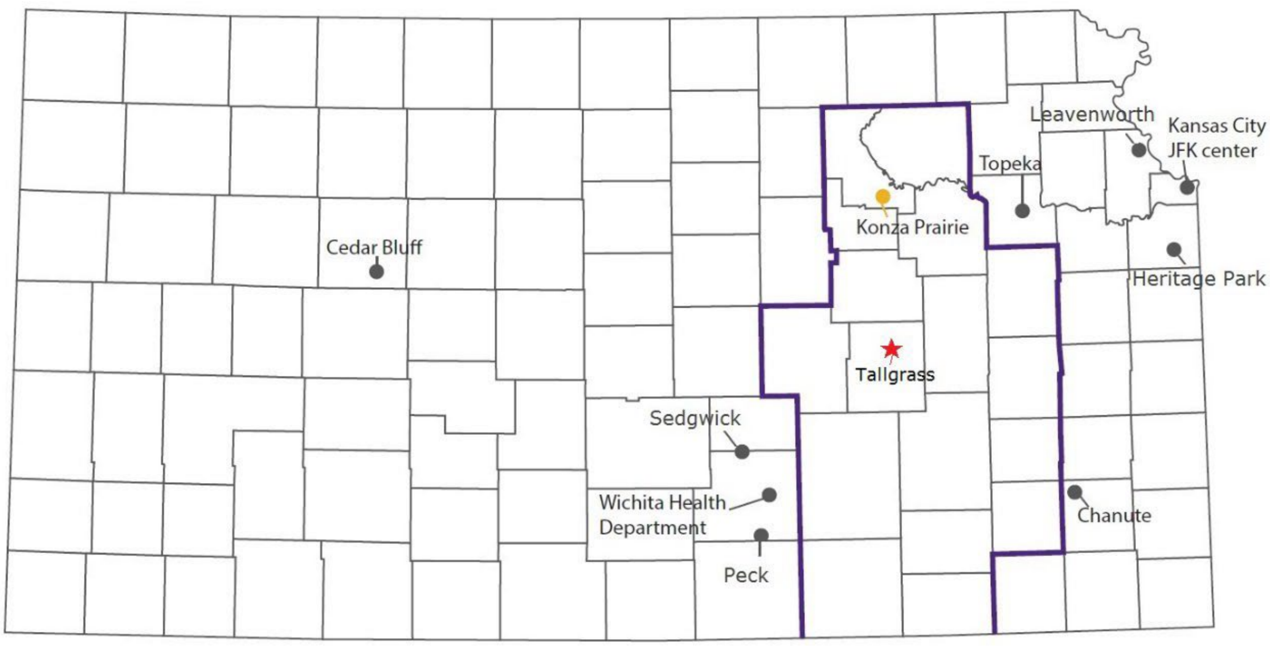


Figure 3. The O_3 and $PM_{2.5}$ monitoring sites in Kansas and perimeter of the Flint Hills region (bold lines)

3.8 The O_3 regression models

Previously, regression models have been developed to simulate background daily O_3 at each of the ten O_3 monitoring sites around the Flint Hills region using data using year-round O_3 and weather data (Liu et al., 2018). In these O_3 models, seasonal cycle was described using the sine term, and influence of O_3 from the previous day was described using the persistent term.

The O_3 regression models at the ten monitoring sites can all be expressed using the following equation. In which, $O_3(d)$ is 8-hour daily maximum O_3 concentration in ppb; O_{3pre} is 8-hour daily maximum O_3 concentration on the previous day in ppb; d corresponds to the day of the year; T_{max} is the daily maximum air temperature in °C; T_{min} is the daily minimum air temperature in °C; RH is daily average relative humidity; V is daily average wind speed in m/s; c_1 to c_7 are model parameters that were different at different sites.

$$OO_3(dd) = cc_1 + cc_2 OO_{3_{pppppp}} + cc_3 \sin \frac{2\pi\pi(dd + 283)}{365} + cc_4(TT_{mmmmmm} - TT_{mmmmmm}) + cc_5 TT_{mmmmmm} - cc_6 RRRR - cc_7 VV$$

As expected, higher solar radiation, higher temperature, lower relative humidity, and lower wind speed generally corresponded to higher O_3 mixing ratios. Solar radiation was not a significant predictor variable once the difference between the daily maximum and minimum air temperature was included in the models. In the models, the effect of solar radiation was likely reflected by the difference between the daily maximum and minimum air temperature, since air was heated by solar radiation. The regression models were able to explain 62 to 76 percent of day-to-day O_3 variation at various sites. At all the ten sites, April had the largest positive residuals compared with other months. The average O_3 model residuals in most other months, were either negative or very close to zero. The high positive residuals in April represented the O_3 daily variations that were not explained by the regression models, and they were likely associated with the impact of the smoke emissions from burning.

In this project, updated regression models were developed to simulate impact of prescribed burning on O_3 by including daily burned-area as a predictor variable in addition to weather predictors, using O_3, weather, and daily burned-area data during the spring burning seasons from 2003 to 2019. The importance of daily burned area and different weather variables as related to the maximum 8-hour O_3 observations at any of the ten monitoring sites were evaluated by the mutual information (MI) scores and the feature importance scores. Multicollinearity tests and stepwise procedures were used to produce parsimonious models that maximizes accuracy with an optimally reduced number of predictor variables.

4. Results and discussions

4.1 Annual burned area and burn percentage

The acres burned in the 17 counties of the Flint Hills region in each spring burning season are presented in Figure 3. In average, around 30% of the rangeland were burned annually in spring. The annual burned percentage ranged from 3% to 48% due to different weather conditions in different years. The drought in 2012 and 2013 resulted in extreme small burned area in these two years.

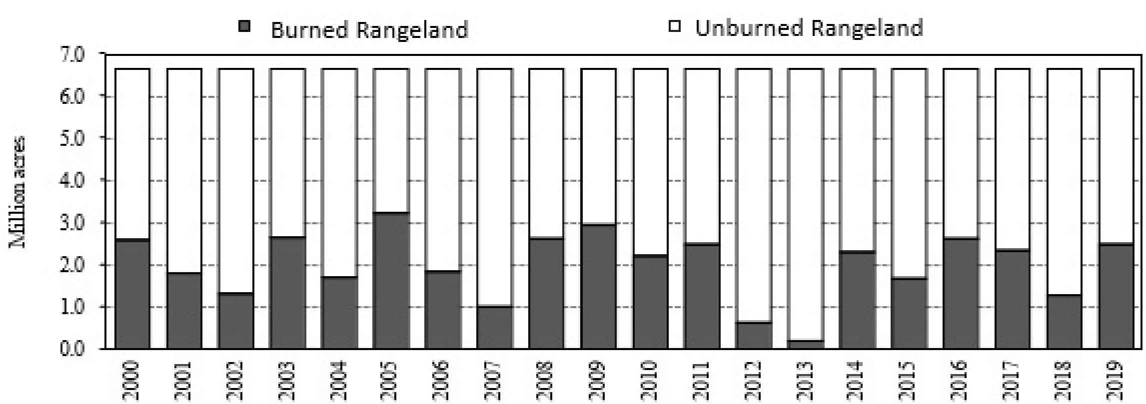


Figure 4. Acres burned in each spring burning season in the 17 counties of the Flint Hills region

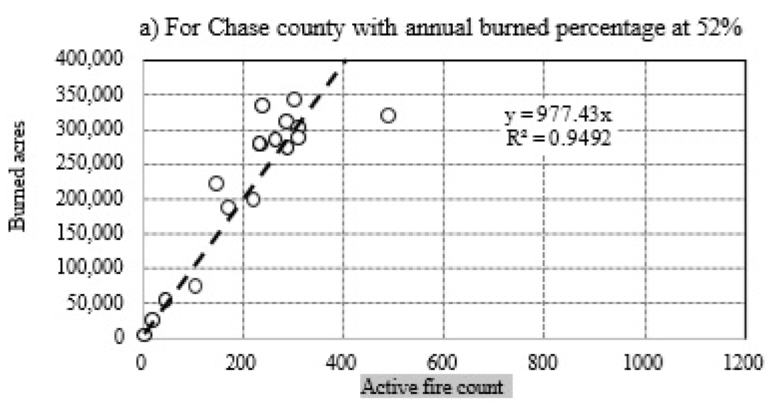
The annual burned percentage also varied at different part of the Flint Hills region. As shown in Table 2, in the central part of the Flint Hills region (Chase, Wabaunsee, Greenwood, Lyon, Elk, and Woodson counties), the annual average burned percentage ranged from 33% to 52%; while in the Southern part and at the edge of the Flint Hills region (Cowley, Chautauqua, Osage, Kay, Pottawatomie, and Marion counties), the annual average burned percentage ranged from 11% to 25%.

Table 2. Annual average burned area and burned percentage from 2003 to 2019 in each of the 17 counties

County	Total rangeland acres	Annual average burned acres	Annual average burned percentage
Kansas, Chase	425,328	222,979	52%
Kansas, Wabaunsee	408,113	171,179	42%
Kansas, Greenwood	623,567	233,778	37%
Kansas, Lyon	369,461	136,310	37%
Kansas, Elk	341,418	113,981	33%
Kansas, Woodson	211,943	69,518	33%
Kansas, Riley	250,844	79,837	32%
Kansas, Coffey	239,245	70,111	29%
Kansas, Morris	326,661	95,010	29%
Kansas, Butler	666,535	180,088	27%
Kansas, Geary	176,081	47,187	27%
Oklahoma, Osage	913,274	229,491	25%
Kansas, Pottawatomie	382,600	95,481	25%
Kansas, Cowley	478,257	109,501	23%
Kansas, Chautauqua	326,431	72,612	22%
Kansas, Marion	287,909	40,665	14%
Oklahoma, Kay	238,056	25,599	11%
Total	6,665,723	1,993,327	30%

4.2 Correlations between burned area and active fire count

The annual burned acres and the active fire count demonstrated strong correlations (R^2 ranged from 0.74 to 0.85 in different counties). The slope of the annual burned acres over the active fire count indicates the average size of one active fire count, and it was higher for counties with higher annual average burned percentage (Figure 5). In Chase County, the annual average burned percentage was as high as 52%, and the average size of one active fire count was 997 acres. In the counties with the annual average burned percentages between 27% and 42%, the average size of one active fire count was 710 acres. Most of these counties are in the central part of the Flint Hills region. For the counties in the Southern part and at the edge of the Flint Hills region (Cowley, Chautauqua, Osage, Kay, Pottawatomie, and Marion counties), the annual average burned percentage were less than 25%, and the average size of one active fire count was only 400 acres. As a comparison, the average burned area in the Flint Hills region in U.S. EPA's National Emission Inventory is 203 acres with many fires exceeding 500 acres (Baker et al., 2019).



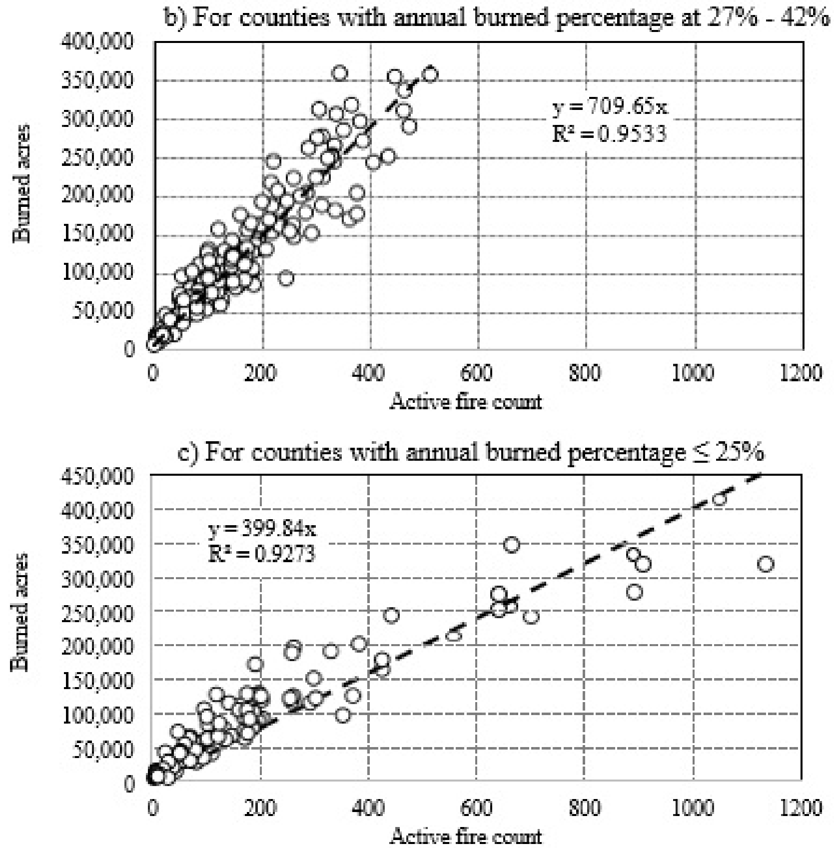


Figure 5. Correlations between the annual burned areas (estimated from burn scars in satellite images) and the active fire count (based on the detection of the released elevated energy) in different counties

4.3 Average and maximum daily burned area

The average and maximum daily burned area from 2003 to 2019 in the 17 counties of the Flint Hills region are plotted in Figure 6. The daily burned area generally started to increase rapidly since the end of March and peaked on April 14th. In average, the burned area from fires between March 31st and April 30th accounted for 86% of the total burned area in the whole burning season. The maximum daily burned area was around 0.5 million acres, which occurred on April 14th, 2005, and was about 1/6 of the total burned area in the 2005 spring burning season.

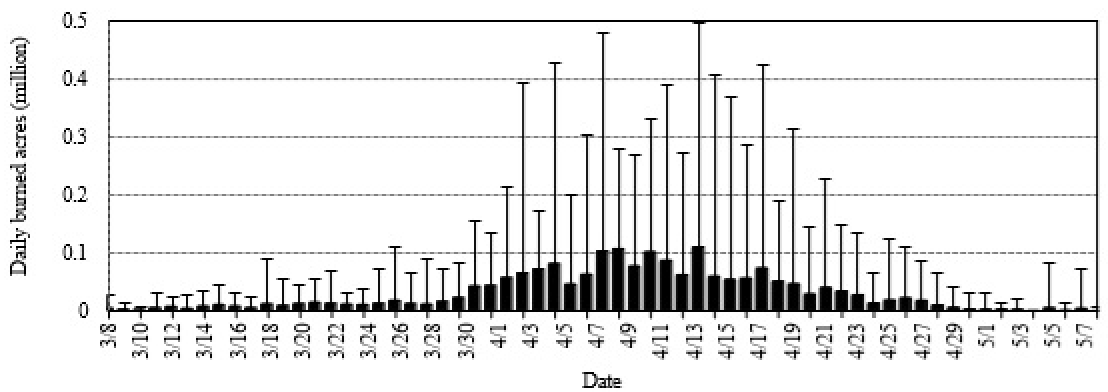


Figure 6. Average and maximum daily burned area from 2003 to 2019 in the 17 counties of the Flint Hills region (The black bars represent the average daily burned area. The error bars represent the maximum daily burned area)

4.4 Classification of daily burned area

All the days in the spring burning seasons from 2003 to 2019 were classified into 4 categories based on the daily burned area in the 17 counties, as shown in Table 3. In average, in the 62 days between March 8th and May 8th, 44 days were no fire days or light-fire days with daily burned area in the 17 counties less than 0.025 million acres, likely due to limited weather or fuel conditions; 12 days were medium-fire days with daily burned area between 0.025 and 0.10 million acres; only 6 days were heavy-fire days with daily burned area larger than 0.50 million acres. Fire activities were largely concentrated in a few days that had desired weather and fuel conditions. In average, 58% of the total burned area in the spring burning season occurred in 6 heavy-fire days. The total burned area in the medium-fire days (12 days) and the heavy-fire days (6 days) accounted for 91% of the total burned area. The median values of weather variables for different fire activity levels in all the days in the spring burning seasons from 2003 to 2019 were presented in Table 4. It showed fire activity level increased with decreasing cloud cover, increasing solar radiation, increasing air temperature, and decreasing RH.

Table 3. Classification of daily burned area of the 17 counties in the spring burn season from March 8th to May 8th (Data were average values for the spring burning seasons from 2003 to 2019)

Category	Range of daily burned area (million acres)	Average daily burned area (million acres)	Total burned area (million acres)	Percentage of burned area	Average days per burning season
No-fire	0	0	0	0%	23
Light-fire	0^+ to 0.025	0.008±0.007	0.18	9%	21
Medium-fire	0.025^+ to 0.10	0.050±0.022	0.64	33%	12
Heavy-fire	0.10^+ to 0.50	0.205±0.091	1.13	58%	6
Total			1.95	100%	62

Table 4. Median values of weather variables for different fire activity levels in all the 62 days in the spring burning seasons (March 8th to May 8th) from 2003 to 2019

	Wind speed (m/s)	RH (%)	Solar radiation (W/m^2)	Cloud cover (%)	Precipitation (mm)	Air temperature (^{o}C)	Soil temperature (^{o}C)
No-fire	4.1	71	260	39.2	0	13.9	13.0
Light-fire	4.2	52	418	16.3	0	14.4	11.0
Medium-fire	4.2	47	486	9.4	0	16.7	13.2
Heavy-fire	3.7	42	520	2.8	0	17.4	13.1

4.5 Spatial and temporal distributions of daily burned area

The Great Plains of the United States have a clear fire frequency relationship, with fire frequency generally increasing from west to east owing to precipitation and north to south due to temperature (Stambaugh et.al., 2011). The frequency and size of wildfires is also dependent on fuel production and ability of fires to spread (Scasta et. al., 2016). Our results showed both the burn frequency and the average sizes of prescribed fires varied at different part of the Flint Hills region. In the central part of the Flint Hills region, landowners tend to burn more frequently, and the fire sizes were generally larger. In the Southern part and at the edge of the Flint Hills region, they burn less frequently, and the fire sizes were generally smaller. This spatial variation agrees with the 2000-2010 data in Mohler & Goodin (2012b), and the observation that small fires are more frequent at the edge and periphery of the Flint Hills region. It reflected different fire management practice in different counties due to variations in weather, fuel, topography, and land use management. The six counties (Chase, Wabaunsee, Greenwood, Lyon, Elk, and Woodson counties) in the central part of the Flint Hills region had annual average burned percentage ranging from 33% to 52%, and they represented almost half of the total burned area in the 17 counties of study area. A well-recognized hypothesis was that burning annually or biennially could maximize productivity (Anderson et al., 1970; Towne & Owensby, 1984), and burning on a 3 year (or less) cycle is needed to maintain vegetative homogenization (Ratajczak et al., 2016). However, many other counties had much lower burn frequencies. In Oklahoma, a minimum, a four-year fire return interval or 25% of the burnable area each year had been recommended (Weir, 2011). The different burn frequency in different counties provided a research opportunity to optimize burn frequency for maximum productivity through a close examination of the historical burn area data.

In order to analyze the spatial and temporal distributions of burned area in the Flint Hills region, Baker et. al. (2019) used three data sources to estimate burned area: the Fire INventory from NCAR (FINN; Wiedinmyer et al., 2011), the Global Fire Emission Database (GFED; Van Der Werf et al., 2017) and the U.S. EPA's National Emission Inventory (NEI; USEPA, 2018), and the burned area assigned to detected prescribed fires were based on default field size assumptions. With the combination of active fire data and burn scar detection algorithm, our method reduced missing daily fire detections, and therefore our estimation of burned area were more accurate and much larger than the estimations from FINN, GFED, and NEI.

Results of daily burned area in our study showed that fire activities were highly concentrated in a few days that had desired weather and fuel conditions. The daily burned area generally started to increase since the end of March and peaked in mid-April. Large daily burned area often resulted in exceedance of air quality standards in daily O_3. If fire activities can be more evenly distributed, smoke impact could be reduced. Recent research suggested a longer spring burning season or burn outside of spring should be considered (Towne & Craine, 2016; Weir & Scasta, 2017), as it would provide more days with acceptable weather conditions for burning, and thus reduce daily burned area and the smoke impact on daily O_3. In order to optimize the timing of fire activities, it is necessary to study how weather conditions affected fire activities, and a clear guideline for better timing may be generated with precisely defined weather conditions for burning.

4.6 The acceptable burning conditions

The weather conditions in all the heavy-fire days from 2003 to 2019 were summarized in Table 5, and they were considered as acceptable burning conditions since majority of fire activities occurred under those conditions. For wind speed and RH, these acceptable weather conditions had a larger range comparing with the optimum burning conditions recommended by KDHE (2010). Land owners sometimes chose to burn when wind speed or RH were a little bit higher or lower than the recommended ranges of optimum conditions. More importantly, KDHE recommended to burn when cloud cover is 30-50% in order to reduce photochemical reactions that form O_3 (KDHE, 2010). However, our data showed most fires occurred in days with high solar radiations when cloud cover is much lower than 30%. Many landowners chose to burn in a day with strong sunshine and moderate temperature. The acceptable burning conditions defined in our study generally agreed with the conditions that were recommended by Weir (2011) and based on Oklahoma weather data, but our data had a narrower range in air temperature, and showed higher tolerance on higher wind speed. Weir (2011) estimated that there was an average of 18.5 days per month with the weather conditions needed for burning, which only considered temperature, RH, wind velocity, and precipitation, but not solar radiation. In the Flint Hills region, many land owners didn’t chose to burn when air temperature was too low or too high.

Table 5. The acceptable burning conditions that were determined from all the heavy-fire days (The total burned area of the 17 counties were average values for the spring burning seasons from 2003 to 2019)

	Wind speed (m/s)	RH (%)	Solar radiation (W/m^2)	Cloud cover (%)	Precipitation (mm)	Air temperature (ºC)	Soil temperature (ºC)	Average days per burn season	Total burned area (million acres)
Acceptable conditions for prescribed fires	1.3 ~ 8.0	20 ~ 80	312 ~ 639	0 ~ 43	0 ~ 2.38	4.2 ~ 25.8	5.6 ~ 19.1	30	1.62
In the whole spring burn season	1.0 ~ 14.7	20 ~ 100	38 ~ 735	0 ~ 100	0 ~ 94.48	-4.6 ~ 31.2	-0.3 ~ 24.3	62	1.95
Conditions recommended by KDHE (2010)	2.2 ~ 6.7	30 ~ 50		30 ~ 50				1	0.05
Conditions recommended by Weir (2011)	1.01~ 4.02	25 ~ 80			0	1.7 ~ 43.3			

4.7 How did weather conditions affect daily burn area?

In average, the optimum burning conditions recommended by KDHE (2010) only occurred in one day in one spring burning season, and the acceptable burning conditions determined from the prescribed fire practices of landowners occurred in around 30 days in one spring burning season. In average, 83% of the burned acres in the spring burning seasons (1.62 out of 1.95 million acres) were burned in these 30 days with the acceptable burning conditions. However, the fire activity levels in these 30 days had large variance, and not all of these 30 days were used for prescribed burning.

The importance of different weather variables as related to daily burned area were evaluated by the mutual information (MI) scores and the feature importance scores using random forest feature selection method (Table 6). The three most important weather variables were solar radiation, cloud cover, and RH. And the majority of the fires occurred when air stability class was B or C. Table 7 presents the fire activity levels in these 30 days, and the corresponding median values of weather variables for each fire activity level. As can be seen in Table 7, In the 30 days with acceptable burning conditions, 6 days were heavy-fire days, 8 days were medium-fire days, 11 days were light-fire days, 5 days were no-fire days. When all the acceptable burning conditions had been met, many landowners chose to burn at lower cloud cover, higher solar radiation, lower RH, higher temperature, and lower wind velocity, which is likely mainly due to considerations on safety or convenience. About 94% of all the heavy-fire days had cloud cover <30%, which were not in the KDHE recommended range of optimum burning conditions. Most heavy-fire days were days with high solar radiations when cloud cover is close to 0. Higher solar radiation and higher temperature favor O_3 production, while lower wind speed may reduce smoke dispersion. If fire activities can be more evenly distributed in all the 30 days that had the acceptable burning conditions, smoke impact can be reduced. In all the 30 days with the acceptable burn conditions, there were only 3.5 days with 30 ~ 43% cloud cover, which was within the KDHE recommended range of optimum burning conditions. Expanding the acceptable burning conditions to more days with optimum cloud cover will further increase the burning capacity of landowners.

Table 6. Mutual Information (MI) and feature importance scores of weather variables as related to daily burned area

Weather variables	MI value	Feature importance (SHAP value, $\times 10^{-3}$)
Solar radiation	0.20	8.39
Cloud cover	0.14	6.09
RH	0.16	5.92
Air stability class	0.08	3.08
Soil temperature	0.04	2.89
Wind speed	0.02	1.86
Air temperature	0.03	1.53
Precipitation	0.07	0.61

Table 7. Median values of weather variables for different fire activity levels in all the days with the acceptable burning conditions in the spring burning seasons (March 8th to May 8th) (The total burned area of the 17 counties were average values for the spring burning seasons from 2003 to 2019)

	Wind speed (m/s)	RH (%)	Solar radiation (W/m^2)	Cloud cover (%)	Precipitation (mm)	Air temperature (°C)	Soil temperature (°C)	Average days per burn season	Total burned area (million acres)
No-fire	3.6	52	459	13.8	0	17.9	14.6	5	0
Light-fire	4.2	48	457	8.6	0	16.3	11.3	11	0.11
Medium-fire	4.0	45	502	6.1	0	16.3	13.1	8	0.46
Heavy-fire	3.7	42	520	2.8	0	17.4	13.1	6	1.05
Total								30	1.62

4.8 The impact of cloud cover on burned acres

The main problem of the acceptable burning conditions that were determined from all the heavy-fire days was cloud cover. As shown in Table 7, many landowners chose to burn at a much lower cloud cover than the recommended optimum cloud cover conditions. Table 8 summarized the impact of cloud cover on the burned acres in the Flint Hills region in the spring burning seasons from 2003 to 2019. It further highlighted how cloud cover had played a role in land owners' decision of burning. As can be seen in Table 8, about 87% of the burned acres were burned with cloud cover <30%, and about 62% of the burned acres were burned with cloud cover <10%. There are a lot of room to reduce smoke impact on O_3, if landowners can choose to burn at higher cloud covers.

Table 8. Burned acres at different cloud covers in the spring burning seasons (March 8th to May 8th) (The total burned area of the 17 counties were average values for the spring burning seasons from 2003 to 2019)

	Total burned area per spring burning season (million acres)	Percentage of burned area	Average days per spring burning season
Cloud cover 0 ~ 10%	1.20	62%	23
Cloud cover 10+ ~ 30%	0.49	25%	15
Cloud cover 30+ ~ 50%	0.21	11%	13
Cloud cover > 50%	0.05	2%	11
Total	1.95	100%	62

4.9 Daily burn area at the county level and the preferred local weather conditions for burning

Daily burned area in 4 counties (Riley and Geary in Kansas, Kay and Osage in Oklahoma) were normalized by dividing the maximum daily burned area in the county so that data from counties with different sizes become comparable. The preferred daily average local weather conditions by land owners for prescribed fires were determined from all the days when daily burned area were larger than 50% of the maximum daily burned area in the county from 2003 to 2019 (Table 9). These preferred daily average local weather conditions generally agreed with the acceptable burning conditions in Table 4, but with narrower ranges. The preferred weather conditions by land owners had a narrow window for high solar radiations. The large differences between the maximum and minimum temperatures also showed that the preferred weather conditions had relatively high daytime temperature and low nighttime temperature, which generally indicated a warm and clear day without much cloud cover. In average, the preferred weather conditions determined from the prescribed fire practices of landowners only occurred in around 10 days in one spring burning season. Table 10 presents the fire activity levels in these 10 days, and the corresponding median values of weather variables for each level. As can be seen in Table 10, when all the preferred weather conditions had been met, most landowners preferred to burn at relatively lower wind velocity, higher solar radiation, and higher temperature, which agreed with the pattern that was observed in Table 7, except for RH. The discrepancy in how RH affected burning decisions was likely due to the fact that day-time average RH were used in Table 7, while daily average RH were used in Table 10. Since almost all the prescribed burning were conducted in day time while large RH variance was expected between day time and night time, the RH pattern observed in Table 7 was more reasonable.

Table 9. Preferred daily average local weather conditions for prescribed fires that were determined from all the days when daily burned area were larger than 50% of the maximum daily burned area in the county from 2003 to 2019

	Wind speed (m/s)	RH (%)	Solar radiation (Langley)	Precipitation (mm)	Maximum temperature (^oC)	Minimum temperature (^oC)	Average days per burn season
Preferred conditions for prescribed fires	1.9 ~ 7.5	34 ~ 82	536 ~ 633	0 ~ 0.5	8 ~ 31	-5 ~ 2	10
In the whole spring burn season	0.2 ~ 12.2	25 ~ 98	19 ~ 760	0 ~ 131	-6 ~ 38	-11 ~ 22	62

Table 10. Median values of daily average weather variables for different fire activity levels in all days with the preferred local weather conditions for prescribed fires

	Wind speed (m/s)	RH (%)	Solar radiation (Langley)	Precipitation (mm)	Maximum temperature (^oC)	Minimum temperature (^oC)	Average days per season
A* > 0.5	3.2	59	595	0	23	4	1
A = 0.10^+ to 0.50	3.6	54	581	0	21	3	3
A = 0^+ to 0.10	3.9	55	572	0	21	3	4
No fire	4.1	55	583	0	21	5	2

* A is normalized daily burned area, which was calculated as the ratio of the daily burned area in the county to the maximum daily burned area in the county. 1 Langley/day = 0.484583 W/m^2.

4.10 The impact of burned area on O_3

The overall R^2 between the total acres burned in the whole spring burning seasons and the highest 8-hour O_3 mixing ratios observed in the same period at any of the ten monitoring sites in Kansas was as high as 0.62 (Figure 7). Generally, for every one million increase of burned acres in the whole spring burning season, the highest 8-hour O_3 mixing ratios increased around 10ppb.

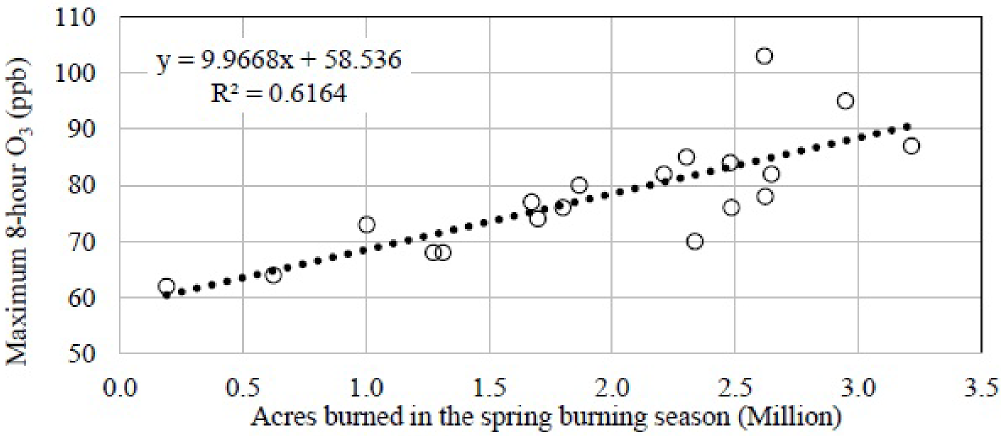


Figure 7. Correlations between the acres burned in the whole spring burning seasons from 2001 to 2019 and the highest 8-hour O_3 mixing ratios observed in the same period at any of the ten monitoring sites

The maximum 8-hour O_3 mixing ratios at different dates in the spring burning seasons from 2003 to 2013, and the corresponding average daily burned area in the same period in the 17 counties of the Flint Hills region are plotted in Figure 6. The O_3 data was from the Konza Prairie CASTNET (Clean Air Status and Trends Network) research monitoring site, which is located at the center of the Flint Hills region. As can be seen in Figure 8, the O_3 mixing ratios generally increased from March 8th to May 8th due to increasing temperature. However, all the O_3 exceedances than 70 ppb were in April, when intensive fires occurred in the Flint Hills region. The O_3 mixing ratios were affected not only by daily burned area, but also temperature, solar radiation, RH, and wind speed (Liu et al., 2018; Baker et al., 2016).

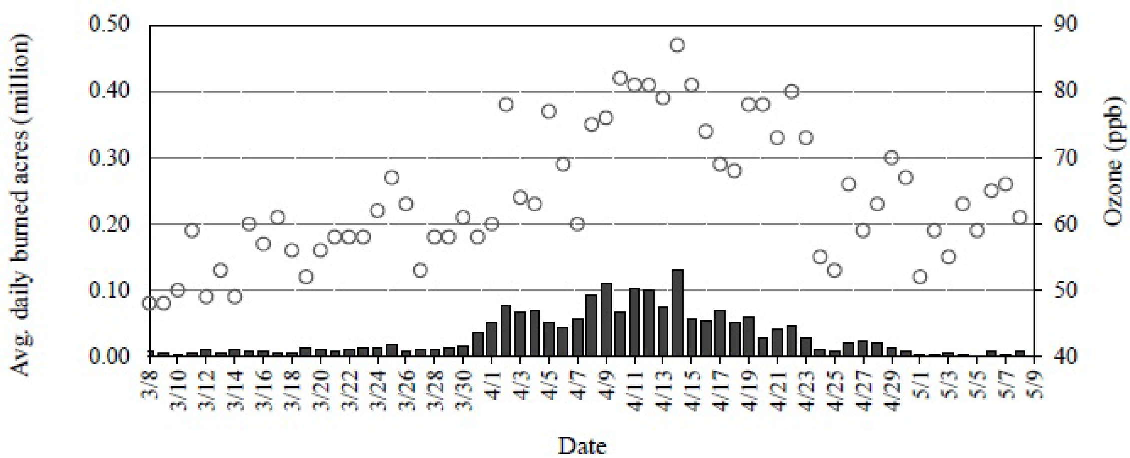


Figure 8. The maximum 8-hour O_3 mixing ratios (represented by the circles) in the Konza Prairie at different dates from 2003 to 2013 and the corresponding average daily burned area (represented by the black bars) in the same period in the 17 counties of the Flint Hills region.

The importance of daily burned area and different weather variables as related to the maximum 8-hour O_3 observations at any of the ten monitoring sites were evaluated by the mutual information (MI) scores and the feature importance scores using random forest feature selection method (Table 11). The most important variable that affected O_3 level were air temperature, followed by cloud cover, daily burned are, solar radiation, and RH.

Table 11. Mutual Information (MI) and feature importance scores of daily burned area and different weather variables as related to the maximum 8-hour O_3 observations at any of the ten monitoring sites

Variables	MI value	Feature importance (SHAP value, $\times 10^{-3}$)
Air temperature	0.26	2.95
Cloud cover	0.20	2.54
Daily burned area	0.15	1.25
Solar radiation	0.22	1.07
RH	0.20	0.70
Air stability class	0.18	0.55
Soil temperature	0.12	0.42
Wind speed	0.01	0.26
Precipitation	0.03	0.12

4.11 The O_3 regression models

An O_3 regression model was developed to simulate the daily maximum 8-hour O_3 mixing ratios in the spring burning seasons at any of the ten monitoring sites in Kansas, using daily burned area and weather variables as predictor variables, as in the following equation:

$$O_3(d) = 42.9 + 0.263 O_{3pre} + 3.16 \sin \frac{2\pi(d + 283)}{365} + 40.3A + 0.28T - 9.22C - 12.3RH - 0.54V$$

In the above equation, $O_3(d)$ is maximum 8-hour O_3 mixing ratio in ppb; O_{3pre} is maximum 8-hour O_3 mixing ratio on the previous day in ppb; d corresponds to the day of the year; A is the daily burned area in the Flint Hills region, in million acres; C is the day-time average cloud cover, ranging from 0 to 100%; RH is the day-time average RH, ranging from 0 to 100%; T is the day-time average air temperature in °C; V is the day-time average wind speed in $m \cdot s^{-1}$. The regression model was developed based on 1054 daily observations in the spring burning seasons from 2003 to 2019, and the R^2 was 0.61. In average, for every 0.1 million increase of daily burned acres, the maximum O_3 mixing ratios increased about 4 ppb.

Sensitivities of the predictor variables in the model were presented in Table 12. The most sensitive predictor variable was O_3 mixing ratio on the previous day, followed by the daily burned area.

Table 12. Sensitivities of the predictor variables on O_3

Variables	Average values ± standard deviation (std) in the spring burning seasons	Percent change of O_3 if the predictor variable increases by one std	Percent change of O_3 if the predictor variable increases by 10%
Maximum O_3 (ppb)	50.5 ± 10.9		
Previous day maximum O_3 (ppb)	50.5 ± 10.9	+5.7%	+2.6%
Daily burned area (million acres)	0.03 ± 0.06	+4.8%	+0.2%
RH	0.58 ± 0.19	-4.6%	-1.4%
Cloud cover	0.26 ± 0.24	-4.4%	-0.5%
Air temperature (°C)	14.7 ± 6.8	+3.8%	+0.8%
Wind speed (m/s)	4.4 ± 1.8	-1.9%	-0.5%

More O_3 regression models were developed using the daily maximum 8-hour O_3 mixing ratios from monitoring sites at Wichita (three sites), Kansas City (three sites), and Konza Prairie respectively (Table 13). It can be seen that, the O_3 regression model for Konza Prairie had the highest R^2, although much less data were available at this site for the development of the regression model. It was likely due to that fact that Konza Prairie was located at the center of the Flint Hills region, and was less affected by urban emissions. As expected, at the three sites around the Wichita area (Sedgwick, Wichita Health Department, Peck) and the Konza Prairie site, O_3 were more sensitive to daily burned area in the Flint Hills region. At the three sites around the Kansas City area (Leavenworth, Kansas City JFK center, Heritage Park), O_3 were less sensitive to daily burned area likely due to the further distances from the Flint Hills region. The O_3 regression model for Wichita had relatively lower R^2, possibly because there were more complex factors that could contribute to the O_3 level in Wichita.

Table 13. The O_3 regression models for Wichita, Kansas City, and Konza Prairie

For Konza Prairie, $OO_3(dd) = 44.5 + 0.221OO_{3_{pppppp}} + 3.14 \sin \frac{2\pi\pi(dd + 283)}{365} + 44.2AA + 0.30TT - 6.17CC - 16.2RRRR - 0.48VV$ n = 616, $R^2 = 0.62$
For Wichita, $OO_3(dd) = 43.5 + 0.278OO_{3_{pppppp}} + 4.80 \sin \frac{2\pi\pi(dd + 283)}{365} + 24.6AA + 0.09TT - 8.95CC - 15.2RRRR - 0.44VV$ n = 1054, $R^2 = 0.53$
For Kansas city, $OO_3(dd) = 40.2 + 0.236OO_{3_{pppppp}} + 2.33 \sin \frac{2\pi\pi(dd + 283)}{365} + 16.2AA + 0.34TT - 10.09CC - 14.2RRRR - 0.15VV$ n = 1054, $R^2 = 0.60$

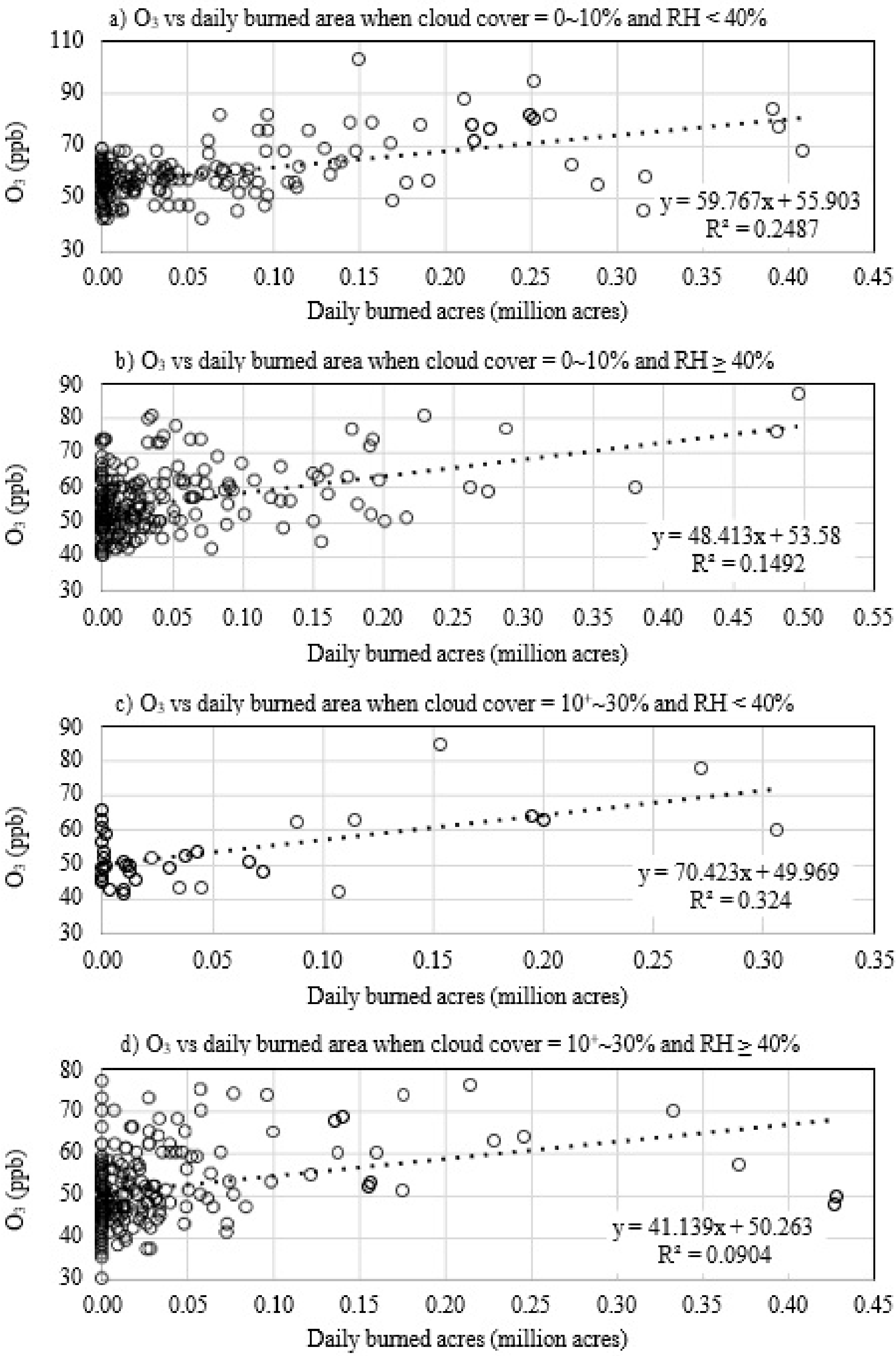
4.12 The burning decision tool

Since O_3 were largely affected by daily burned area, previous day O_3, RH and cloud cover, the maximum daily burned area in the Flint Hills region to avoid O_3 >70 ppb were estimated under various weather and previous day O_3 conditions, based on simplified O_3 regression models (Table 14). The daily burned area in the Flint Hills region and the corresponding maximum 8-hour O_3 mixing ratio under various weather conditions were plotted in Figure 9.

Table 14. The maximum daily burned area in the Flint Hills region in to avoid O_3 >70 ppb

Cloud cover	RH	Simplified O_3 models	A_{max} in order to avoid O_3 >70 ppb	Recommendations
0~10%	< 40%	$O_3 = 38.9+0.32O_{3pre}+49.8A$ $R^2 = 0.33$, n = 169	If O_{3pre}=50, A_{max} = 0.30 If O_{3pre}=60, A_{max} = 0.24 If O_{3pre}=70, A_{max} = 0.17 O_3 is most sensitive to fire	Marginal conditions for burning. Burn with constraints considering O_{3pre}.
	≥ 40%	$O_3 = 29.5+0.46O_{3pre}+46.8A$ $R^2 = 0.41$, n = 222	If O_{3pre}=50, A_{max} = 0.37 If O_{3pre}=60, A_{max} = 0.28 If O_{3pre}=70, A_{max} = 0.18 O_3 is sensitive to fire	
10^+~30%	< 40%	$O_3 = 38.7+0.24O_{3pre}+45.7A$ $R^2 = 0.40$, n = 37	If O_{3pre}=50, A_{max} = 0.42 If O_{3pre}=60, A_{max} = 0.37 If O_{3pre}=70, A_{max} = 0.32 O_3 is sensitive to fire	Second-class conditions for burning. It is OK to burn but heavy fire is not recommended.
	≥ 40%	$O_3 = 27.9+0.45O_{3pre}+28.9A$ $R^2 = 0.36$, n = 213	If O_{3pre}=50, A_{max} = 0.68 If O_{3pre}=60, A_{max} = 0.52 If O_{3pre}=70, A_{max} = 0.37 O_3 is less sensitive to fire	Recommended conditions for burning. Heavy fire is OK if O_{3pre} <60 ppb.
30^+~50%	-	$O_3 = 41.7-13.8RH+0.28O_{3pre}$ $R^2 = 0.25$, n = 212	O_3 is not sensitive to fire	Optimum conditions for burning.

Notes: O_{3pre} is maximum 8-hour O_3 mixing ratio on the previous day in ppb; A is the daily burned area in the Flint Hills region, in million acres; A_{max} is the maximum daily burned area in the Flint Hills region, in million acres, in to avoid O_3 >70 ppb; RH is the day-time average RH, ranging from 0 to 100%; n is number of days used in the models.


a) O_3 vs daily burned area when cloud cover = 0~10% and RH < 40%
O_3 (ppb)
Daily burned acres (million acres)
y = 59.767x + 55.903
R^2 = 0.2487
b) O_3 vs daily burned area when cloud cover = 0~10% and RH ≥ 40%
O_3 (ppb)
Daily burned acres (million acres)
y = 48.413x + 53.58
R^2 = 0.1492
c) O_3 vs daily burned area when cloud cover = 10^+~30% and RH < 40%
O_3 (ppb)
Daily burned acres (million acres)
y = 70.423x + 49.969
R^2 = 0.324
d) O_3 vs daily burned area when cloud cover = 10^+~30% and RH ≥ 40%
O_3 (ppb)
Daily burned acres (million acres)
y = 41.139x + 50.263
R^2 = 0.0904

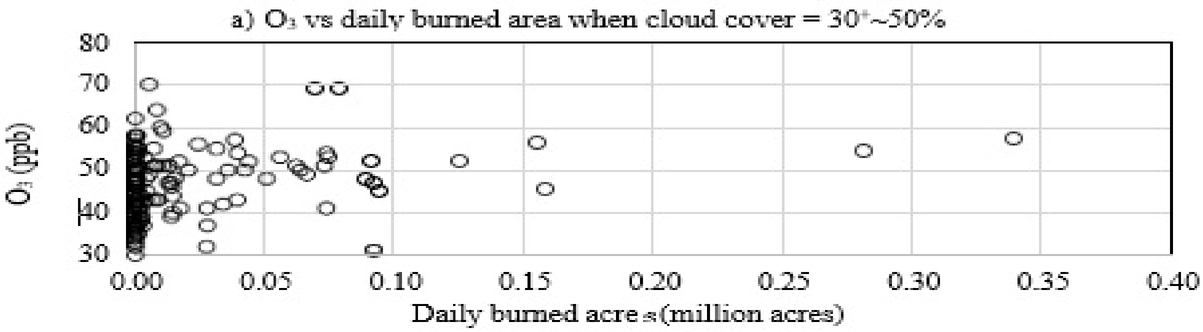


Figure 9. Daily maximum 8-hour O_3 mixing ratios vs daily burned area in the Flint Hills region from 2003 to 2019 under various weather conditions

As can been seen in Table 14 and Figure 9, when cloud cover is between 30 to 50%, O_3 is not sensitive to fire activities. From 2003 to 2019, there were 5 days with heavy fires activities (daily burned area >0.1 million acres) under this condition, and none of these 5 days had O_3 >70 ppb. It can be concluded that, in order to avoid O_3 >70 ppb, the best time to burn is when cloud cover = 30~50%. Using the acceptable ranges of RH, wind speed, air temperature, and precipitation in Table 4, the whole set of this first recommended conditions for prescribed burning are: cloud cover = 30~50%; RH = 20~80%; wind speed = 1.3~8.0 m/s, air temperature = 4.2~25.8 ºC, precipitation < 2.38 mm. In average, there were 8 days with these conditions in one spring burning season from March 8th to May 8th, based on the data from 2003 to 2019. Because 8 days may not be enough to complete all the needed burning, landowner may also need to consider burning in other days with lower cloud cover.

Another recommended weather conditions that are suitable for burning are when cloud cover = 10~30%, and RH ≥40%. Under these conditions, the O_3 background is generally less than that when cloud cover is lower, and O_3 is less sensitive to fire activities. In average, for every 0.1 million increase of daily burned acres, the maximum O_3 mixing ratios increased around 2.9 ppb. But O_3 is more sensitive to the O_3 level on the previous day, likely due to the higher RH. Generally, if the O_3 level on the previous day is at the average level (50.5 ± 10.9 ppb in the spring burning season) or less, burning under these conditions will not likely result in O_3 >70 ppb. From 2003 to 2019, there were 16 days with heavy fires activities (daily burned area >0.1 million acres) under these conditions, and only 2 days (12% chance) had O_3 >70 ppb mostly due to higher O_3 level on the previous day (Figure 9-d). The whole set of this recommended conditions for prescribed burning are: cloud cover = 30~50%; RH = 40~80%; wind speed = 1.3~8.0 m/s, air temperature = 4.2~25.8 ºC, precipitation < 2.38 mm. In average, there were 10 days with these conditions in one spring burning season from March 8th to May 8th, based on the data from 2003 to 2019.

When cloud cover = 10~30% and RH <40%, O_3 is less sensitive to the O_3 level on the previous day, but is more sensitive to fire activities. In average, for every 0.1 million increase of daily burned acres, the maximum O_3 mixing ratios increased around 4.6 ppb. From 2003 to 2019, there were 7 days with heavy fires activities (daily burned area >0.1 million acres) under these conditions, and 2 days (28% chance) had O_3 >70 ppb (Figure 9-c). These conditions can be considered as second-class conditions for prescribed burning. Under these conditions, it is OK to burn but heavy fire is not recommended. The whole set of this second-class conditions for prescribed burning are: cloud cover = 30~50%; RH = 20~40%; wind speed = 1.3~8.0 m/s, air temperature = 4.2~25.8 ºC, precipitation < 2.38 mm. In average, there were 2 days with these conditions in one spring burning season from March 8th to May 8th, based on the data from 2003 to 2019.

When cloud cover = 0~10%, the O_3 background is generally higher, and O_3 is also most sensitive to fire activities, especially when RH is also low. In average, for every 0.1 million increase of daily burned acres, the maximum O_3 mixing ratios increased around 4.7 to 5.0 ppb. From 2003 to 2019, when cloud cover = 0~10%, there were 34 days with heavy fires activities (daily burned area >0.1 million acres) when RH<40%, and 16 days (47% chance) had O_3 >70 ppb (Figure 9-a). And there were 29 days with heavy fires activities when RH≥40%, and 7 days (24% chance) had O_3 >70 ppb (Figure 9-b).The conditions when cloud cover = 10~30% can be considered as marginal conditions for prescribed burning. Under these conditions, burning should be managed not to exceed the maximum daily burned area which can be determined by the O_3 level on the previous day and the RH. For example, when the O_3 level on the previous day is in the average level around 50 ppb and RH<40%, the maximum daily burned area will be around 0.30 million acres. When the O_3 level on the previous day is higher, the maximum daily burned area need to be lower in order to avoid O_3 >70 ppb.

5. Challenges

There were many technical challenges in the process of retrieving daily burned area from satellite observations, which has delayed the project for more than 6 months. But the main challenges of this project is the organization of smoke management workshops and communication during the COVID-19 pandemic. Plans of face to face workshop has to be cancelled for multiple times, while the effectiveness of an online virtual workshop to engage landowners and stakeholders is questionable.

6. A summary of outputs with links

- Demilade, A. and Liu, Z. 2021. Identification of meteorological factors affecting the timing of prescribed burning in the Flint Hills. ASABE paper No. 2100194. St. Joseph, MI.: ASABE. Available at https://elibrary.asabe.org/abstract.asp?aid=52331
- Demilade, A. and Liu, Z. 2020. A Spatio-temporal approach for daily burned area mapping at 250 m from MODIS data of Kansas Flint Hill region. ASABE paper No. 2001254. St. Joseph, MI.: ASABE. Available at https://elibrary.asabe.org/abstract.asp?aid=51552
- Regression Models to Simulate O_3 Contributions from Prescribed Burning in Flint Hills Using Daily Burned-Area Data. Presented in ASABE annual meeting, on July 12, 2021,
- Preliminary results of the project were virtually presented at the SWCS CIG Showcase in July 26-29, 2020.
- Fact sheet: How much does Kansas Rangeland Burning Contribute to Ambient Ozone? Available at https://bookstore.ksre.ksu.edu/pubs/MF3357.pdf
- Data sheets including all the retrieved daily burned area data, processed weather data, and O_3 data from 2003 to 2019 will be available upon request.

7. Discussion of the impact or potential impact of the project to conservation in the US

Prescribed burning is a long standing practice to maintain the ecosystem in the Flint Hills region, which extends throughout much of eastern Kansas, and contains 7 million acres of rangeland and the largest remaining area of unplowed tallgrass prairie in North America. Burning is ecologically and financially important to the rangeland communities. Approximately one third of the rangeland are burned each year, mostly in April. Smoke from the fires causes elevated O_3 in ambient air, contributing to O_3 exceedances, and have affected several states downwind of Kansas. For decades, O_3 has been the most persistent and perhaps the most dangerous air pollutants in the U.S. The smoke impact of rangeland burning has been subject to intense discussion and public debate.

The O_3 exceedance could have been avoided if majority of prescribed burning were conducted on the right timing. However, many landowners lack scientific understanding of how burn and weather conditions affect smoke impact, and lack tools for better management and timing of prescribed fires. The current smoke management tools are not sufficient to prevent exceedance of the ambient O_3 standard.

The detailed guidelines generated from this project can assist land managers to better plan their burning activities and enable the continuous practice of burning in a manner that minimize adverse air quality. It will not only help to reduce the impacts of smoke, but also increase capacity of land management by allowing more burning when conditions are favorable, and ultimately to transform the traditional prescribed burning into a safe, effective, and sustainable practice.

Prescribed rangeland burning has been held accountable for the smoke impact on air quality. It is expected that, after the project, both land managers and the general public will feel more knowledgeable about the actual smoke impact from prescribed rangeland burning, and will be more confident to participate in the discussion and more likely to cooperate in efforts to reduce the smoke impact. Therefore, the social impact of smoke from burning will also be reduced through better communication.

Project results can be incorporated into models to assist policy decisions on all timescales, from the short-term: fire management and health advisories, to the mid-term: air quality waiver, and the long-term: ecosystem and urban-wildland interface management.

8. Potential next steps if relevant.

- Revise the three ASABE conference papers/presentations and publish the project results in peer reviewed journals.
- Conduct face to face smoke management workshops to disseminate project results to land managers, county Extension agents, regulators, and other stakeholders.
- Complete and publish the final fact sheet for use in public settings.
- The project team will continue to track the burning activities in the region and the O_3 levels under smoke impact after the project. Comparison will be made before and after the project to evaluate the lasting impact of project results, and the results will be made available online and communicated with NRCS technical contact.

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