Spring 2012

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Great Plains Research 22 (Spring 2012):15–25

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ABSTRACT—Prescribed burning is commonly used to prevent succession of tallgrass prairie to woody vegetation, which preserves the prairie's value to ranching and native wildlife. However, burning has negative effects as well, including potentially harming wildlife and releasing pollutants into the atmosphere. Research concerning the effects of fire on vegetation dynamics, wildlife, and air quality would benefit greatly from maps of burned areas in the Flint Hills, as no reliable quantification of burned areas currently exists. We used Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery to map burned areas in the Flint Hills for each year from 2000 to 2010. Our maps revealed the total amount and spatial pattern of burning for each year. They also revealed the frequency with which different parts of the study area were burned during the 11-year study period. Finally, our maps showed that nearly all burning took place during the month of April.

Key Words: burned-area mapping, MODIS, prescribed fire, remote sensing, tallgrass prairie

INTRODUCTION

Effects of Prescribed Burning in Tallgrass Prairie

Prescribed burning greatly influences the sustainability, species composition, and productivity of plant communities in tallgrass prairie (Knapp and Seastedt 1998), and is partly responsible, along with drought and grazing, for the evolution of grasslands in central North America (Anderson 1990, 2006). Burning suppresses the growth of woody plants, allowing prairies to maintain their current extent (Collins 1992; Glenn et al. 1992; Collins and Steinauer 1998; Hartnett and Fay 1998), and to expand their range into forests (Keeley and Rundel 2005). Burning also prevents nonnative cool-season grass species from decreasing the abundance of native warm-season grasses and forbs (Abrams and Hulbert 1987; Smith and Knapp 1999; Towne and Kemp 2003; Simmons et al. 2007). Because many nonnative grasses and woody species are less palatable to livestock, properly timed prescribed burning represents a cost-effective way to increase cattle weight gain, particularly when burning occurs in mid- to late spring (Anderson et al. 1970). This increases the economic viability of ranching in tallgrass prairie (Bernardo et al. 1988).

Manuscript received for review, July 2011; accepted for publication, October 2011.

In addition to plant communities, prescribed fire affects wildlife. Wilgers and Horne (2006) found that different reptile species show a preference for specific burn frequencies, while Kaufman et al. (1998a) noted that fire can cause direct mortality of reptiles, particularly when they are less mobile due to cool temperatures. Small mammal communities also vary depending on the frequency and timing of burning, with some species increasing and some decreasing due to the same conditions (Kaufman et al. 1990; Kaufman et al. 1998b). They also suffer direct mortality from fires (Kaufman et al. 1990). Changes in vegetation communities due to burning can also affect insect populations. Evans (1984) notes that grasshopper diversity is greatest on areas with intermediate burn frequencies, as these areas are used by both forb- and grass-feeding species. Like with small mammals, the effects of fire on grassland birds can be positive or negative depending on species, drought status, and the spatial scale at which burning takes place (Zimmerman 1992; Fuhlendorf et al. 2006; With et al. 2008).

A negative consequence of prescribed burning is the release of chemical and particulate pollutants, which can have serious health implications for humans living within the airsheds of burned areas (Radke et al. 2001). Moreover, these airsheds can extend for hundreds of miles (Niemie et al. 2005). Chemicals commonly produced

by biomass burning, both directly and indirectly, are oxocarbons (CO_X), sulfur oxides (SO_X), ozone (O_3), ammonia (NH_3), nitrogen oxides (NO_X), methane (CH_4), and other nonmethane hydrocarbons (NMHC) (Dennis et al. 2002; Pope et al. 2002). Although brief exposure to these chemicals causes little risk, longer-term exposure can be harmful, particularly in the case of sulfur oxides (Pope et al. 2002) and ozone (Meng et al. 1997). More likely to affect health in the short term are particulates released during burning—particularly those less than 2.5 μm in size—which are strongly associated with elevated mortality due to lung cancer and other cardiopulmonary-related causes (Pope et al. 2002).

Burned-Area Mapping in Tallgrass Prairie

Remotely sensed imagery is ideal for burned-area mapping because of its high temporal resolution, wide spatial coverage, cost effectiveness, and ability to access otherwise inaccessible areas (Pereira et al. 1997; Al-Rawi et al. 2001; Roy et al. 2002). Currently, most remote sensing–based burn-mapping research done in temperate rangelands has been done in semiarid areas rather than in mesic tallgrass prairies (e.g., Rahman and Gamon 2004; Cao et al. 2009). Because burning in tallgrass prairie typically occurs in the spring, burn scars disappear quickly as both burned and unburned areas rapidly regrow vegetation (Mohler and Goodin 2010). This is not necessarily the case in savannahs and semiarid grasslands—particularly when fires do not coincide with the growing season. For this reason, we used a burned-area mapping method that was developed specifically for tallgrass prairie (Mohler and Goodin 2011).

Prescribed burning affects a wide range of human and natural systems in the Flint Hills, and studying the effects of fire on these systems is important. These studies would benefit from maps showing how much of the Flint Hills is burned in a given year, the exact location of the burned areas (including spatial pattern), how frequently different parts the region are burned, and the temporal pattern of the fires throughout the burn season. Currently, the only existing sources of burned-area information are products derived from satellite imagery and a voluntary burning report. The global nature and relatively coarse spatial resolution of the former poses problems for burned-area mapping in grasslands (Eva and Lambin 1998; Boschetti et al. 2004), while the latter is not designed to be a complete catalog of burned areas in the Flint Hills. Our objective, therefore, was to quantify and map burned areas in the Flint Hills of Kansas and Oklahoma on an annual basis between 2000 and 2010.

METHODS

Study Area

We mapped burned areas across 18 counties in Kansas and Oklahoma (Fig. 1). These counties were chosen because they contain the major grassland portions of the Flint Hills physiographic region, which is the largest extant tract of tallgrass prairie in the world (Kollmorgen and Simonett 1965; Knapp and Seastedt 1998). Nongrassland vegetation types include crops in the area's floodplains as well as trees and shrubs in riparian areas and in areas where burning has been suppressed. Additionally, many species of forbs are common throughout the region (Freeman 1998).

Data Acquisition and Processing

We used Moderate Resolution Imaging Spectroradiometer (MODIS) data (MOD09GQ, MYD09GQ) due to its balance of temporal (twice daily) and spatial (250 m) resolution. We downloaded all images acquired between March 1 and May 10 (an image from February 28, 2002, was also used) in each of 11 study years (2000–2010) from the Warehouse Inventory Search Tool (WIST) of the National Aeronautics and Space Administration (NASA). This provided two images per day except in 2000, 2001, and 2002, when only one MODIS sensor was in orbit. Each image consisted of MODIS band 1 (red, 0.62–0.67 μm) and band 2 (NIR, 0.841-0.876 μm). We converted all images from their native hierarchical data format (HDF) to tagged image file format (TIFF), georectified them to the Universal Transverse Mercator (UTM) coordinate system (zone 14), and subset them to the 18-county study area.

We visually checked each image and did not use images in which clouds or their shadows were present across the entire study area. Images with partial cloud cover were used, as burns could still be detected in cloud-free areas. However, burns mapped in cloudy areas were not included in the final results, as cloud shadows are spectrally similar to burned areas and cause burn overestimation. These burns did not go unmapped, since they were visible in images from the dates surrounding the cloudy image. In order to reduce data redundancy, we used only the best image for each date. We kept the image that had the best combination of

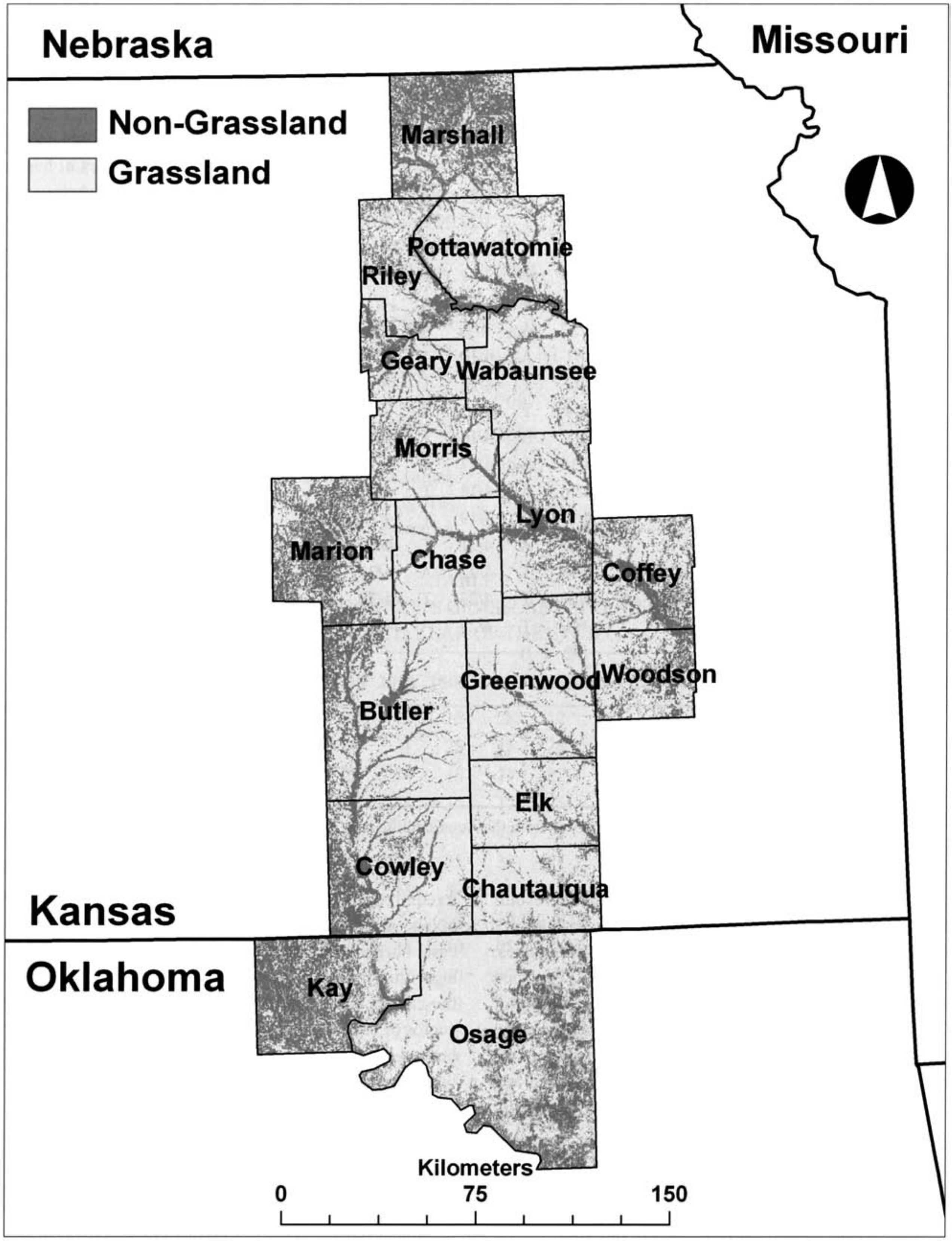

Figure 1. The 18-county study area showing grassland and nongrassland areas. Land cover was adapted from Gap Analysis Program data (KARS 2001).

TABLE 1
DATES OF MODERATE RESOLUTION IMAGING SPECTRORADIOMETER SCENES USED IN THIS STUDY

2000	2001	2002	2003		2004		2005		2006		2007		2008		2009		2010	
3/5	3/8	2/28	3/2	A	3/7	T	3/1	T	3/2	T	3/3	A	3/1	A	3/1	T	3/2	A
3/25	3/13	3/9	3/6	A	3/9	T	3/4	A	3/3	A	3/4	T	3/4	T	3/8	A	3/3	T
3/28	3/20	3/29	3/9	T	3/11	A	3/5	T	3/16	A	3/8	A	3/8	A	3/16	T	3/4	A
3/30	3/22	4/1	3/13	A	3/12	A	3/11	A	3/24	T	3/9	T	3/10	A	3/17	A	3/18	A
4/2	3/31	4/3	3/15	A	3/14	T	3/12	T	3/27	T	3/16	T	3/11	T	3/19	A	3/25	A
4/4	4/7	4/5	3/23	T	3/18	T	3/13	A	3/28	A	3/17	A	3/15	A	3/21	T	3/26	T
4/7	4/9	4/9	3/24	A	3/21	T	3/19	T	3/31	T	3/18	T	3/19	A	3/24	A	3/29	T
4/8	4/11	4/10	3/26	A	3/23	T	3/20	T	4/2	A	4/1	T	3/20	T	3/30	T	3/31	T
4/10	4/12	4/17	3/29	A	3/28	A	3/27	A	4/9	A	4/2	A	3/21	A	3/31	A	4/1	A
4/11	4/13	4/22	3/30	T	3/31	A	4/1	A	4/10	A	4/3	T	3/23	T	4/3	A	4/2	T
4/14	4/18	4/23	3/31	A	4/1	T	4/2	T	4/12	T	4/4	A	3/25	A	4/4	T	4/3	A
4/17	4/21	4/24	4/1	T	4/2	A	4/4	T	4/13	A	4/7	A	3/27	T	4/7	A	4/4	T
4/18	4/25	4/25	4/2	A	4/4	A	4/7	B	4/16	T	4/8	T	4/1	A	4/8	T	4/5	A
4/19	4/27	4/28	4/7	A	4/8	T	4/14	A	4/17	A	4/15	T	4/2	A	4/10	A	4/6	A
4/22	5/9	5/5	4/9	T	4/11	A	4/16	A	4/18	T	4/16	A	4/4	A	4/11	T	4/9	T
5/10		5/9	4/10	A	4/16	A	4/17	B	4/19	T	4/19	T	4/5	T	4/14	A	4/10	A
			4/11	T	4/17	T	4/23	A	4/21	T	4/20	A	4/6	A	4/20	T	4/14	A
			4/12	A	4/19	T	4/24	T	4/22	A	4/21	A	4/13	A	4/21	A	4/17	A
			4/14	A	4/27	A	4/27	T	4/23	T	4/28	T	4/14	T	4/22	T	4/19	A
			4/18	A			5/1	T	4/27	A	4/29	A	4/15	A	4/23	A	4/23	A
			4/21	A			5/2	B					4/19	T	4/24	T	4/27	T
			4/22	T			5/4	T					4/22	A	4/28	A	4/29	T
			4/26	T									4/25	A	5/8	T		
			5/5	A									4/28	T				
													4/29	A				
													5/3	T				

Notes: Letters beside each scene denote whether it was from the Aqua satellite (A), Terra satellite (T), or both (B). All scenes from 2000 to 2002 are from Terra.

cloud cover (as little as possible) and high spatial resolution (where the study area was closest to nadir), except for three dates in 2005, for which we used both images. Table 1 shows the dates of all scenes used in the burned area reconstruction, and the specific satellite (Aqua or Terra) from which each scene originated. In order to prevent all nongrassland cover types and areas outside the study region from being analyzed, we created and used a mask based on the procedure outlined in Mohler and Goodin (2011).

Classification

We applied a supervised, minimum distance classification technique to each masked image in each of the 11 years. Because this classification technique is supervised, it required training data, which are user-selected example pixels of each land cover type being classified (in this case, burned and unburned areas). A minimum distance algorithm then assigns each pixel in the image to one of the classes based on its Euclidean distance to the mean vector of each training class (Jensen 2005). We selected burned-area training pixels only from the most recently burned areas in each image, which minimized false positives that would otherwise occur due to the spectral similarity of unburned areas and older burns. This allowed accuracy levels of approximately 90% or greater when burned areas were mapped less than two weeks after they were burned (Mohler and Goodin 2011). When clouds prevented burned areas from being mapped in all or part of the study area for more than two weeks, we assumed accuracy values below 90%.

RESULTS

The amount of grassland burned annually within the study area ranged from as low as 414,456 ha in 2007 to as high as 1,320,556 ha in 2005. This translates to between 15% and 48% of the grasslands in the study area being burned in each of the 11 years. Although these percentages varied greatly from year to year, no trend was apparent over the 11 years covered by the study (Table 2). The estimate of total grassland area (2,778,643 ha) is based on Kansas Gap Analysis Program (GAP) data (Kansas Applied Sensing Program [KARS] 2001).

At the county level, the mean percentage of total grassland area burned across all 11 years of the study varied from as high as 56% for Chase County (which is 87% grassland) to as low as 11% for Kay County (which is 40% grassland; Table 3). In Chase County, the percentage of grassland burned each year varied from a high of 80% in 2005 to a low of 13% in 2007. In Kay County, these values ranged from 24% in 2003 to 3% in 2002, respectively (Table 3). Chase and Kay counties demonstrate the extremes

TABLE 2
TOTAL AND PERCENT OF GRASSLAND BURNED WITHIN THE STUDY AREA FOR EACH OF THE 11 YEARS OF THE STUDY

Year	Burned grassland (ha)	Percentage burned
2000	1,064,994	38
2001	760,769	27
2002	543,119	20
2003	1,077,588	39
2004	696,594	25
2005	1,320,556	48
2006	755,813	27
2007	414,456	15
2008	1,074,944	39
2009	1,212,281	44
2010	905,738	33

TABLE 3
PERCENTAGE OF EACH COUNTY'S GRASSLAND AREA THAT WAS BURNED IN EACH YEAR OF THE STUDY

County	Grass (ha)	Grass (%)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Mean
Marshall	77,514	33	22	42	15	8	12	24	15	12	17	25	12	**18**
Riley	101,515	64	36	31	28	25	28	51	39	28	37	46	35	**35**
Pottawatomie	154,836	70	28	34	18	11	27	44	24	15	32	33	31	**27**
Geary	71,259	67	26	23	17	17	25	59	34	13	39	43	35	**30**
Wabaunsee	165,161	80	48	32	33	43	39	69	67	22	59	64	45	**47**
Morris	132,198	73	41	24	25	33	21	53	42	6	38	34	39	**32**
Lyon	149,519	67	45	23	39	51	28	58	60	17	43	55	33	**41**
Marion	116,515	48	23	9	4	19	9	28	6	4	18	22	21	**15**
Chase	172,128	87	75	43	40	65	44	80	46	13	67	73	66	**56**
Coffey	96,821	57	29	12	40	37	17	47	42	26	32	51	18	**32**
Greenwood	252,354	85	49	24	29	54	24	57	29	22	49	57	44	**40**
Butler	269,743	72	45	27	11	39	19	47	14	18	40	44	36	**31**
Woodson	85,772	65	35	35	23	40	29	47	25	26	41	46	28	**34**
Elk	138,170	83	38	34	17	46	31	47	20	18	43	52	37	**35**
Cowley	193,548	67	36	23	5	42	24	41	13	14	40	31	27	**27**
Chautauqua	132,105	81	28	15	8	38	23	35	20	7	26	38	12	**23**
Osage (OK)	369,597	63	33	35	10	45	26	38	11	9	30	37	26	**27**
Kay (OK)	96,340	40	12	11	3	24	9	14	7	5	17	12	12	**11**

Note: The first column is the total amount of grassland in each county, while the second column is the percentage of each county's area that is grassland.

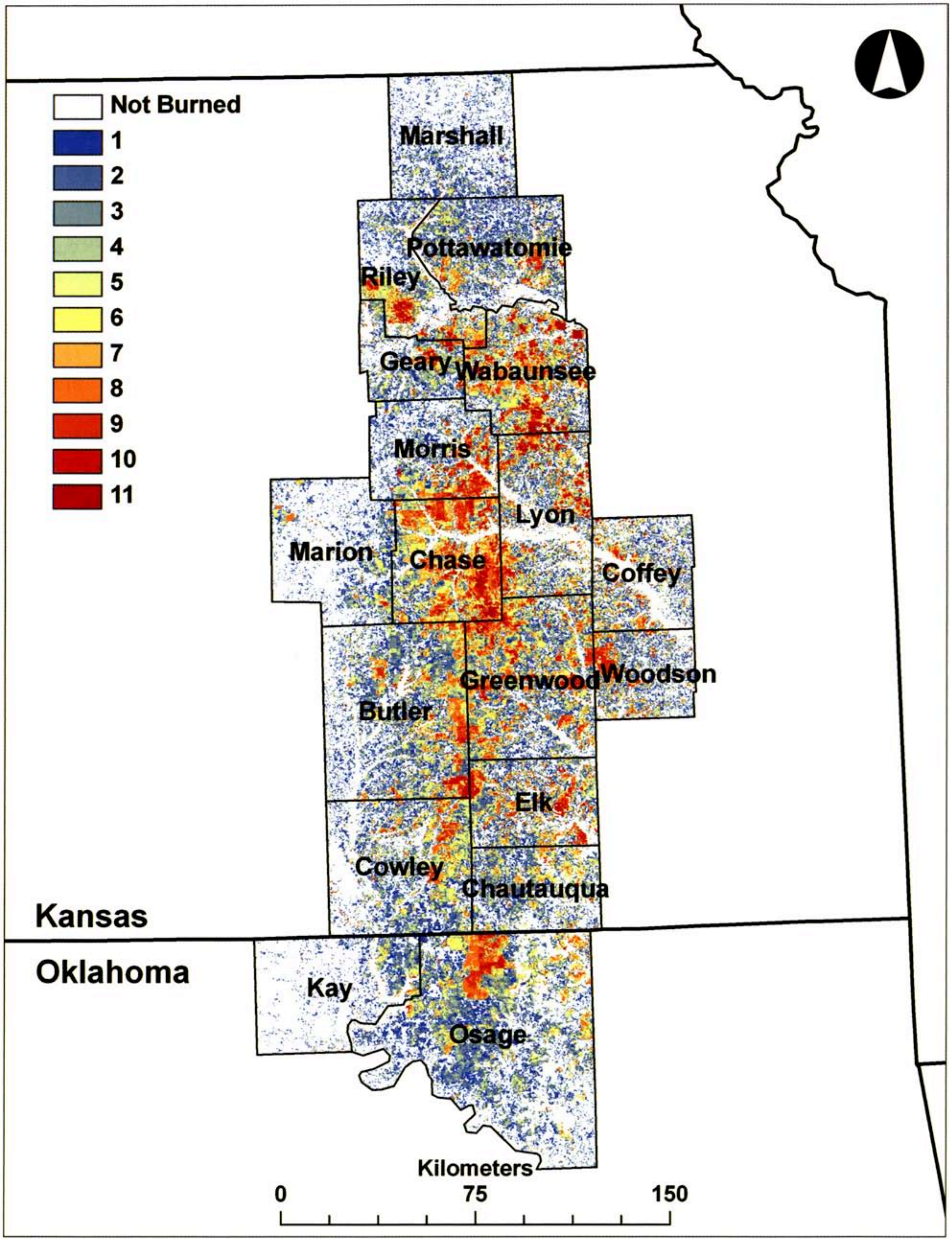

Figure 2. Burn frequency for the study area from 2000 to 2010. The value in the legend indicates the number of years out of 11 that an area was burned.

of a general trend apparent in the data—that parts of the study area with higher percentages of grassland will have more of that grassland burned in a given year than areas with low percentages of grassland.

The frequency with which grassland areas were burned varied throughout the study area (Fig. 2). Of all grassland burned at least once, only 1% was burned in all 11 years of the study, while 15% was burned in only one year (Table 4). This represents the extremes of a general trend in which the amount of grassland burned at a given frequency decreased as burn frequency increased. This trend was only apparent at the scale of the whole study area.

At the county level, grasslands in counties with low percentages of grassland, such as Marshall (33% grassland), Marion (48%), and Kay (40%), were generally burned less frequently than grasslands in counties with higher percentages of grassland, such as Chase (87%). For example, most areas in the former three counties were burned between one and three years out of 11 (if at all), and less than 1% of grasslands in these counties were burned more frequently than eight years out of 11. In Chase County, however, most grassland was burned at frequencies between five and nine years out of 11, with 2% of grasslands burned in all 11 years of the study (Table 5; Fig. 3). As with total burned area, these counties are

TABLE 4
CUMULATIVE GRASSLAND BURNING STATISTICS FOR ALL 11 YEARS OF THE STUDY

Burn frequency (years)	Total burned (ha)	Percentage burned
1	419,738	15
2	347,031	12
3	305,219	11
4	260,356	9
5	228,906	8
6	202,813	7
7	172,006	6
8	153,838	6
9	119,913	4
10	61,200	2
11	24,419	1

Note: Total percentage of grassland burned does not equal 100% because not all grassland was burned during the study period.

TABLE 5
PERCENTAGE OF GRASSLAND BURNED BY BURN FREQUENCY (YEARS OUT OF 11 TOTAL) FOR EACH COUNTY IN THE STUDY AREA

County	Grass (ha)	Grass (%)	1	2	3	4	5	6	7	8	9	10	11
Marshall	77,514	33	38	22	14	8	4	2	1	0	0	0	0
Riley	101,515	64	14	11	11	10	8	8	7	6	4	4	1
Pottawatomie	154,836	70	22	17	13	10	8	5	4	4	2	1	0
Geary	71,259	67	15	15	15	13	9	6	4	3	3	2	1
Wabaunsee	165,161	80	9	8	8	9	11	11	11	9	7	5	4
Morris	132,198	73	15	11	9	7	7	6	5	6	7	3	1
Lyon	149,519	67	11	12	12	11	10	9	8	7	6	4	2
Marion	116,515	48	18	11	9	6	4	3	2	1	0	0	0
Chase	172,128	87	4	5	6	8	11	13	14	15	13	6	2
Coffey	96,821	57	17	14	13	11	10	7	6	4	3	1	1
Greenwood	252,354	85	11	11	11	11	10	10	9	8	6	3	1
Butler	269,743	72	15	14	12	10	9	6	6	5	3	2	0
Woodson	85,772	65	16	15	13	10	8	6	6	6	8	1	0
Elk	138,170	83	12	12	10	9	8	8	6	6	5	4	1
Cowley	193,548	67	16	13	10	9	9	7	5	4	3	0	0
Chautauqua	132,105	81	14	13	12	10	8	6	4	2	1	0	0
Osage (OK)	369,597	63	19	15	13	10	7	6	4	5	3	1	0
Kay (OK)	96,340	40	17	10	7	5	3	2	1	1	0	0	0

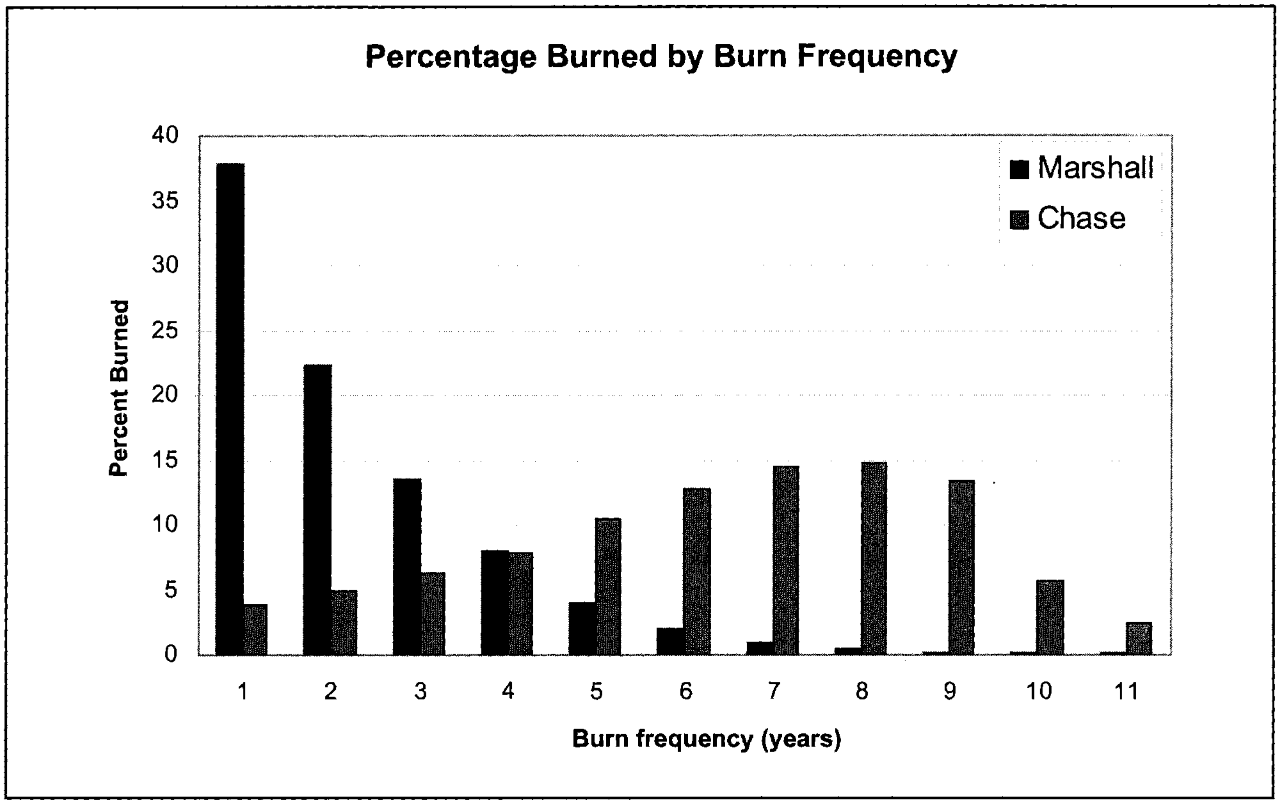

Figure 3. Burn frequency comparison for Marshall and Chase Counties.

used for descriptive purposes only, and the trend was not affected by the arbitrary county boundaries.

Finally, in all 11 years of the study, the vast majority of burning occurred in April (Fig. 4).

CONCLUSIONS

Our maps have quantified the annual amount of burning in the Flint Hills from 2000 to 2010, the location and spatial pattern of that burning, the timing of that burning, and the frequency with which different parts of the area were burned. This data can serve as the basis for many studies that investigate the effects of burning on human and natural systems. For example, With et al. (2008) noted declines in three common grassland bird species in the Flint Hills, where the continuous, intact nature of the prairie was thought to serve as a demographic source for these species, rather than a sink. They suggest that land management practices, including burning, may be responsible. Additionally, Robbins et al. (2002) suspect that the current burning regime, in conjunction with intensive early-season stocking of cattle, is responsible for declines in greater-prairie chicken populations throughout the Flint Hills. Our data allow for direct investigations into the effects of burning amount, frequency, and timing on these and other grassland bird species, as well as on small mammal and insect species.

Another use of our maps and burn data will be to investigate the effects of prescribed prairie burning on air quality. Currently, the link between burning and air quality problems in Kansas City and other urban areas is largely speculative and based on anecdotal evidence. Our maps and data will allow for an investigation into (and quantification of) the precise influence of prescribed burning on air quality, and the role of climate in this relationship.

Finally, the production of these burned-area maps exposes one trend that should be the focus of a future study: that grasslands are burned more frequently (and therefore more likely to be burned in a given year) when they reside in regions of the study area with larger percentages of grassland (typically in the center of the Flint Hills, rather than on the periphery; Figs. 1 and 2). In fact, grasslands on the periphery are often burned only one to three years out of 11. This frequency is well below that predicted by the dominant philosophy of burning annually or biennially to maximize productivity (Towne and Owensby 1984). Possible reasons for this tendency include safety,

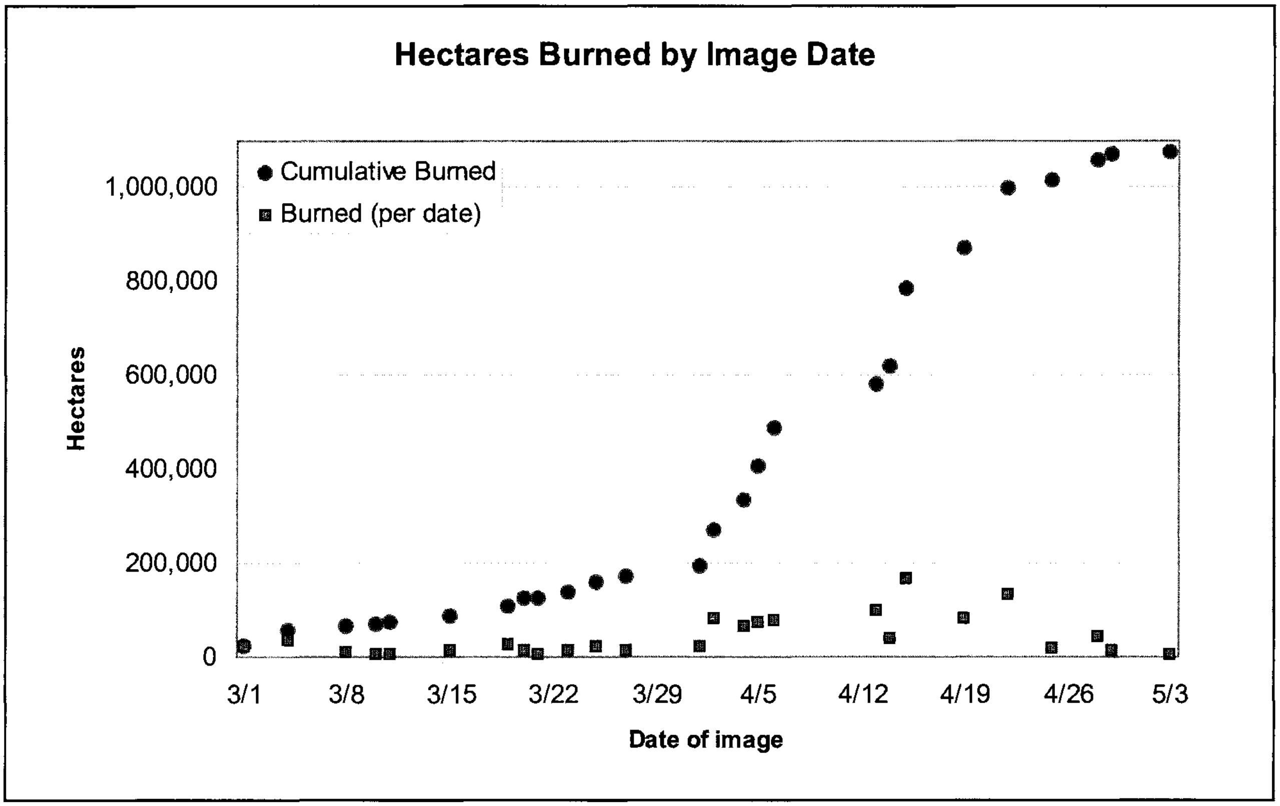

Figure 4. Temporal distribution of burned areas detected in 2008.

liability, and efficiency considerations associated with smaller patches and patches interspersed with croplands, a lack of a burning mindset or tradition, the possibility that infrequently burned Conservation Reserve Program (CRP) grasses make up a large share of these grasslands, that cropland burning is creating noise in the data, and that areas where farming is more prevalent place less emphasis on rangeland management.

ACKNOWLEDGMENTS

This research was supported by a grant from the USDA-NIR Air Quality Program (award #2008-55112-18801), and by a grant from the NSF DDRI Program (award #1003116). We would like to thank numerous colleagues who improved this research through their comments and suggestions. Finally, we would like to thank two anonymous reviewers, whose suggestions were critical in revising the manuscript.

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