Shifting Tallgrass Prairie Management Practices:
The Influence of Fire on Public Health, Grassland Ecology, and Ranching Activities

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Abstract

The Flint Hills is home to the largest area of remaining tallgrass prairie in the United States. Every spring, ranchers and land managers in the Flint Hills burn about 2.8 million acres of prairie to maintain the landscape and to stimulate new growth of native grasses for cattle foraging. Prescribed fire is a common tool in tallgrass prairie management, but recently concerns have arisen about smoke from fires negatively impacting public health. We used the BlueSky modeling framework to create smoke dispersion models under several grassland management regimes to understand the role of land management in the public health conversation. We compared the results of each management scenario in terms of public health (using high and moderate risk individuals affected the fire event as a measure), forage quality, and wildlife habitat. We found that changing the burn season, reducing the percentage of land, and utilizing a patch burn grazing method all had >40% reductions for the total number of individuals affected by the highest concentration plumes and the total number of high and moderate risk individuals affected. These results, when cross-referenced with literature on cattle performance and grassland ecological dynamics, suggest that patch-burn grazing in spring may be a viable alternative to the traditional land management regime.

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Introduction

Prescribed fire is a common tool in tallgrass prairie management, but recent concerns have arisen about smoke from the fires negatively impacting public health. The Flint Hills of Kansas and Oklahoma are home to the largest area of remaining tallgrass prairie in the United States. Every spring, ranchers and land managers in the Flint Hills burn about 2.8 million acres of prairie to maintain the prairie landscape and to stimulate new growth of native grasses for cattle foraging (Blocksome 2012). Prairie, or grassland, wildlife and cattle benefit from fire, as fire can promote optimal habitat, habitat diversity, and high quality foraging grounds. While prescribed burning has positive economic and wildlife impacts (Allen et al. 1979, as cited by Bernardo et al. 1988; Powell 2008), it also produces emissions of particulate matter and ozone precursors into the atmosphere (McGinley 2015). As these fires take place in about a two-week window in the late spring, high concentrations of ozone and particulate matter can accumulate in the air column. These concentrations have negative impacts on public health in the surrounding regions (Kansas State Research and Extension B). The city of Omaha, Nebraska has had to issue public warnings to limit outdoor recreation and cancel recess for public schools because of poor air quality from burning in the Flint Hills (Withrow and Gaarder, 2016). The local Sierra Club chapter has also called upon the EPA to increase restrictions on grassland burning to protect human health, which has caused tension with ranchers who believe increased burning regulation would be intruding on their private property rights (Beckman 2017; Gaarder 2016).

Public health issues in the Flint Hills have been correlated with the particulate matter and ozone precursors released by smoke from prescribed pasture and agricultural burns (Liu 2014). Fine particulate matter ($PM_{2.5}$), refers to the mass concentration of airborne particles that are less than 2.5μm in diameter. $PM_{2.5}$ is a particular concern because the small sizes of the particles allows them to travel farther from the fire in the air column, and also allows them to travel deeper into the human lungs where they can cause significant health issues (McGinley 2009). Ozone is created in the air column, downwind from the fire, from the precursor volatile organic compounds (VOCs) and nitrogen oxides (NO_x). Temperature and meteorological conditions control how much ozone is produced downwind (Kansas State University). Cardiopulmonary illnesses, such as asthma and chronic lower respiratory disease, are linked to high $PM_{2.5}$ and/or ozone concentrations (Wyzga and Rohr 2015). For example, elevated ozone and particulate matter levels have been linked to increases in hospital visits for cardiopulmonary illnesses and self-reports of increased asthma attacks (Hu et al. 2008). However, public health is not the only point of concern; land managers must also take into consideration the implications of fire for ecosystem health and grassland wildlife.

To improve forage quality, maintain grassland, and prevent woody encroachment ranchers use a fire return interval[1] (FRI) of one to three years since the last ignition (Ratajczak et al. 2016). Typically, fire is applied in a uniform manner, creating a relatively homogenous landscape. In general, tallgrass prairie wildlife benefits from the use of fire on the landscape, but the amount of land burned, frequency of fire, and season of burn all influence the impacts of fire on grassland wildlife. Animal species that require tallgrass prairie for habitat and breeding grounds, such as the greater prairie chicken (*Tympanuchus cupido*) and the regal fritillary butterfly (*Speyeria idalia*), have varying disturbance needs. Some require newly burned areas, while others require the presence of plant litter for suitable nesting habitat (Ratajczak et al. 2016). Historically, grasslands experienced more unpredictable fire regimes, both spatially and temporally, which created a patchwork across the landscape. This patchwork provided a wider range of habitat conditions for wildlife than exists today. Current fire management practices have created a more homogeneous landscape and, in turn, a narrower range of habitat conditions. A possible solution to this problem is to utilize land management techniques that increase heterogeneity of the landscape. Options for increasing landscape heterogeneity are shifting the season of the burn, burning with different fire return intervals, or combining fire and grazing in a patch-burn system all of which have the potential to change fuel loading which may result in positive impacts on human health and increase the diversity of available wildlife habitat (McGinley 2009, Weir et al. 2013).

We investigated the effect of different management regimes, such as reducing the amount of land burned, decreasing the fire frequency, and applying a patch burn grazing technique

[1] The terms *fire frequency* and *fire return interval* refer to the years that have elapsed since the last burn.

(PBG)[2], to reveal their effects on the spatial patterns of $PM_{2.5}$. Additionally, we reviewed what the effect of these burn regimes are for the plant community composition and wildlife. These burn regimes were presented as a series of dispersion models to determine if the ground level exposure to $PM_{2.5}$ increases or decreases with the amount of land burned, seasons after the spring, and/or burning between one to three years in a patch burn scenario. This helped to determine which regimes reduced harmful exposure of $PM_{2.5}$ for the public, if forage quality is maintained to satisfy ranching needs, and the impacts on ecosystem health. We did this by using a framework of a literature review and application of spatial modeling. In the Flint Hills, land managers use spatial modeling as a tool to make decisions about burns. Models can be combined to understand the implications of fire and smoke for variables such as wildlife and public health. The simplifying and predictive power of these models can help to mitigate conflict for complex issues. These models can be used to inform burn decisions by land managers which contribute to particulate matter and ozone concentrations in nearby urban areas (Rapp, 2006).

Background

Fire and the Flint Hills

Fire is necessary to prevent shrubland and woodland encroachment in the North American tallgrass prairie system (Owensby et al. 1973). Prehistorically, the tallgrass prairie system of the Flint Hills was maintained by lightning-ignited fires. There is strong evidence in protohistoric periods that the majority of prairie fires were anthropogenic in origin. Before European settlement, Native American tribes of the area, predominantly Osage, utilized fire to maintain travel routes as well as for hunting purposes (Earls 2006). Archaeological data also suggests that tribal warfare played an important role in igniting fires. Early European settlers continued to utilize fire as a management tool, but there was an overall mentality that fire was destructive and unnecessary, which eventually led to a widespread fire suppression dogma (Earls 2006).

After European settlement, there were several intellectual shifts in the usage of fire in the Flint Hills. In the 1880s, there was a large influx of cattle ranchers from Texas into the Flint Hills region. With these ranchers came the viewpoint that fire was beneficial for cattle production because it removed dead underbrush (Kollmorgen and Simonett 1965; Isern 1985). This caused conflict between the ranchers and the other land managers of the area. In 1918, Kansas State University established the Kansas Agricultural Experiment Station to further study the use of fire as pasture management tool. Early studies by Hensel (1923) failed to find any destructive effect of fire on native prairie. In a subsequent study, Aldous (1934) found that while burning increased the number of plant stems, it also reduced soil moisture and average biomass production. Academics, land managers, and ranchers used the findings of this study to argue that burning pasture was not a beneficial practice. With ranchers' acceptance of burning as a negative practice, fire suppression in the Flint Hills expanded, and this fire suppression dogma lasted for more than 30 years. The lack of fire led to the encroachment of eastern redcedar (*Juniperus virginiana*). Owensby (1973) explored this expansion of eastern redcedar and evaluated the best management practice to remove it and return the system to tallgrass prairie. He concluded that physical removal and fire were the best removal methods for eastern redcedar. This study shifted

[2] *Patch burn grazing* is the practice of burning only some patches of the landscape each season and rotating which patches are burned the following season to create a mosaic of various fire frequencies across the landscape (Limb et al. 2011)

the dogma in the Flint Hills to widespread acceptance that fire is beneficial to pasture maintenance.

Although the need for fire became widely accepted, the best way to utilize fire was not understood. Owensby and Anderson (1967) assessed the average production of biomass after burning at different times during the spring and compared it to the production of an unburned pasture. They found that early and mid-spring-burned pastures had a decrease in biomass while late spring burned prairie had the same production as an unburned pasture. This 1967 study has been the most influential determinant of modern fire usage in the Flint Hills. Ranchers and land managers have used the findings of Owensby and Anderson (1967) to justify only burning their pastures in the late spring for more than 40 years. This tradition, although not based on current research which suggests that prairie is resilient to burning during different seasons (Towne and Craine 2011; Towne and Craine 2014; Towne and Kemp 2003), has gone largely uncontested. The compression of burning into a short period in the late spring has led to an increase in ground-level ozone and particulate matter (Baker et al 2016). Ozone and particulate matter have been linked to acute and chronic respiratory and cardiovascular illnesses (Pražnikar and Pražnikar 2012); thus there is concern for the health of impacted individuals in the Flint Hills due to these burns (Liu 2014).

Fire management consequences for tallgrass prairie

Landscape Heterogeneity and Biodiversity

Vegetation species diversity and richness within a grassland are not independent from the disturbance of fire. Tallgrass prairies consist of two different graminoids: warm-season and cool-season grasses. Plant community composition varies with the frequency and season of burns within a tallgrass prairie landscape. An eight-year study by Towne and Kemp (2003) in the Flint Hills found that species richness decreases when the prairie is burned during the autumn or winter; this implies that grasses become more diverse, even after annual burning, when burned outside of the late-spring season.

Maintaining tallgrass prairie requires repressing invasive and/or overly dominant species of grasses and woody species. Within the Flint Hills, there has been a long-standing goal to restore and preserve tallgrass prairie (Ratajczak et al. 2016). Fire management has become recognized as one of the most effective methods of conservation restoration. Traditionally, the tallgrass prairie is burned in the spring to maintain the warm season grasses desired by ranchers. Without a burn frequency of at least once every three years, herbaceous species begin to diminish, litter accumulates, invasive species richness increases, and the landscape transitions into a forb and/or shrubland landscape, which is largely considered undesirable by the ranching community (Ratajczak et al. 2016, Towne and Craine 2016). For example, areas near watersheds with a 3-5 year fire interval have experienced more than a 40 % increase in forb cover, resulting in less graminoid species diversity and richness due to only a small change of fire frequency (Ratajczak et al. 2016). If time since fire surpasses three years in a grassland, it may be difficult to reverse a dominant shrubland or woodland landscape (Ratajczak et al. 2016). An intensive management plan is needed to effectively remove woody encroachment[3]. Woodland species are

[3] Spring burning has been reported to be most effective for eliminating woody encroachment (Towne and Craine 2016). A twenty-year study at Konza Prairie Biological Station by Briggs, Knapp, and Brock (2002), found that tree density increased during a fifteen-year study, but not all species in the study responded similarly under high frequency burns. For example, red cedar (*Juniperus virginiana*) and hackberry (*Celtis occidentalis*) in the study site are sensitive to fire and can be eradicated by frequent fire, but if given a longer fire return interval, they become

considered a threat by land managers, because they reduce the ecological, societal, and economic value tallgrass prairie provide.

Wildlife

Fire followed by grazing, a common practice of historic disturbance regimes, is being reintroduced as a tool for restoration, conservation, and economic gains. This coupled interaction is known as *pyric herbivory* (Fuhlendorf et al. 2009). Historically, this interaction would occur after wildfires as a recently burned area would become heavily utilized by grazers while other areas were less utilized. Fire in another location would result in a shift in grazing pressure to the new area, and this process would repeat with varying spatial distribution across the landscape (Weir et al. 2013). This uncontrolled and random distribution of fire and grazing resulted in habitat heterogeneity within the landscape (Weir et al. 2013).

To preserve the great plains and its ecosystems without the presence of bison (*Bison bison)*, which historically maintained the tallgrass prairie, ranchers transitioned into using cattle with fire as burning techniques evolved in the twentieth century (Rensink 2009). This transition benefited both ranchers and the ecosystem, because the cattle provided economic gains as they also helped to increase both plant productivity and strengthen resilience towards invasive plant species through disturbance. As a result of this fire and grazing interaction, forage value increases and cattle (or bison) favor these patches (Scasta et al. 2015).

Grassland wildlife also benefits from the interaction of fire and grazing, applied as the PBG method of rangeland management. Pyric herbivory has also resulted in heterogeneity of herbaceous communities important for avian communities within grasslands (Coppedge et al. 2008). Avian communities' population density and/or nesting behavior are affected by burn practices, however not all birds respond the same to fire disturbances. Different PBG or FRI practices result in suitable or unsuitable habitat for some species of grassland birds. Powell (2008) investigated avian communities in Konza Prairie and found that annual burning resulted in constraints on the nesting of birds compared to conservation burn practices, such as applying patch-burn intervals from one to four years. Some species, such as the Upland Sandpiper (*Bartramia longicauda)* and Grasshopper Sparrow (*Ammodramus savannarum)* were more abundant during the year of a burn, while Prairie Chickens (*Tympanuchus sp.)* were more abundant in areas one to three years after the first burn, and birds such as Bell's Vireo (*Vireo bellii)* were more abundant in transects more than four years after the first burn (Powell 2008). When burn intervals approached four years, the population densities of these grasslands birds (with the exception of the Bell's Vireo) began to decrease, because woody encroachment began to decrease the availability of their nesting spaces (Powell 2008; Coppedge et al. 2008; Hovic et al. 2015). Thus, applying strategic burns to create a landscape that is patch burned with intervals under 4 years, is beneficial for the wellbeing of the landscape, and for existing avian communities.

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persistent over time. In contrast, American Elm (*Ulmus americana*) and Thorny Locust (*Gleditsia triacanthos*) were present in intermediate or low frequency treatment due to their aggressive resprouting characteristics after disturbance. The resilience of certain woody species and their ability to invade grassland ecosystems has put pressure on both researchers and land managers to find an effective solution for maintaining grassland ecosystems. An additional tool for reducing forb, shrub, and woody encroachment is the coupled interaction of fire and grazing.

Community composition of herpetofauna (reptiles and amphibians) is different under varying fire regimes, which is likely due to the response of changing vegetative structure (Steen et al. 2013; Wilgers and Horne 2006). A herpetofaunal study in the Flint Hills using an annual burn treatment, a four-year treatment, and no burning, found that reptile community composition in response to the regimes were significantly different from one another, as species have habitat preferences, such as moisture content and temperature, that are impacted by time since burn (Wilgers and Horne 2006). The application of fire is critical for herpetofauna (and other animals) because they respond to the changes in vegetation structure, or insect populations due to fires (Steen et al. 2013). Fire return intervals, such as two to three years, may be sufficient for restoring reptile assemblages (Steen et al. 2013).

Mammal species diversity and richness may also respond to fire-grazing practices within the Flint Hills. Since they are short lived and produce many offspring over the course of their lifespan, small mammals can be used as an indicator species to assess the impact of burn practices on biodiversity. Species diversity increased under a PBG treatment compared to a more uniform fire and grazing regime (Ricketts and Sandercock 2016). Ricketts and Sandercock (2016) investigated the response of small mammal species diversity and richness within Konza Prairie to changed fire return intervals. They found that, as fire return intervals increased to four years, species diversity increased as well, but species richness decreased. This was because species such as the Deer Mouse (*Peromyscus sp.)* became more abundant in recently burned areas and as the fire return interval increased, rare species of small mammals become present and/or more abundant. Fuhlendorf et al. (2010) similarly found that some species' abundances decreased, but small mammals that were less common became more prevalent under varying fire-grazing treatments. Overall, the application of a shifting mosaic management strategy, such as PBG, increases the heterogeneity of the landscape, which benefits both native plant and animal communities.

Fire management consequences for public health

Smoke from prescribed burns can negatively influence human health. The two components of smoke that are most commonly linked to adverse health effects are particulate matter ($PM_{2.5}$) and ozone precursors (McGinley 2009). These two air pollutants have many sources at all times of the year, but prescribed burning and wildfires cause a sharp increase in short-term concentrations of $PM_{2.5}$, which can influence the quality of life for residents in the immediate area, and also in nearby regions. $PM_{2.5}$ has the capacity to aggravate existing health conditions, and to cause inflammation in healthy individuals. It is particularly likely to have an effect on high risk individuals, the young and old (Diaz 2012). A study by Hu et al. (2008) found that a burn in Georgia, USA had the potential to impact nearly one million residents of the city of Atlanta with high hourly $PM_{2.5}$ levels, even though the residents of the city were about 80km from the burned area. $PM_{2.5}$ has been linked to cardiopulmonary issues such as asthma, increased risk of lung cancer, heart disease, chronic obstructive pulmonary disease, and respiratory infections, and a growing body of evidence suggests that exposure to high $PM_{2.5}$ levels during prescribed burning may contribute to non-traumatic mortality rates (Haikerwal et al. 2015). The chronic effects of long term exposure to $PM_{2.5}$ have not been studied as well, but a review by Wyzga and Rohr (2015) reported associations between $PM_{2.5}$ exposure and cardiopulmonary-issue related death, preterm birth, decrease in lung function, and hospitalization for coronary heart disease. Additionally, the state of Kansas currently reports that death from chronic lower respiratory disease is the third largest cause of death in the state, which is 9% higher than the national average, and occurrences of chronic obstructive pulmonary disease in the Medicare population are equal to the national average (Kansas Health Matters). There are multiple sources of $PM_{2.5}$, both anthropogenic and natural, at all times of the year and chronic health effects cannot be directly attributed to one or the other (Wyzga and Rohr 2015). However, during the burn season, fires are the primary source of $PM_{2.5}$ and contribute to an increase in hospital visits for pulmonary diseases (Haikerwal et al. 2015). To reduce the health impacts felt by residents of the study area, it is important to research options for reducing $PM_{2.5}$ production.

Ground-level ozone production, from precursors released by burning biomass, is of concern to public health because ozone can cause otherwise healthy people to have reduced lung capacity, and exacerbate the symptoms of those who are at risk, especially the young and elderly, and those with cardiopulmonary illnesses such as asthma and emphysema (McGinley 2015, Diaz 2012). Ozone is currently of high concern in the study region as Kansas City, and Wichita had documented air quality exceedances in 2010 (Liu 2014). McGinley (2015) explored the relationship between ozone and $PM_{2.5}$ levels and respiratory-related hospital admissions in the Flint Hills region and found that there is a significant positive relationship between ozone concentrations and the number of individuals admitted for respiratory illnesses. As with $PM_{2.5}$, long term ozone exposure has not been well studied. However, there is a correlation between long-term ozone exposure and mortality. Jerrett et al. (2009) found a positive correlation between increases in ozone concentration and risk of death from respiratory illness and Hao et al. (2015) found a significant association between chronic lower respiratory disease and mortality rates across US counties after controlling for demographics such as behavior (smoking) and socioeconomic status. When doing public health assessments, it is challenging to assess the impacts of $PM_{2.5}$ and ozone separately as they are both produced during a fire event. Thus, while some negative health effects reported during a fire event are more strongly associated with one pollutant or the other, the true cause is confounded.

The Environmental Protection Agency (EPA) has air quality guidelines in place to mitigate human health and environmental issues relating to air quality (Liu 2014, Environmental Protection Agency). Currently, the EPA's National Ambient Air Quality Standards (NAAQS) state that $PM_{2.5}$ must not exceed 35µg/m^3 over a 24-hour period. The annual standard is calculated by averaging the past 3 years of data, if the 98th percentile of that data is 35 µg/m^3 or less than the standard is met (Environmental Protection Agency). This allows a region to have a couple of days that exceed the standard as long as the majority of days meet the standard. The primary standard, designed to promote public health protection, is 12µg/m^3 averaged annually and the secondary standard, designed to protect against visibility problems, damage to buildings and vegetation, and health problems in livestock and pets, is 15µg/m^3 averaged annually. The primary and secondary standards for ozone are 0.070ppm. This standard is assessed as the annual fourth highest daily maximum 8-hour concentration, averaged over three years (Environmental Protection Agency). Because annual standards are compared against the average $PM_{2.5}$ concentration over the whole year, a high value over the short duration of a burn event will be mitigated by the lower concentrations during the rest of the year. Thus, for our study we will focus on the 24-hour standard for $PM_{2.5}$, as that is the standard that is likely to be impacted by a burn event. Despite these regulations, any burning may result in health issues, any quantity of $PM_{2.5}$ or ozone concentrations may result in human health issues. Because of this, analysis of $PM_{2.5}$ must take into account the entire population, not just people who have preexisting health conditions, and is typically assessed by age since people under 5 and over 65 are at highest risk for negative health effects, followed by people aged 6-18 at moderate risk, and individuals between 19 and 64 having low risk of health effects (Diaz 2012). By assessing the entire population, and breaking a smoke plume into concentration levels that range from safe to unhealthy according to EPA NAAQS, we gain an understanding of the impact of smoke beyond that shown simply in acreage covered by the smoke plume.

Research Objective and Approach

Our study seeks to understand the impacts of shifting management regimes on public health, grassland wildlife, and ranchers' motivations for land management practices. We utilized the BlueSky modeling framework to create particulate matter emissions models, and dispersion models, under several alternative fire management regimes. The majority of models assembled to understand implications for public health are based on the western United States (Strand et al. 2012; Reid et al. 2015). Forest wildfires are a major point of concern in the western United States for both public health as well as public safety, thus several modeling frameworks have been developed to more fully understand wildland fire impacts. One such model that has been used is the Version 2.0 beta BlueSky modeling framework developed by the Environmental Protection Agency (EPA) and US Forest Service (USFS) to model particulate matter outputs from wildland fire events. The BlueSky modeling framework has also previously been modified for grassland fires in the Flint Hills (Douglas Goodin, personal communication).

We used the BlueSky modeling framework to investigate the influence of percentage of land burned, fire return interval, and season of burn on the concentration and dispersion of $PM_{2.5}$. We also used a detailed literature review to connect these changes in fire patterns to land managers' needs and ecological changes, particularly as they relate to landscape heterogeneity and wildlife needs. This allowed us to answer the question: What are the spatial and temporal patterns of ground level $PM_{2.5}$ exposure across different grassland management regimes, and how do varying tallgrass prairie management regimes relate to forage composition (quality) for livestock and habitat for grassland wildlife? We hypothesized that concentrations of particulate matter would decrease by reducing the percentage of land burned in the Flint Hills region annually and that it would be possible to shift the fire regime used, from the traditional spring burns practiced by the majority of the region to a more varied combination of burns, without negatively affecting ecosystem health and ranching operations. It is beyond the scope of this study to model ozone and its precursors, however they are important to the conversation about smoke impacts.

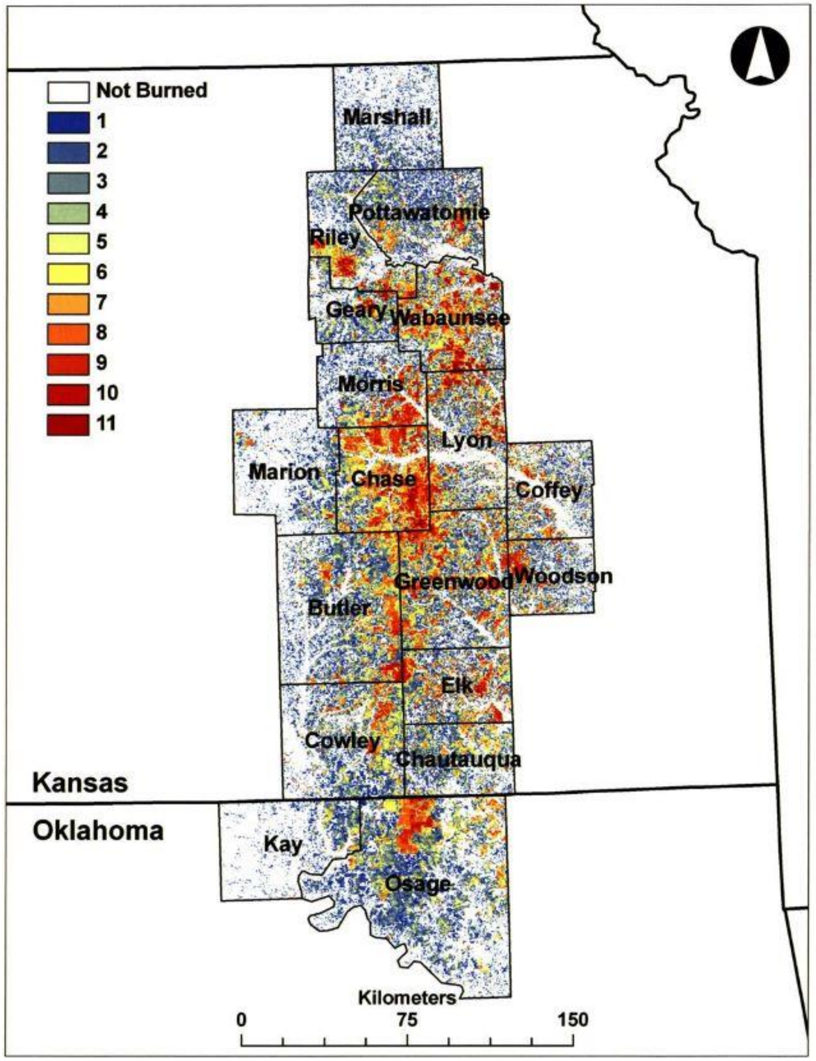

Figure 1. Shows the extent of the 18 counties that make up the Flint Hills region. Colors indicate the burn frequency for the study area from 2000 to 2010; the value in the legend indicates the number of years out of 11 that an area was burned. Figure taken from Mohler and Goodin 2012.

Methods

Study Area

Our study area is the Flint Hills of eastern Kansas and northern Oklahoma. The Flint Hills is comprised of 18 counties (16 in Kansas and 2 in Oklahoma) (Figure 1). The Flint Hills has the highest density of intact tracts of unplowed prairie in North America. The area was left unplowed by early settlers because of the very shallow rocky soil. This has led to large-scale cattle operations throughout the Flint Hills. Nearly 2.8 million acres of land in the region is regularly burned to maintain the tallgrass prairie system. The burn frequency of the region is shown in Figure 1.

The BlueSky modeling framework

The Blue Sky modeling framework was developed by the Environmental Protection Agency (EPA). Blue Sky exists as an online portal called *Blue Sky Playground.* The workflow of the modeling framework is detailed in Figure 2 (taken from Larkin et al. 2009). The framework allows characterization of a fire event using variables such as location, acreage, fuel loading, moisture, and fuel consumption. An emissions model is produced from the variables that define the fire event. BlueSky then integrates actual weather data to create a dispersion model, which shows how the smoke plume disperses over the region. Past research has shown that BlueSky is an effective framework for modeling emissions from biomass burning[4].

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[4] Choi et al. (2013) used the framework to conduct an air quality model for Asia to calculate emissions from open biomass burning. They used imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite that allowed them to designate areas for fire and emission assessments and to determine the fuel load of each burn. Each fire was assigned to an area and and BlueSky was used to calculate plume-rise and emissions. They compared their findings to on the ground emissions readings, and found good agreement with actual emissions from the fire events.

Strand et al. (2012) used the modeling framework to conduct an analysis of wildfires in California during 2007-08. Both meteorological and emissions data were utilized in the modeling process and the BlueSky predictions were compared to monitoring station data to test the results. They found that BlueSky overpredicted maximum values for half of their study, and underpredicted them in the other half of the study area, suggesting that complex terrain and the resulting variable wind patterns may have an impact on BlueSky's assessment of emissions.

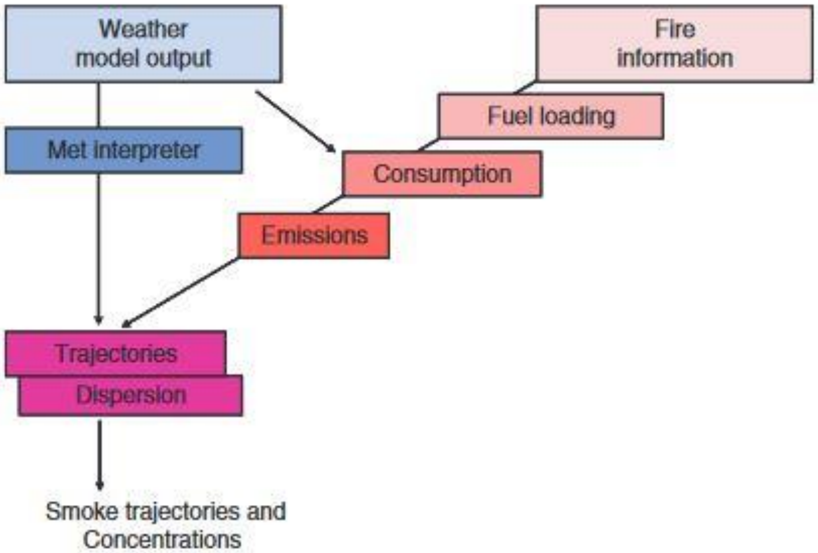

Figure 2. Modeling framework used in BlueSky to create concentration and smoke trajectory (dispersion) models. Weather information used to create dispersion model is part of the modeling framework that does not require manual inputs. Colors indicate the direction of the workflow with lighter colors being earlier and darker colors being later in the workflow. Explanation and an example of fire information and fuel loading inputs can be found in Table A2. Consumption inputs were left unaltered. An example of the final smoke trajectory can be found in Figure A1. Figure taken from Larkin et al. (2009).

Collecting Variables for BlueSky

We collected input variables from previously published literature (Table A1) and from personal communications with experts in the field: Brian Obermeyer of the Nature Conservancy, Douglas Goodin of Kansas State University, and Sherry Leis of the Heartland Inventory and Monitoring Network. The fuel loading variables are: canopy, shrubs, grass, litter, rotten, and moisture level (Table A2). The necessary inputs were derived from the following *Fuel Formula*:

1. $1500 lbs/acre * (2.8\, million\ acres * (1 + Percent\ of\ land))$

2. $\#\ of\ tons\ = Output/2000 lbs$

3. $\#\ of tons/acre = \#\ of tons/2.8\, millions\ acres$

For the 2.8 million acres burned, we used the unit of 1,500 lbs/acre for one hour of fuel, which has been recorded as the minimum to sustain a large-scale prescribed fire (Stevens 2015). Variables within each scenario are listed as the proportion of the total acres burned within the given scenario (Table A1). Any justification for error and significance is based on the previous studies that reported their results in PBG experiments and those from the personal communications.

BlueSky Modeling Process

We modeled our management regime scenarios by adjusting three variables (fire return interval, season, and percentage of land) individually and then in combination to create complex patch-burn scenarios. We did this to ensure that we understood the influence of each variable in isolation on the concentration and dispersion of the smoke plume before modeling the more complex patch-burn scenario that adjusted multiple variables at once. Each scenario involved creating a new dispersion scenario in BlueSky Playground that involved the following: 1) inputting the amount of acres burned in the Flint Hills for the specific scenario 2) manually adjusting the fuel loading variables per scenario, and 3) choosing the appropriate date for the season of the burn: March 17, 2016 for the spring, and December 1, 2016 for the winter. BlueSky Playground limits the number of acres burned per single day. To ensure that we were consistent across all scenarios we ran a 3-day burn for all scenarios by dividing the acreage of the burn up among three days.

First, we varied the percentage of land burned annually. Our baseline model was 100% of the acreage (about 2.8 million acres) in the Flint Hills. Other models were 80%, 50% and 33% of total acreage burned. We chose 80% because ranchers in the Flint Hills have self-selected into two groups based on land uses. The Flint Hills region is roughly two concentric rectangles. The interior rectangle of the Flint Hills region is burned annually to support short-season grazing. The exterior rectangle tends not to be burned annually as that land is mostly used to graze cow-calf pairs, so having extra forage is valuable to land managers there (Brian Obermeyer, personal communication; Mohler and Goodin 2012). Based on this knowledge, we estimate that burning 80% of the land annually is a reasonable assumption. To explore the relationship between percentage of land burned and particulate matter produced, we modeled 50% of the total acreage of the study area. If the relationship were linear we could predict that half the quantity of $PM_{2.5}$ produced by the baseline scenario would be observed. However, we predict that it may be nonlinear since the fire dynamic is not uniform across varied landscapes and our study region is diverse. 33% was chosen because many PBG systems operate on a three-year cycle, resulting in 33% of the land being burned each year (Scasta et al. 2015). We hypothesized that decreasing the quantity of land burned annually will decrease the concentration of $PM_{2.5}$ in the smoke plume.

Second, we varied the FRI in isolation. In our models, we investigated the following scenarios, with 100% of the land burned in each return interval. Our baseline was a one year return interval. Our other FRI model was 2 years-3 years since fire. A combined variable of 2-3 years was chosen because there is no appreciable change between community composition and litter between 2 and 3 years since fire (Sherry Leis, personal communication). Fire intervals greater than 3 years have been associated with increases in woody plant material (Ratajczak et al. 2016) and we therefore did not include them. We hypothesized that increasing the number of years between burns will increase the concentration of $PM_{2.5}$ in the smoke plume.

Third, we varied the season in which burns occur in isolation, again burning 100% of the land in each season. We compared the baseline spring burn to a winter burn. We chose to exclude summer from our analysis because in a grazed prairie, the reduced fuel load will likely lead to incomplete burning (Towne and Kemp 2008). We chose to exclude fall from our analysis because we were unable to find fuel loading data for fall burns in the study area. Burning outside of the growing season will allow time for the fuel to dry, and drier fuels have more efficient combustion which produces less smoke (Liu 2014). We hypothesized that changing the season of burning will decrease the concentration of $PM_{2.5}$ in the smoke plume.

Fourth, we created a scenario to understand the influence of a patch-burn grazing system (defined above) on the smoke plume. To do this, we set the area burned to 33% annually, which creates a three year return interval on the total parcel, and varied the season of the burn. To account for the accumulation of litter on sections that are not being annually burned, we increased the inputs for fuel loading, specifically litter, and varied the input for moisture by combining data from a 2-3 year FRI and the seasonal moisture input, since increased amounts of litter may contain more moisture in general or seasonally (Brian Obermeyer, personal communication). We hypothesized that this patch-burn model will decrease the concentration of $PM_{2.5}$ in the smoke plume.

GIS Modeling Process

The output dispersion models of BlueSky were exported to GoogleEarth. Within GoogleEarth, we zoomed on the daily maximum concentration plumes for the three-day burn that BlueSky Playground created, and took a screenshot when we could see the county lines (Figure A1). Some images had to be manipulated with Photoshop because the extent was too large to clearly see distinct county lines. Next, we imported the 2010 county outlines and county level census data for all of the states in our study area into ArcGIS. We georeferenced these images in ArcGIS, then manually outlined the smoke concentration polygons contained by the images to analyze them as their own layer (Figure A2, Choi et al., 2013). Each plume contained up to five different polygons denoting concentrations from 0μg/m^3 to over 90μg/m^3 of $PM_{2.5}$ (Figure A3).

In ArcGIS, we conducted an overlay analysis using our dispersion models and the following variables: smoke concentration (0-90 μg/m^3), area, total population, and age (classified into high risk, moderate risk, and low risk by combining the census categories of proportion of the population within a given age group for Nebraska, Kansas, Missouri, Oklahoma, and Arkansas (Diaz 2012)). Within ArcMap, the county census data was categorized into the proportion of High Risk individuals for those under 5 and over 65 years old, 6 to 18 years old for Moderate Risk, and 19 to 64 years old for Low Risk (Diaz 2012). All variables are analyzed at the county level. The smoke plumes were classified into two groups: the first contained the entire extent of the smoke plume, and the second contained only polygons that had the potential to cause a 24-hour $PM_{2.5}$ exceedance. This was defined as all polygons representing 20μg/m^3 of $PM_{2.5}$ or more in each scenario. We chose 20 - 40μg/m^3 of $PM_{2.5}$ as our cutoff for high concentration plumes since the coarse level of analysis possible with BlueSky did not allow us to select only sections of the polygon that contained 35μg/m^3 of $PM_{2.5}$ or higher, and this range contains the desired EPA standard.

Next, the county-state level files were overlaid with the plumes to identify affected counties (Figure A4). For each scenario, all of the plumes from days one, two, and three were merged to create one layer containing all of the counties affected by the scenario. The same was done for polygons representing the highest concentrations of particulate matter (20-40μg/m^3). Each scenario was overlaid with the study area base map to obtain the counties impacted by the entire fire event and the highest concentrations of particulate matter.

Quantitative Process

Data was collected from the attribute tables of the total counties plumes and the high concentration plumes for each scenario. For each scenario, we collected the total number of counties affected, the total number of individuals affected, the mean number of individuals affected, the total number of high risk individuals, and the total number of moderate risk individuals affected by the entire smoke plume. We also collected the total number of counties affected, the total number of individuals affected, mean number of individuals affected, total number of high risk individuals and total number of moderate risk individuals affected by high concentration plumes. Percent difference from the baseline was manually calculated, and data was graphed using Microsoft Excel.

Results

Affected Counties and Individuals

The number of counties affected by the fire event and the number of counties affected by the highest concentrations of the plume differed among management regime scenarios. For the spring, PBG (three-year patch burn) and the FRI of 2 to 3 years had the greatest difference between scenarios for the highest concentration of particulate matter. The number of counties affected by the entire plume had a small difference between the PBG spring (-6%; Figure 3A-B, 4A-B) and the 2-3 FRI (-3%, Figure 3C-D, 4C-D) scenarios, but fewer counties were affected in both compared to the baseline (Figure 3I, 4I; Table 1). However, the number of affected counties that fell within the high concentrations of the plume were the opposite (Figure 3B, 3D, and 3J). The PBG scenario (Figure 3B) generated a smaller high concentration plume than the 2-3 FRI scenario (Figure 3D). We found that PBG for the spring decreases the number of affected counties exposed to higher concentrations of $PM_{2.5}$ by 27% (Table 1). This is visually represented when comparing PBG spring high concentrations (Figure 3F) to spring 2-3 year FRI high concentrations (Figure 3D). The 2-3 FRI spring scenario (Figure 3D) more than doubled the number of counties exposed to high concentrations to 64% (Table 1).

Spring 2-3 year FRI affected more individuals within the higher plume concentration than spring PBG. Both scenarios reduced the mean number of individuals exposed to high concentrations, but PBG affected 18% (on average) fewer individuals (Figure 3B, 3D, 4B, and 4D; Table 1). Spring PBG decreased the total number of individuals affected by the higher plume concentration by 51%, and the 2-3 year FRI increased the total number of individuals by 40% (Table 1). The higher plume concentration in the spring PBG (Figure 3B) was equal to or less than half of the higher plume concentration of the spring 2-3 FRI (Figure 3D).

Winter burn scenarios reduced the overall negative health risks associated with the plume. Winter PBG (three-year patch burn) affected 86 fewer counties and the one-year FRI for the winter 100% affected 63 fewer compared to the baseline (Figures 3E, 3G and 4E, 4G; Table 1). The number of affected counties within the higher concentrations of the plume were lower for both the winter 100% (-32%; Figure 3H) and PBG winter 3 year (-59%; Figure 3F; Table 1). Winter PBG (Figure 3F, 4F) affected 10 fewer counties than the winter 100% (Figure 3H, 4H) burn for the higher concentrations of the plume. Comparing PBG for the winter (Figure 3F, 4F) to the baseline (Figure 3I-J, Figure 4I-J), a change in season and FRI reduced the total number of affected counties by more than half. The winter burn scenarios resulted in a 55-68% decrease for the total number of individuals affected compared to the baseline (Figure 3, Figure 4; Table 1). The mean number of individuals affected by the high concentrations was 20 % less for the winter 100% (-48%) than the mean number of individuals for the PBG winter (-27%, Figure 3, 4; Table

1). Between the winter burns, the PBG winter burn scenario had the greater positive impact and reduced the total number of affected individuals by 70%, which is approximately 828,000 fewer individuals than the baseline (Figure 3, 4; Table 1).

To better understand the impacts of the burns on public health, we assessed the total number of high risk and moderate risk individuals impacted by both the entire smoke plume and the high concentration plume. In both the total plume and high concentration analyses, the spring burns supported our hypothesis that reducing land area would also reduce the number of affected individuals (Figure 3). Over the entirety of the smoke plume, the number of high and moderate risk individuals affected was similar across the spring 100%, spring 80%, FRI, and PBG spring burn scenarios. Spring 33%, PBG winter, and winter 100% had the least impact on high and moderate risk individuals, with about half as many individuals affected by these burns as by the baseline scenario (Figure 3A; Table 2).

In counties affected by the high concentration plumes, the PBG spring, PBG winter, and winter 100% scenarios affected similar numbers of individuals, all at a reduction of more than 60% compared to the baseline scenario (Figure 3; Table 2). Spring 50% and spring 33% impacted the lowest numbers of both high and moderate risk individuals, consistent with our hypothesis (Figure 3B; Table 2). The scenario with the largest impact on high and moderate risk individuals compared to the baseline annual burn was the 2-3 year FRI burn. The numbers of high and moderate risk individuals affected by its smoke plume was more than twice the impact of all scenarios other than the baseline, and 41% greater than the baseline (Table 2).

Table 1. The percent change for each management scenario compared to the baseline scenario (Spring, 100% land burned, and 1 yr since fire). Positive values indicate a percent increase in individuals or counties affected and negative values indicated a percent decrease. The baseline scenario is reported in counts to give perspective on the number of counties and people impacted. The number of counties affected is reported in parentheses after the percent change of counties from the baseline. Numbers in bold indicate changes that are greater than 40% in either direction, which is our threshold for major change. We chose 40% as that represents a natural break in our data.

	Spring					PBG		Winter
	100%	80%	50%	33%	2-3 years	Spring	Winter	100%
Total number of counties affected by fire event	182	-6.59 (170)	-29.67 (128)	**-69.78 (55)**	-3.84 (175)	-6.59 (170)	**-47.25 (96)**	-34.61 (119)
Total number of individuals affected by fire event	8,802,365	-2.07	-36.79	**-96.26**	-2.04	-2.81	**-68.19**	**-55.25**
Mean number of individuals affected by fire event	48,364.54	+4.83	-10.13	+23.63	+1.87	+4.05	-39.70	-31.56
Number of counties affected by highest concentrations	37	-16.21 (31)	**-67.56 (12)**	**-86.48 (5)**	**+64.86 (61)**	-27.02 (27)	**-59.45 (15)**	-32.43 (25)
Total number of individuals affected by highest concentrations	2,827,104	-33.65	**-86.75**	**-95.91**	**+40.98**	**-51.02**	**-70.71**	**-65.30**
Mean number of individuals affected by highest concentrations	76,408.22	-20.81	**-59.14**	**-69.78**	-14.48	-32.89	-27.77	**-48.65**

Total counties affected by fire event **Counties affected by maximum concentrations**

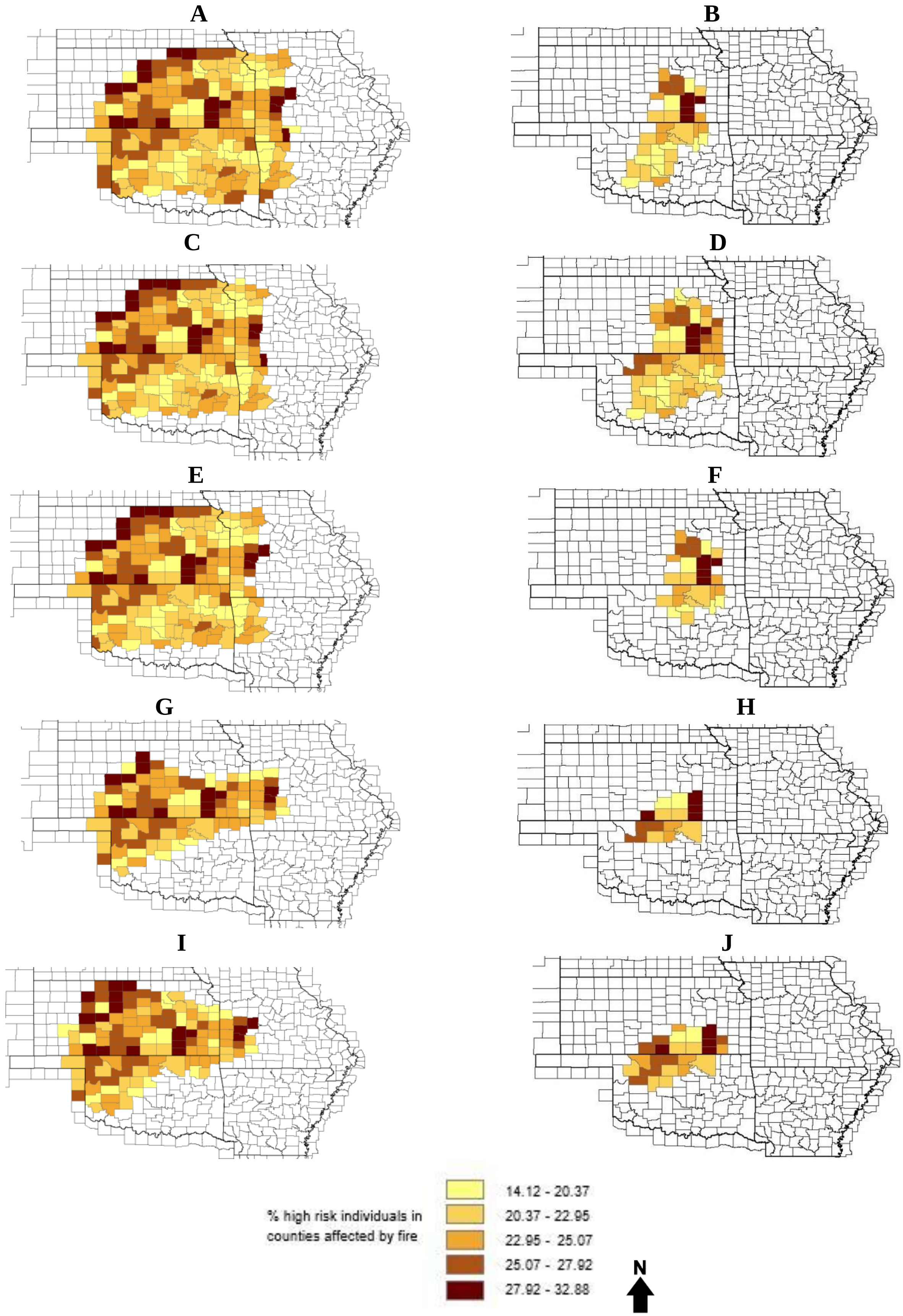

Figure 3: Counties in color represent the counties impacted by the entire fire event (left column) and the counties impacted by only the highest concentrations in the plume ($\geq 20\mu g/m^3$ of $PM_{2.5}$) (right column). State outlines represent the southern area of Nebraska, Kansas, Missouri, Oklahoma, and Arkansas. Color gradation shows the percentage of high risk individuals who live in each of the counties. (A-B) Baseline, (C-D) Spring 2-3yr fire return interval scenario, (E-F) Spring patch-burn grazing, (G-H) Winter patch-burn grazing, (I-J) Winter 100% land.

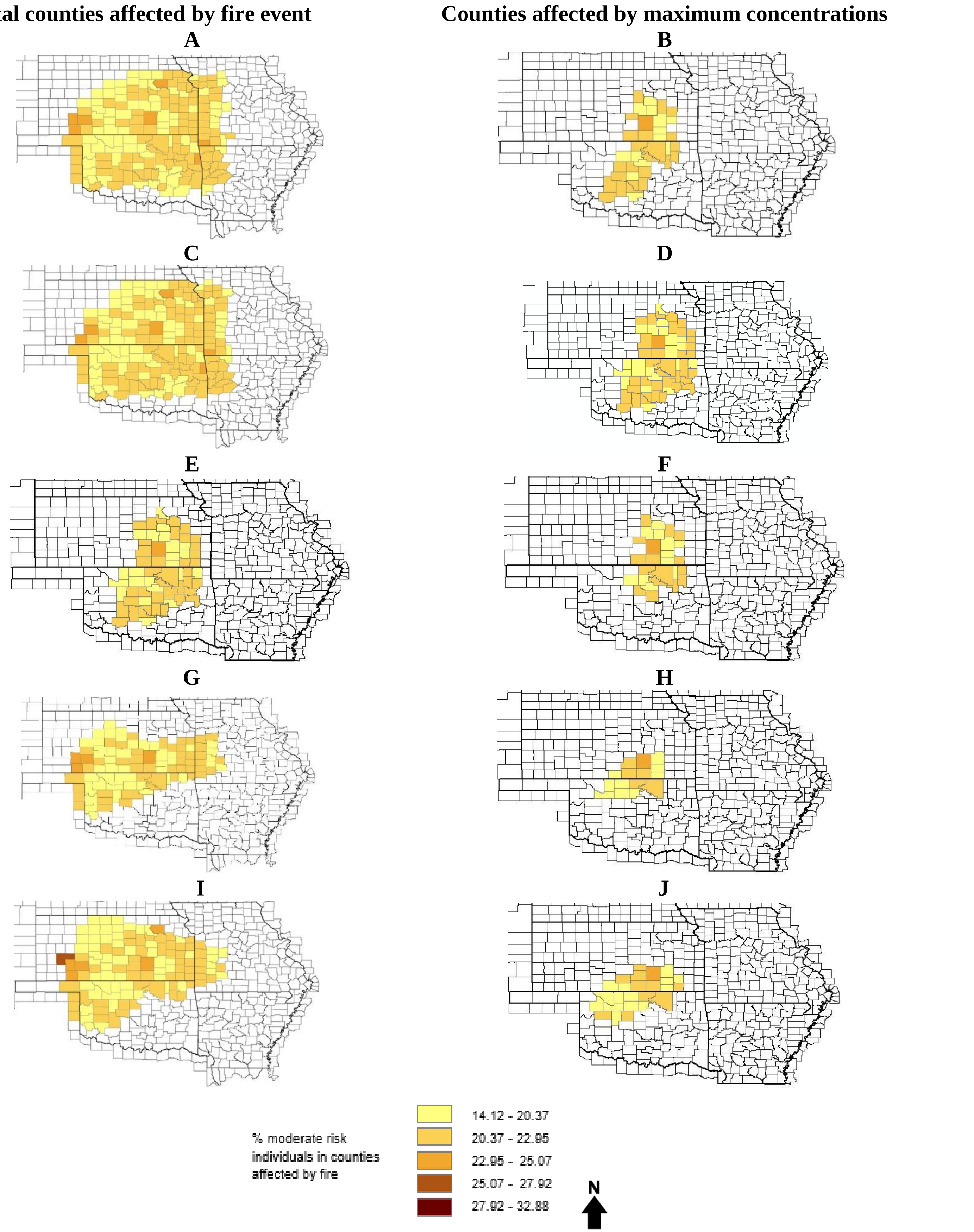

Figure 4: Counties in color represent the counties impacted by the entire fire event (left column) and the counties impacted by only the highest concentrations in the plume ($\geq 20 \mu g/m^3$ of $PM_{2.5}$) (right column). State outlines represent the southern area of Nebraska, Kansas, Missouri, Oklahoma, and Arkansas. Color gradation shows the percentage of moderate risk individuals who live in each of the counties. (A-B) Baseline, (C-D) Spring 2-3yr fire return interval scenario, (E-F) Spring patch-burn grazing, (G-H) Winter patch-burn grazing, (I-J) Winter 100% land.

Table 2: The percent change in total number of affected high risk and moderate risk individuals compared to the baseline scenario (Spring, 100% land burned). Positive values indicate a percent increase in the number of individuals affected and negative values indicate a percent decrease. The baseline scenario is reported in counts to give perspective on the number of high and moderate risk individuals that the baseline scenario impacts. Numbers in bold indicate a change from baseline greater than 40% in either direction, which our threshold for major changes. We chose 40% as that represents a natural break in our data.

	Spring					PBG		Winter
	100%	80%	50%	33%	2-3 years	Spring	Winter	100%
Total Counties High Risk	1790104	-2.15	-35.95	**-62.78**	-2.26	-3.13	**-66.58**	**-54.18**
Total Counties Moderate Risk	1839665	-2.08	-37.63	**-62.75**	-2.02	-2.78	**-68.27**	**-55.25**
High Concentration Counties High Risk	563237	-33.96	**-85.93**	**-95.61**	**+41.94**	**-65.98**	**-69.68**	**-63.25**
High Concentration Counties Moderate Risk	589222	-34.14	**-86.60**	**-95.66**	**+41.85**	**-50.65**	**-69.75**	**-64.53**

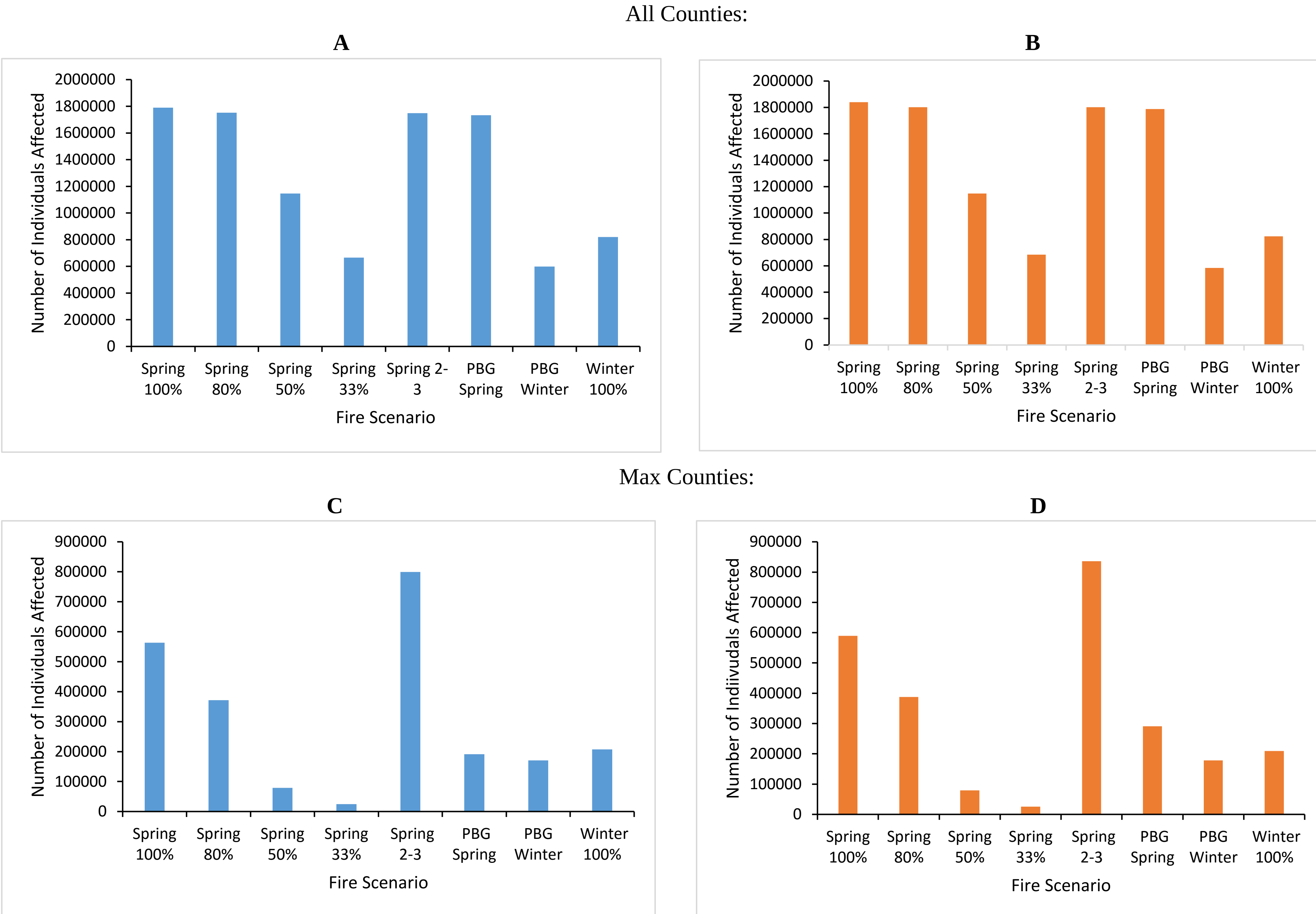

Figure 5. Total number of individuals affected by the fire event across all management regime scenarios separated by risk categories. (A-C) High risk individuals. (B-D) Moderate risk individuals. High risk individuals are people under 5 years of age and over 65. Moderate risk individuals are people between 6 and 18 years old.

Discussion

Of the scenarios considered in our study, the scenario with the greatest potential benefit to ranchers, wildlife, and public health was patch-burn grazing in spring. While different scenarios provide different advantages depending on the management goal, patch-burn grazing had the most positive impact across the factors considered by our study. Burning during the winter had the greatest decrease in impacts on public health but is not a practical alternative because of implementation difficulties.

Public Health

Reducing the number of individuals affected by smoke plumes is important for addressing public health, particularly for those at high and moderate risk of cardiopulmonary illness. With this in mind, the scenarios that were most likely to assist in the mitigation of the public health issues experienced in the region were the scenarios that decreased the quantity of land burned by at least 50%, or shifted the season of the burn from spring to winter. These scenarios all reduced the total number of individuals affected by the high concentration plumes by at least 48%, and reduced the total number of high risk and moderate risk individuals affected by at least 63% (Tables 1, 2). The total number of affected individuals matters when discussing public health because risk of illness is not a homogenous variable that is spread evenly over the landscape. Groups of high risk and moderate risk people tend to be concentrated in some counties and nearly non-existent in others in the study area. This is due to the way that homes and farms are distributed over the study area. Since people tend to gather together in central areas, there are pockets where population is higher and thus the numbers of high and moderate risk individuals are also higher.

While all individuals in an area may be affected by $PM_{2.5}$ and decreasing the total number of individuals experiencing smoke events is an important goal, we found that assessment of totals broken down into risk levels provided more detail about of the impact of smoke plumes from each fire regime than other possible analysis options, such as the average number of individuals affected. Scenarios that consistently reduced the total number of affected high and moderate risk individuals were those that burned the lowest amount of land annually, and burns that took place in the wintertime. Seasonal differences in weather patterns may help to explain some of the observed differences between spring and winter burns in our study. Weather patterns control how quickly the smoke cloud disperses and how low it stays to the ground (Rapp 2006, Brian Obermeyer personal communication). The only scenario that impacted more individuals located in the highest concentrations of the plume was the one that increased time since burn. This scenario impacted 64% more counties than the baseline, 41% more high risk individuals, and 41% more moderate risk individuals (Table 1, Table 2, Figure 3a). It was the only scenario that we assessed that increased the negative impact on public health from the baseline scenario. It is likely that the model with an increased time since burn had a larger smoke cloud than other burns considered, as there was more time for biomass accumulation between burns. This scenario did not take into consideration the impact of cattle on reducing biomass, so on the ground applications of decreased fire frequency may not result in as large an impact on at-risk humans as we observed.

Overall, a 50%, or greater, decrease in the total land burned, or changing the season of the burn is associated with a greater than 50% decrease in the number of high risk and moderate risk individuals affected by high concentrations of smoke (Table 2). This reduction in the number affected individuals would be preferable to the baseline scenario for decreasing public health impacts of $PM_{2.5}$ in the study area.

Ecology and Wildlife

Changing the season of the burn and the application of fire and grazing not only reduced the amount of $PM_{2.5}$, but resulted in more heterogeneity within the plant community. Spring 2-3 year FRI did not reduce overall exposure to $PM_{2.5}$, but increasing time since fire results in higher vegetative biomass that provides a higher fuel load to help eradicate shrub and woodland encroachment by burning at different growth periods, and with a more intense fire (Towne and Craine 2015). A change in fire season, such as winter burns has been reported to result in higher plant species diversity (Towne and Kemp 2003). Ranchers are concerned that burning outside of the late spring results in an increase in shrub biomass, but Towne and Craine (2014) found that grass biomass after burning outside the spring is not statistically different than traditional annual spring burns. A third method for burning outside of the spring is PBG. This practice not only reduces the magnitude at which fire affects public health by increasing fire fuel loads for a more intense fire, but it also increases plant heterogeneity by providing different patches of habitat (Weir et al. 2013).

In addition to the positive impact PBG has on public health and plant community composition, there is also a benefit to wildlife. The direct effects on wildlife were not measured in our study as that is beyond the scope of our models, but increased plant heterogeneity as a result of PBG is known to increase species diversity for birds, small mammals, and herpetofauna species. PBG creates multiple habitats as a result of each patch having different growth stages of the vegetation since time since fire is not homogenous over the landscape (Weir et al. 2013). This difference in plant community composition, between patches, provides for diverse habitat requirements, that include varying depths of litter, exposure of bare ground, and plant species diversity, for a variety of ground nesting birds (Figure A5, Weir et al. 2013). This results in higher survival rates for rare species of bird, and a higher chance of producing surviving offspring (Coppedge et al. 2008; Davis et al. 2016). Therefore, PGB is beneficial for grassland bird conservation, because it provides suitable habitat for more than just the generalist species this grassland avian communities.

Small mammals respond positively to increased plant heterogeneity after prescribed fire, but especially under PBG treatments. Since the spring 2-3 year scenario has a longer growing period, it results in more litter, less bare ground, and varying plant functional groups (Fuhlendorf et al. 2010), small mammal species diversity is likely higher compared to the traditional spring burns. Studies, such as Fuhlendorf et al. (2010), reported this sensitivity of small mammal communities towards vegetative structure under different fire regimes. Similar to the winter PBG scenario increasing bird species diversity, ecological niches containing a variety of grasses created by the FRI's of the patch burn, increase species diversity of small mammals (Ricketts and Sandercock 2016).

Herpetofauna species respond positively to fire and grazing treatments as well, but their response is likely due to both vegetative and invertebrate population dynamics. However, there is a lack of research to confidently state that herpetofauna species diversity increases within PBG grazing scenarios. Some studies found that species richness was higher during the annual burns (Wilgers and Horne 2006), but others suggest that reptiles assemblages respond to shifts in insect populations from fire (Steen et al. 2013). Under PBG grazing, invertebrate species richness varies between the different patches, but overall, invertebrate biomass increases (Engle et al.

2008). There was no difference in diversity, for invertebrates, between patches (Doxon et al. 2011). Since herpetofauna mostly prefer invertebrates for a food source, we can infer that if invertebrate biomass increases under PBG, then herpetofauna populations may also increase. Additionally, many invertebrates and herps are dormant during the winter, so applying a winter PBG treatment may be beneficial for herpetofauna and some invertebrate populations.

Factors influencing the motivations of ranchers

Through conversation with Brian Obermeyer, Landscape Programs Manager for the Nature Conservancy in the Flint Hills, we identified an important motivation for ranchers. Ranchers in the Flint Hills of Kansas and Oklahoma have a deep sense of place and feel an obligation to the land, which can be thought of as a land ethic. According to Brian Obermeyer, there is a sentiment among ranchers that managing in a different manner may damage the landscape, thus convincing ranchers to shift to burning in winter or using a patch-burn grazing technique may be difficult. Early European settlers believed that nature had to be subdivided and put into agriculture for it to be considered productive to society. In short, the goal was to dominate the land and very literally own it. While the end results of this mentality still exist in the form of property rights, the overall mentality of today's ranchers is different (Smith 2001). People reliant on the land have adopted a land ethic that is similar to what Aldo Leopold describes in his 1949 "A Sand County Almanac." The caveat is that many of their best management practices are couched in tradition and not scientific research. There is skepticism among ranchers because many scientific studies do not perfectly replicate the conditions on ranching operations. For example, much of what we know about grassland dynamics was learned from experiments on land that had not presently or previously had cattle grazing. Land managers and ranchers alike find difficulty in accepting results of these studies because they understand that there is a strong interaction between fire and grazing (Limb et al. 2011). When presenting alternative land management techniques such as patch-burn grazing to ranchers, information from studies on working landscapes that include cattle grazing should be prioritized.

When introducing alternative management practices, it is also important to consider how practical the implementation of the method will be. Our results suggest that burning in the winter and utilizing patch-burn grazing in the winter can have the greatest benefit to public health but, through conversation with Brian Obermeyer, we discovered that burning in winter cannot be easily implemented by ranching operations. The main issue is equipment maintenance, because water sprayers, necessary for conducting prescribed burns, can freeze overnight causing damage. It is unlikely that a ranching operation can burn during the winter unless they have access to heated storage facilities, which is not the case for most operations throughout the Flint Hills.

Another important factor that influences land management practices for ranchers is livestock productivity, which is measured as cattle weight gain (Limb et al. 2011). The appeal of a late spring burn for ranchers is that it has been shown to support increased weight gain in cattle over the short term (Anderson et al. 1970, Owensby and Smith 1979) as a result of increased forage quality (Allen et al. 1979, as cited by Bernardo et al. 1988). However, this dogma of spring burning as the only effective management approach has been recently challenged. Towne and Craine (2014) conducted research in the Flint Hills by applying burn experiments that shifted prescribed burns to the fall, winter, and spring to compare community composition and grass production. Within the twenty-year study at Konza Prairie Biological Research Station, there were no differences for average grass production or biomass between the different burn seasons. However, in response to fall and winter burns, cool season grass species had a longer growing season. Limb et al. (2011), explored the effect of an alternative management regime (pyric-herbivory) on cattle performance. They combined the spatial and temporal interaction of fire and grazing to understand how cattle performed on traditionally managed grasslands (i.e., frequent fire and continuous grazing) as compared to a conservation-based approach (pyric-herbivory applied as patch burn grazing). They found that cattle weight gain, calf weight gain, and cow body condition did not differ between conservation-based and traditional management in tallgrass prairie. Grazing season variability among cattle performance was also lower when conservation-based management was used. They concluded that pyric-herbivory is a rangeland management strategy that does not negatively impact cattle performance and does not require reduction of the number of grazing cattle (i.e., stocking load). Winter et al. (2014), also explored the effect of PBG in spring on cattle performance in a working ranch environment. They found no statistical differences between a traditional late-spring burn and PBG for cow average body condition, cow average body mass, and calf average body mass. Although there were no significant differences, trends suggest that PBG may actually produce greater body mass for both cows and calves from increased forage quality. Thus, patch-burn grazing during the spring may be a viable option for maintaining the economic viability of ranching operations while also mitigating the negative impacts on public health.

Conclusions, Limitations, and Future Research

Conclusions

The results of this study suggest that patch-burn grazing may be the most viable alternative to the traditional land-management regime practiced by land managers in the Flint Hills. While other scenarios had a more positive impact on the reduction of potential public health impacts, we feel that the PBG scenarios, particularly PBG with spring burning, would be the most amenable to rancher's traditional beliefs about the value of spring burning, their land ethic values to maintain the prairie, and their economic desire to increase cattle weight gain. PBG has also been shown to be the most beneficial to prairie wildlife and to increasing landscape heterogeneity, which may increase the prairie's resilience to woody encroachment. Thus, we propose that patch-burn grazing is the best solution to mitigate tensions between public health issues, ecosystem health needs, and the objectives of ranchers while maintaining the tallgrass prairie system.

Limitations

There are several limitations of our study that may impact our assessment of the public health impacts of the scenarios considered. First, we had to generalize the at-risk individuals to all of those within specific age brackets, instead of being able to quantify the numbers of people who may actually be entering the hospital with cardiopulmonary illnesses due to a lack of hospital admission data for the study area. This means that we may be over-predicting the number of high and moderate risk individuals impacted by smoke plume exposure. Second, previous studies have found that BlueSky may under-predict the quantity of $PM_{2.5}$ created by a fire event (Adkins et al. 2003). Thus, our assessment may under-represent the concentrations of $PM_{2.5}$ experienced on the ground in our study region and more people may be affected than our study suggests. Third, results provided by BlueSky provide a range of $PM_{2.5}$ from 20-40 μg/m^3, which contains the EPA's standard of 35μg/m^3 over a 24-hour period. This means that our assessment of individuals affected by high concentrations of $PM_{2.5}$ may over-predict the true number of people that are truly experiencing $PM_{2.5}$ at a higher level than recommended by the

EPA. Fourth, we were unable to model a fall burn scenario, for comparison. We could not obtain sufficient data from previous studies to determine fuel loading variables necessary for creating a dispersion model within BlueSky. Data for the winter scenarios were not available annually, so we were constrained to using biannual data. Additionally, due to the nature of land management research, our input data was collected from studies that had study sites from various geographic locations. Finally, assessing the statistical significance of our results was not possible, due the time required to conduct burn scenarios.

Further Research

In the future, this study can be improved by having a more robust fire and fuel loading data set that includes more management regime scenarios. In particular, these data should encompass fall burns, PBG in fall, summer burns, and PBG in summer. This study can also be improved by having fuel loading data that is site specific to the Flint Hills, to eliminate error from spatial variation in the model. The method for fuel loading can also be improved by using remote sensing to better estimate fuel loading across the Flint Hills by capturing the heterogeneity of vegetation composition. BlueSky was originally developed for wildland fires in the western United States, and thus an emissions and dispersion model specific to grassland fires may provide more accurate outputs. Additionally, our assessment of wildlife impacts are based on small scale studies, and the results from these studies may not be accurate on a landscape scale. A beneficial direction of study would be fire impacts on wildlife at the landscape scale since that is the scale of the burn. Future studies should also look into the demographics of the region. This could help to determine if smoke impact is evenly distributed among all individuals, or if there are any groups that are disproportionately affected by high smoke concentrations. Our study models particulate matter but ozone is also an important pollutant to assess for public health. Future studies should also model the production and dispersion of ozone precursors from grassland fires. Lastly, further research is needed to fully understand the feasibility of implementing a PBG system over the study area. This is because PBG requires increased infrastructure in the form of fire breaks and increased human effort to control the fire. Not all ranchers may have these additional resources available to them.

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Appendix

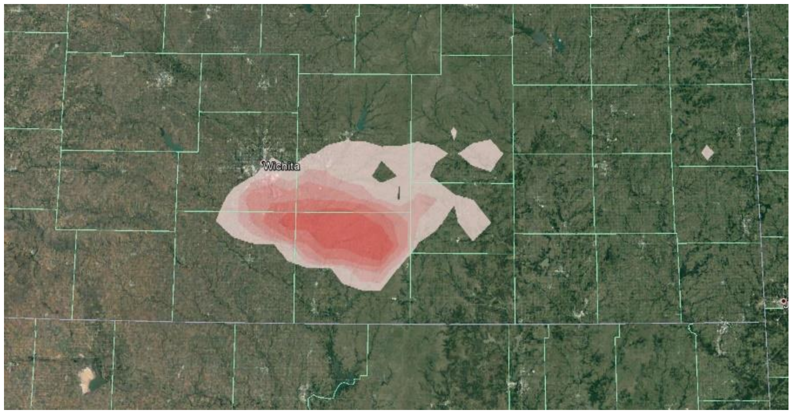
Table A1. Source of fuel loading information for each management scenario.

Management Regime Scenario	**Source of community composition data**	**Data used**	**Notes**
Spring- 1 year fire return interval	Towne and Kemp 2003, Towne and Owensby 1984	Table 1, Table 2, Table 3	Also encompasses 100% land burned
Spring- 2-3 year fire return interval	Towne and Owensby 1984	Figure 4	
Winter- 2 year fire return interval	Towne and Owensby 1984	Figure 4	
Winter- Patch-burn grazing	Towne and Owensby 1984	Figure 4	
Spring- Patch-burn grazing	Towne and Owensby 1984	Figure 4	

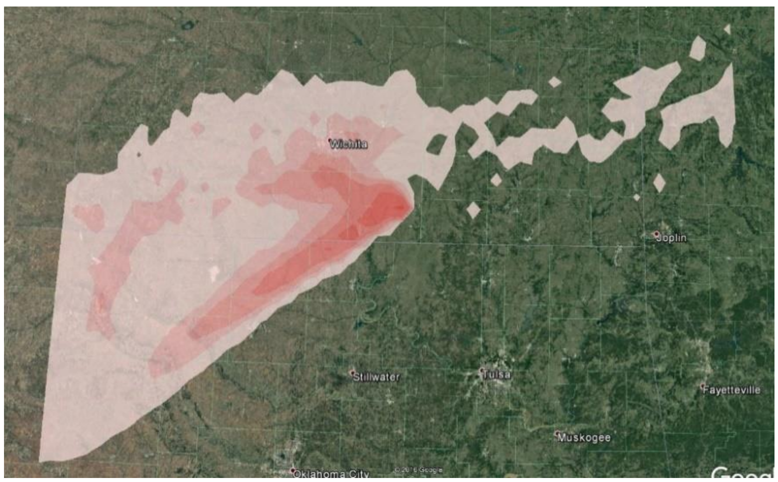
Table A2. Variables used to define a fire event in the BlueSky modeling framework. The third column are the inputs for a Spring- patch burn grazing scenario.

BlueSky variable	**Variable explanation**	**Input**
Location	The geographic location of the fire event	Flint Hills region
Acreage	The amount of land to be burned measured in acres	2.8 million acres
Number of days for burn	The timeframe for which a given acreage is burned within one burning event	3 days
Fuel Loading:	The composition of vegetation present at time of fire ignition	
Canopy	Proportion of vegetation classified as burnable material on trees	0 tons/acre
Shrubs	Proportion of vegetation classified as woody vegetation below 2 meters tall	0.1016 tons/acre
Grass	Proportion of vegetation classified as grasses or sedges	0.8983 tons/acre
Litter	Proportion of senesced vegetation	0.005 tons/acre
Rotten	Proportion of decomposing senesced vegetation	0.0050 tons/acre
Moisture	Categorical measurement of ground-level moisture	Moderate-Moist

A



B



C

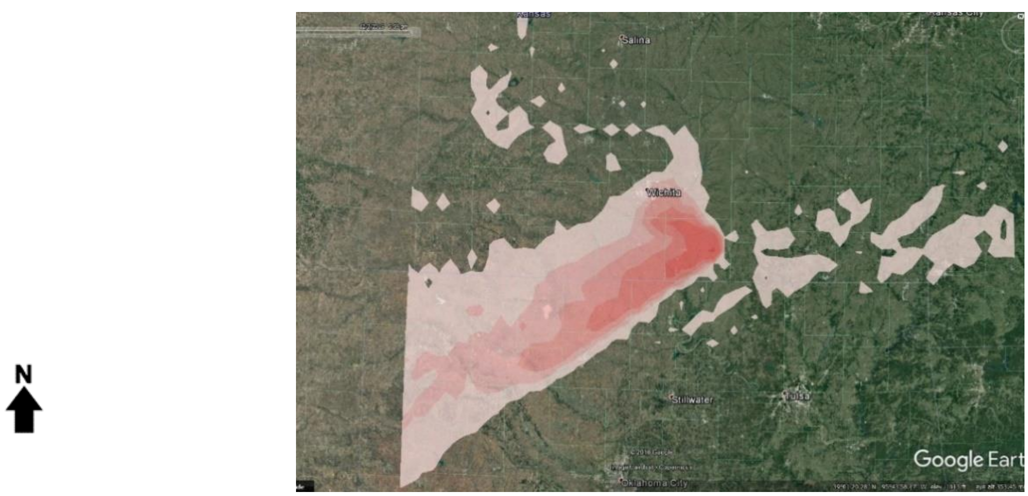


Figure A1. Example of BlueSky output for PBG winter scenario. Output is exported to GoogleEarth and screenshot into a jpeg file. This is done for all the management scenarios. (A) Day 1. (B) Day 2. (C) Day3.

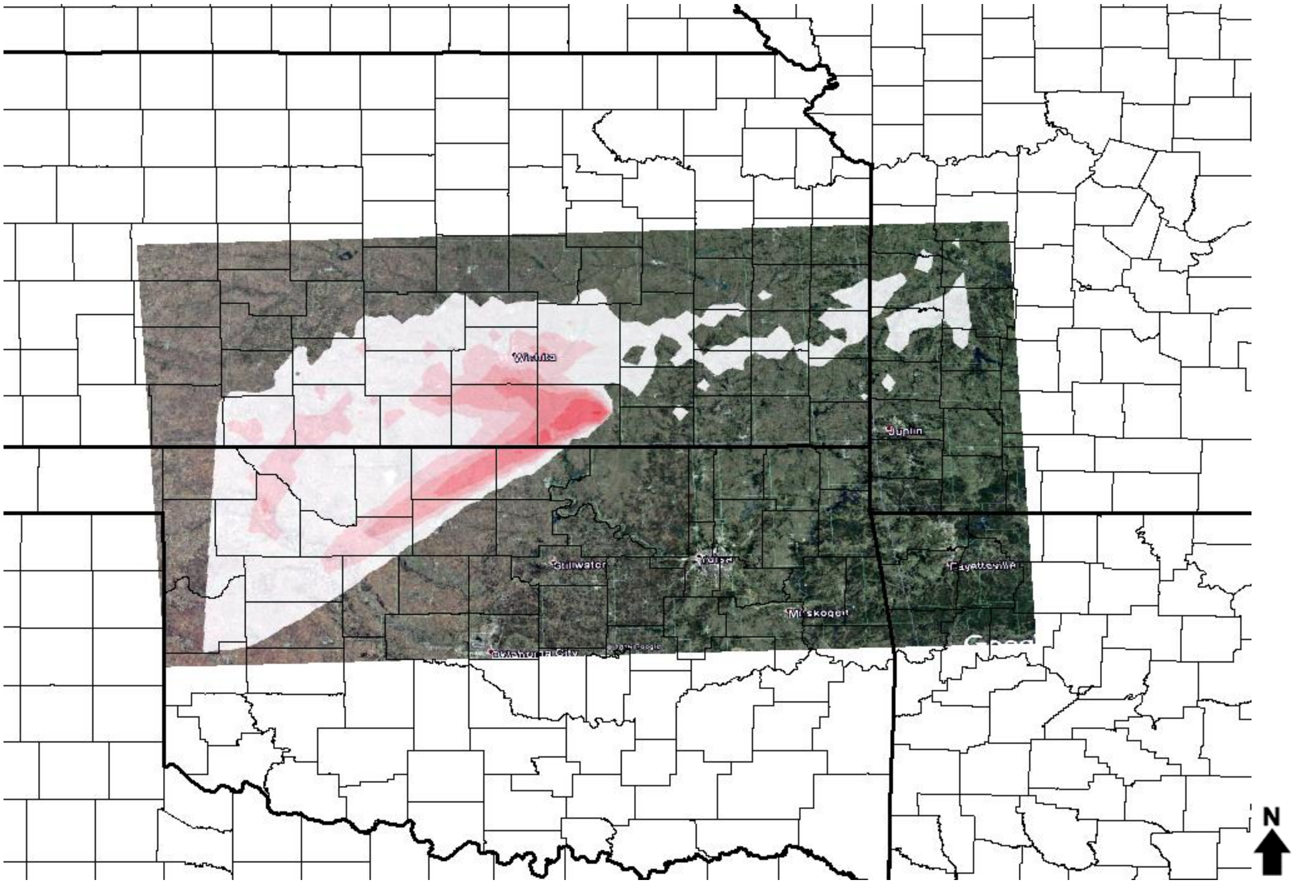


Figure A2. Example of jpeg image of BlueSky output for PBG winter day 2 being georeferenced into ArcMap. Image is georeferenced using US counties base map as reference This is done for all 3 days of the fire event and all management regime scenarios

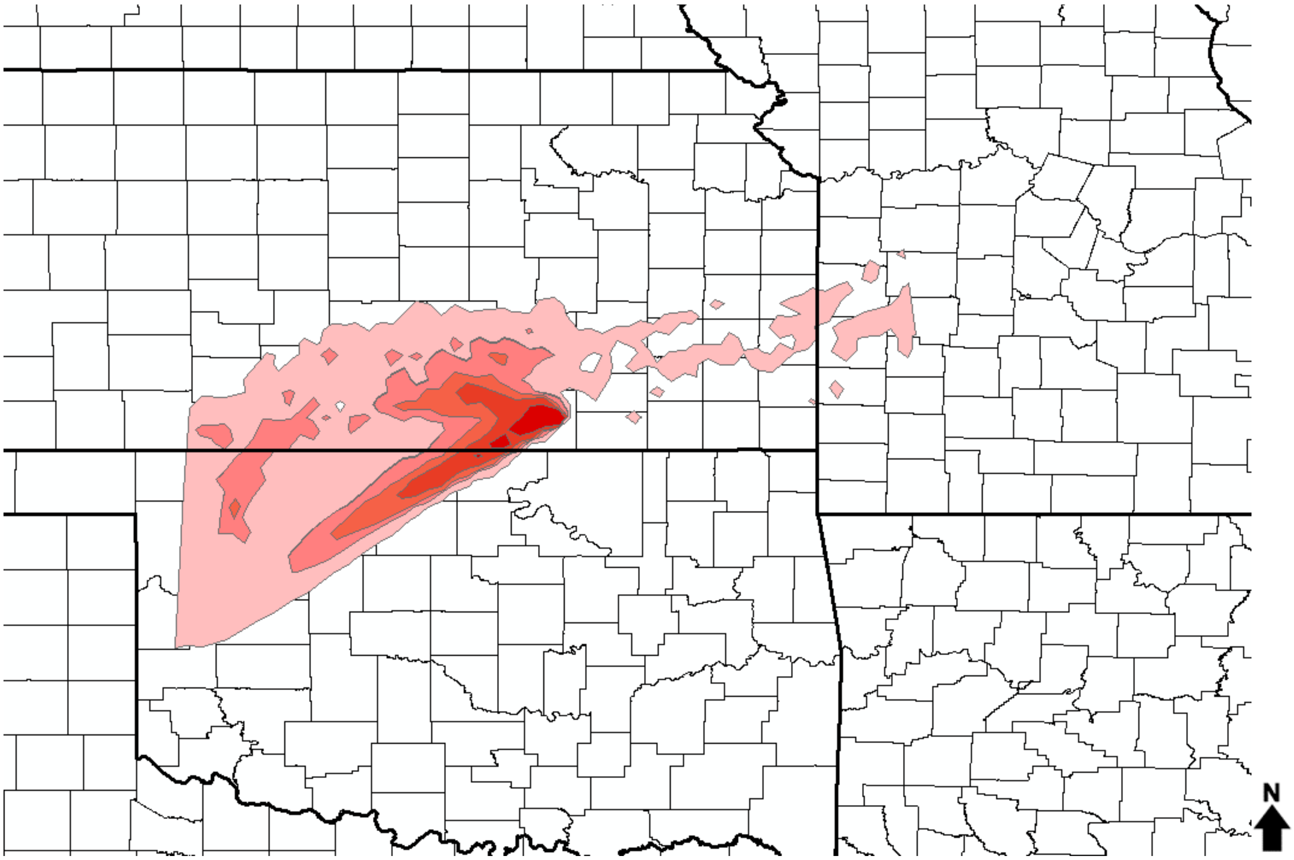


Figure A3. Example of polygons created from GoogleEarth jpeg images for PBG winter day 2. This is done using the editing tool in ArcMap. Polygons were created for all 3 days of every management regime scenario.

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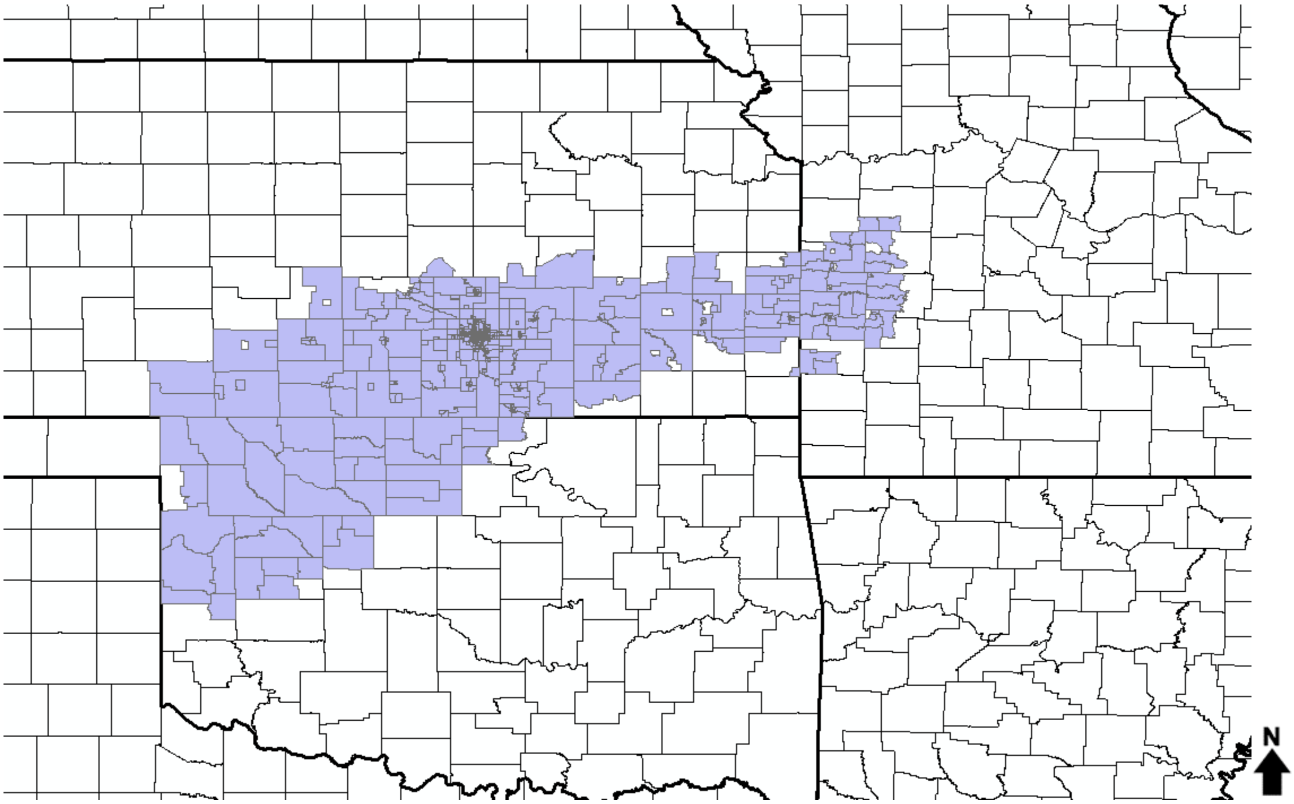

Figure A4. Example of output from overlay of smoke plume polygons with US counties map for PBG winter day 2. Smoke plume polygons were buffered at 0.5 miles. This is done for all 3 days of the fire event and all management regime scenarios

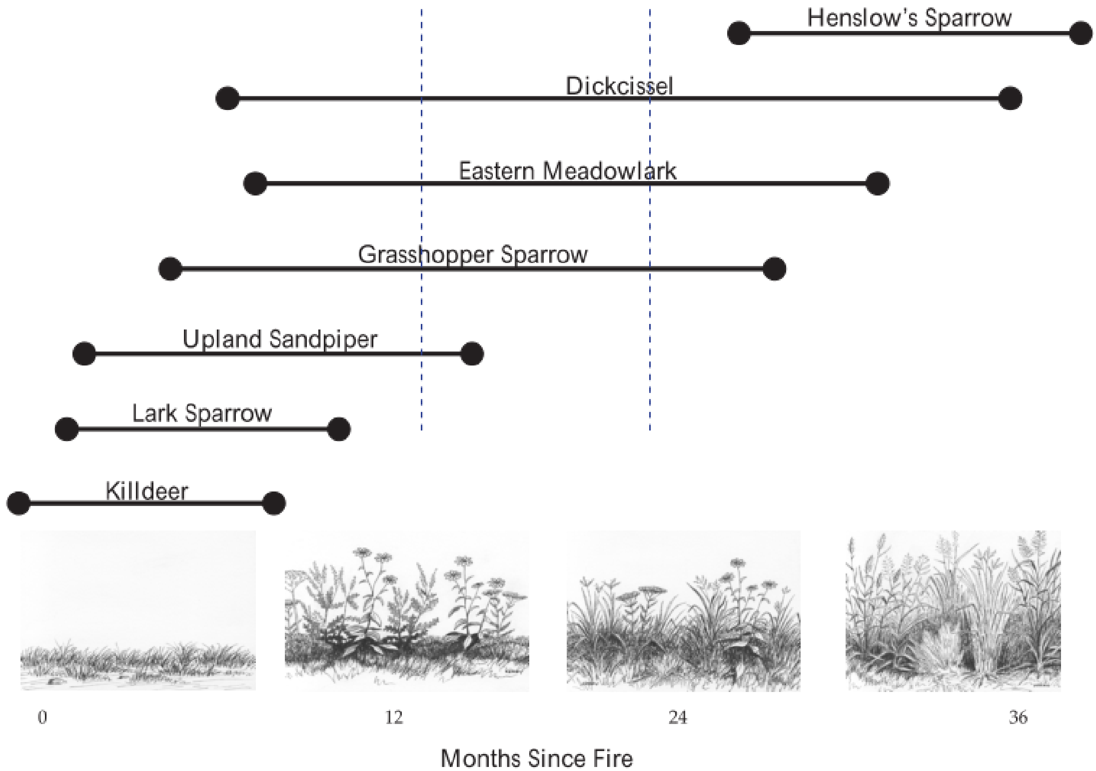

Figure A5. Range of habitat for prairie birds. Patch burning increases heterogeneity by providing multiple habitats for multiple species in the same area. Traditional burning generally provides one kind of habitat that excludes certain species of bird. Derived from Weir et al. (2013).

Questions Asked During Interviews with Experts:

Conversation with Brian Obermeyer, Landscape Programs Manager at The Nature Conservancy (10/17/16)

Any questions about our project proposal as it currently stands?
Does blue sky work and are there any other models that are feasible for us?
Does this all make sense? Is someone else already doing this?
Could this be used or is there a different approach: Format?
Which management scenarios should we explore?
Current status quo? Management goals?
What data is available for us to use?
Anything that is more important to look into regarding ecological concerns?
Resources on public health? What are the key issues in the Flint Hills?
Is there anything that is preventing people from burning outside of that early spring window? Or just tradition dictating that?
Any other regulation from counties?
Are there any changes happening? Is there a direction that people are going already?
What is the existing conflict between ecologists, ranchers, and those in the public health field?
What is the Nature Conservancy doing about burns?
Is there any other research or sources that ranchers are getting their practices from? Is it just tradition?
Anyone else we should contact?
Questions for us?

Conversation with Doug Goodin, Professor of Geography at Kansas State University (1/13/17)

How far are you on the project? How is it going?
Fuel load estimation stuff
-Did you figure out how to do it? Can provide us with some data from what they have done?
What is your perception of land manager responses to burning suggestions? Particularly responses to suggestions that land managers change their burning practices.
Suggestions for improving the accuracy of our models?
Extra comments:

Conversation with Sherry Leis, Fire Ecologist at the Heartland I&M Network and Prairie Cluster Prototype Monitoring Program (1/24/17)

What data do you have?
How was it collected?