Research Article

Historical Pyrogeography of Texas, USA

Michael C. Stambaugh[1*], Jeffrey C. Sparks[2], and E.R. Abadir[1]

[1] Department of Forestry, University of Missouri,
203 ABNR Building, Columbia, Missouri 65211, USA

[2] State Parks Wildland Fire Program, Texas Parks and Wildlife Department,
12016 FM 848, Tyler, Texas 75707, USA

[*] Corresponding author: Tel.: +001-573-882-8841; e-mail: stambaughm@missouri.edu

ABSTRACT

Synthesis of multiple sources of fire history information increases the power and reliability of fire regime characterization. Fire regime characterization is critical for assessing fire risk, identifying climate change impacts, understanding ecosystem processes, and developing policies and objectives for fire management. For these reasons, we conducted a literature review and spatial analysis of historical fire intervals in Texas, USA, a state with diverse fire environments and significant fire-related challenges. Limited literature describing historical fire regimes exists and few studies have quantitatively assessed the historical frequency of wildland fire. Written accounts provided anecdotal fire information that is spatially and temporally constrained. Three spatial datasets depicting historic mean fire intervals (MFIs) showed agreement in that the majority of Texas consisted of frequent fire regimes (MFIs = 1 yr to 12 yr), and that a gradient of decreasing fire return intervals existed from west to east. Much potential likely exists for acquiring fire history data in the Piney Woods region, the Oak Woods and Prairies region, and the mountain ranges of the Trans

RESUMEN

La síntesis de múltiples fuentes de información sobre historia del fuego, incrementa el poder de confiabilidad en la caracterización de regímenes de fuego. La caracterización de estos regímenes es crítica para determinar el riesgo de incendio, identificar impactos del cambio climático, entender procesos ecosistémicos, y desarrollar políticas y objetivos para el manejo del fuego. Por esas razones, hicimos una revisión bibliográfica y un análisis espacial de los intervalos históricos del fuego en Texas, EEUU, un estado con diversos ambientes de fuego y desafíos importantes en el tema de incendios. La literatura que describe regímenes históricos de fuego es limitada, y muy pocos estudios han determinado cuantitativamente la frecuencia histórica de fuegos de vegetación. Algunos escritos proveyeron de información anecdótica de incendios que es espacial y temporalmente restringida. Tres bases de datos que presentan intervalos históricos medios en la ocurrencia de incendios (MFIs), muestran coincidencias sobre que en la mayor parte de Texas, los incendios son frecuentes (MFIs = 1 a 12 años), y que existe un gradiente de decrecimiento en la frecuencia de incendios de oeste a este. Afortunadamente existe mucho potencial para adquirir datos históricos de incendios en las regiónes llamadas Piney Woods, Oak Woods and Prairies, y de los pastizales montañosos de la región llamada Trans

Pecos region. These data will be valuable for improving fire regime characterization to guide fire planning and budget processes, for the restoration and maintenance of fire-adapted landscapes, and for informing fire prevention and education activities.

Pecos. Estos datos serán invaluables para mejorar la caracterización del régimen de incendios y servirán para guiar los procesos de planificación y la elaboración de presupuestos, para la restauración y mantenimiento de paisajes adaptados al fuego, y para informar actividades de educación y prevención de incendios.

Keywords: fire regimes, literature review, map, mean fire interval, natural subregions, restoration

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INTRODUCTION

Characteristics of historical fire regimes underlie a multitude of present day societal and natural resource challenges (Wildland Fire Leadership Council 2014). Historical fire regime data aid in assessing fire risk (Hardy 2005), identifying climate change impacts (Westerling *et al.* 2006, Guyette *et al.* 2014), understanding ecosystem processes (Bond and Keeley 2005), and developing policies and priorities for fire and land management (Wildland Fire Leadership Council 2014). Synthesis of multiple sources and types of information increases the power and reliability of historical fire regime interpretation (Morgan *et al.* 2001) and, because fire regimes are dynamic, long-term information is needed to define them. Since Euro-American settlement (EAS), historical fire regimes throughout North America have been highly altered to lengthened fire intervals and changed seasonality of occurrence (Stewart 2002, Keane *et al.* 2007, Knapp *et al.* 2009), making them difficult to quantitatively define, particularly through analysis of modern data.

The state of Texas, USA, presents unique fire research opportunities because it has perhaps the greatest diversity of fire regimes, fire conditions, and fire concerns represented in the US (Wildland Fire Leadership Council 2014). Even though fire is generally regarded as a historically important disturbance in most Texas ecosystems, little work has been done to describe and synthesize historical fire regime characteristics. In this paper, we focus on information from prior-to EAS influences (i.e., on ignitions, fuels, suppression) because it describes the historical fire characteristics and ecosystem processes, the legacies for which are still evidenced (e.g., seedbanks, soil conditions, relict long-lived organisms). Our objective was to review and integrate literature and data describing the historical fire return intervals of Texas, thereby aiding future efforts towards restoring fire regimes, conserving fire-adapted species and communities, and informing fire risk and prevention.

METHODS

We reviewed and summarized published literature describing historical fire regimes in the state of Texas. We searched agricultural and biological literature databases (Agricola, Scopus, Biological Abstracts, BioOne) for keywords related to fire and the ecosystems of Texas. We conducted further literature searches using reference citations within papers. Over one hundred sources of fire information were reviewed including travelers' journals, federal agency proceedings, theses and dissertations, and scientific publications. We organized fire regime information by Texas' natural subregions (LBJ School of Public Affairs 1978) (Figure 1) because of the close relation-

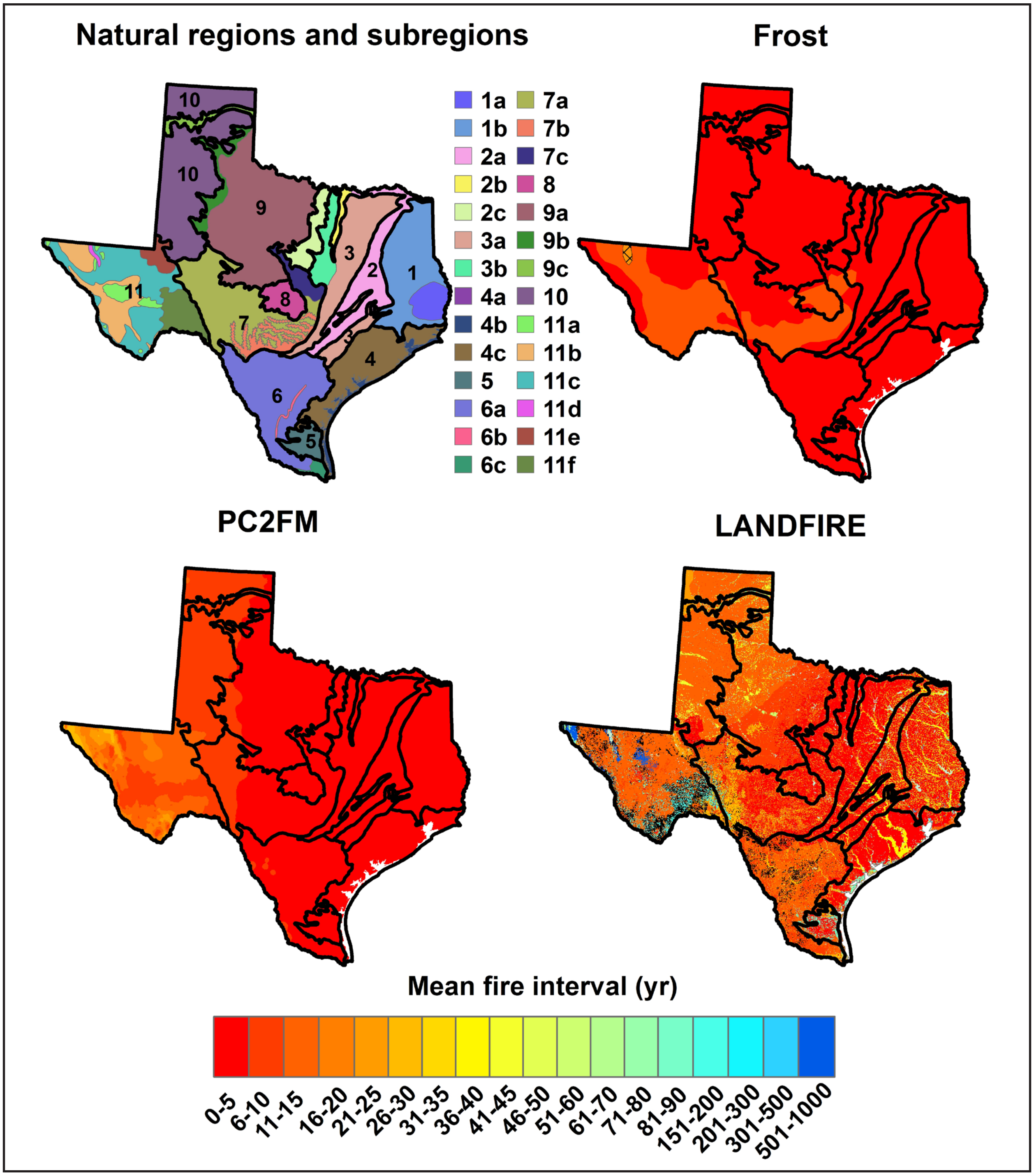

Figure 1. Texas natural regions and subregions and historical fire return intervals. Natural regions and subregions of Texas were used to stratify descriptions of historical fire regime literature and geodatabases. Refer to Table 1 for region and subregion names (source: Lyndon B. Johnson School of Public Affairs Policy Research Project Report No. 31, Preserving Texas' Natural Heritage). The three historical fire frequency maps are: Frost (1988), pre-settlement fire frequency regions (see methods and original publication for description of the development of this coarse-scale map; PC2FM, pre-settlement fire frequency estimates by Guyette *et al.* (2012); and LANDFIRE National (Keane *et al.* 2002) Mean Fire Interval Map. See methods for more detailed descriptions.

ship between fire environment conditions and natural subregion characteristics (e.g., vegetation, climate, landforms, and soils). Organizing the review by natural subregions was also an attempt to make the information useful to a wide range of fire information user groups. The relatively large areas of natural subregions typically allowed consideration of multiple sources of information. In the absence of qualitative or quantitative information from Texas, results of studies from regions with similar vegetation types were included.

In addition to qualitative historical fire information from published literature, we evaluated three sources of historical fire interval estimates that included maps or geodatabases. The first source was Frost's (1998) first approximation of pre-settlement fire frequency regions of the United States based on fire history studies, landforms, and vegetation characteristics. This qualitative, coarse-scale characterization of fire intervals represents all fire severity types. Fire interval representation is for the most frequent fire commonly found within regions and covering at least 10% of the landscape. Fire intervals represent local site intervals (i.e., intervals for fire compartments) for the most fire-exposed parts of the landscape (e.g., flats, dry uplands, south slopes) (Frost 2000). The second source was the Physical Chemistry Fire Frequency Model (PC2FM; Guyette *et al.* 2012)—a quantitative, physical chemistry model developed from pre-industrial era fire history data (fire scars, charcoal, and expert estimates) from 178 sites across North America. The PC2FM does not use vegetation to estimate mean fire intervals (MFIs) and represents fires of all severity types (i.e., low, mixed, high). The MFIs estimated by the PC2FM represent frequencies within approximately 1.2 km^2 areas. The third source was the LANDFIRE National (Keane *et al.* 2002) MFI map. Quantitative estimates of MFIs were made using a spatially explicit, state-and-transition model that simulates vegetation and fire interactions over long time spans. Simulation results were summarized into high-resolution estimates of historic MFIs. The LANDFIRE MFIs represent the average period between fires under the presumed historical fire regime. MFIs are derived from vegetation and disturbance dynamics simulations at a 30 m resolution using LANDSUM—a landscape fire succession model (Keane *et al.* 2002, Hann *et al.* 2004).

For each historical fire interval source, raster grid data of MFIs were used to calculate zonal statistics by natural subregion using ArcGIS software (ESRI 2011; Table 1). Raster cell size varied among sources (Table 1). Minimum, maximum, and majority MFIs were determined for each natural subregion. Because of the finer resolution of LANDFIRE data (i.e., 30 m^2), a high range of MFIs resulted for each natural subregion. Frost's map and LANDFIRE classified some areas as unburnable landtypes. For display purposes only, we re-classed estimates of Frost (1998) and the PC2FM to the LANDFIRE classification scheme, which resulted in MFI map simplification in some regions (Figure 1). Bar plots were used to describe the relative areas of each MFI class using the original source classification (Figure 2).

RESULTS

Literature Review

Piney Woods. While no quantitative studies of fire history were found for the longleaf pine (*Pinus palustris* Mill.) forest subregion of eastern Texas, many studies from the southeastern US suggest a frequent fire regime (Platt *et al.* 1991). Longleaf pine requires frequent fire for reproduction, healthy stand structure and composition, and disease control (Wright and Bailey 1982), and effects of fire exclusion can be obvious and detrimental (Varner *et al.* 2005). Pre-EAS fire regimes of longleaf pine ecosystems were characterized by frequent, low-intensity surface fires, with

Table 1. Pre-Euro-American settlement period fire interval estimates for Texas natural subregions (LBJ School of Public Affairs 1978) based on a map analysis of three modeling and mapping efforts. Different sources of information were used for developing each map. Historical mean fire interval maps and estimates are based on one or more of the following: fire history studies, climate parameters, human population estimates, topography, vegetation, and expert opinion. The number of quantitative fire history studies for each natural subregion is given in the right column. Numbering of natural subregions corresponds to Figure 1. NP = nonpyrophytic, Indet. = indeterminate, SV = sparsely vegetated.

Data source :		Frost (1988)		PC2FM		LANDFIRE		
Scale of estimates :		coarse (undefined)		coarse (1.2 km²)		fine (30 m²)		
		Historical Mean Fire Interval (yr)						
Texas natural region and subregion	**Area (km²)**	**Range**	**Majority**	**Range**	**Majority**	**Range**	**Majority**	**Studies (*n*)**
1. Piney Woods								
a. Longleaf Pine Forest	10762	1 to 6	1 to 3	3 to 5	4	1 to Barren	1 to 5	0
b. Mixed Pine to Hardwood Forest	49397	1 to 6	4 to 6	3 to 5	4	1 to Barren	1 to 5	0
2. Oak Woods and Prairies								
a. Oak Woodlands	35034	1 to 6	4 to 6	3 to 4	3	1 to Barren	1 to 5	0
b. Eastern Cross Timbers	4287	1 to 6	1 to 3	3 to 4	3	1 to Barren	1 to 5	0
c. Western Cross Timbers	13045	4 to 6	4 to 6	3 to 4	3	1 to Barren	1 to 5	0
3. Blackland Prairies								
a. Blackland Prairie	51227	1 to 6	4 to 6	2 to 4	3	1 to Indet.	1 to 5	1
b. Grand Prairie	12652	1 to 12	4 to 6	3 to 4	3	1 to Barren	1 to 5	0
4. Gulf Coast Prairies and Marshes								
a. Dunes and Barrier	1422	4 to 6	4 to 6	3 to 4	3	1 to Barren	1 to 5	0
b. Estuarine Zone	6836	1 to 6	1 to 3	3 to 4	4	1 to Indet.	11 to 15	0
c. Upland Prairies and Woods	44156	1 to 3	1 to 3	2 to 5	3	1 to Indet.	1 to 5	0
5. Coastal Sand Plains	9660	1 to 6	1 to 3	3 to 5	4	1 to Indet.	1 to 5	0
6. South Texas Brush Country								
a. Brush Country	64121	1 to 12	4 to 6	2 to 6	5	1 to Indet.	11 to 15	0
b. Bordas Escarpment	1272	4 to 6	4 to 6	3 to 5	4	1 to Indet.	6 to 10	0
c. Subtropical Zone	2843	1 to 3	1 to 3	3 to 5	4	1 to Indet.	26 to 30	0
7. Edwards Plateau								
a. Live Oak to Mesquite Savanna	56262	1 to 12	4 to 6	3 to 12	3	1 to Indet.	1 to 5	0
b. Balcones Canyonlands	13335	4 to 12	7 to 12	3 to 4	3	1 to Indet.	1 to 5	0
c. Lampasas Cut Plain	8654	1 to 12	4 to 6	3 to 4	3	1 to Barren	1 to 5	0
8. Llano Uplift	10823	4 to 12	7 to 12	3 to 4	3	1 to Indet.	1 to 5	0
9. Rolling Plains								
a. Mesquite Plains	93854	1 to 6	1 to 3	3 to 7	4	1 to Indet.	6 to 10	0
b. Escarpment Breaks	11871	1 to 6	4 to 6	5 to 7	5	1 to Barren	11 to 15	0
c. Canadian Breaks	6248	1 to 6	4 to 6	5 to 8	7	1 to SV	11 to 15	0
10. High Plains	88311	1 to 6	1 to 3	5 to 14	7	1 to Indet.	11 to 15	0
11. Trans Pecos								
a. Mountain Ranges	6261	4 to NP	7 to 12	6 to 27	8	1 to Indet.	11 to 15	3
b. Desert Grassland	23071	1 to NP	7 to 12	6 to 32	8	1 to Indet.	11 to 15	0
c. Desert Scrub	44704	1 to NP	7 to 12	6 to 35	13	1 to Indet.	11 to 15	0
d. Salt Basin	824	7 to NP	NP	12 to 30	26	1 to Indet.	Barren	0
e. Sand Hills	6354	1 to 12	1 to 3	10 to 15	13	1 to Indet.	11 to 15	0
f. Stockton Plateau	14886	4 to 12	7 to 12	6 to 15	10	1 to Indet.	Indet.	0

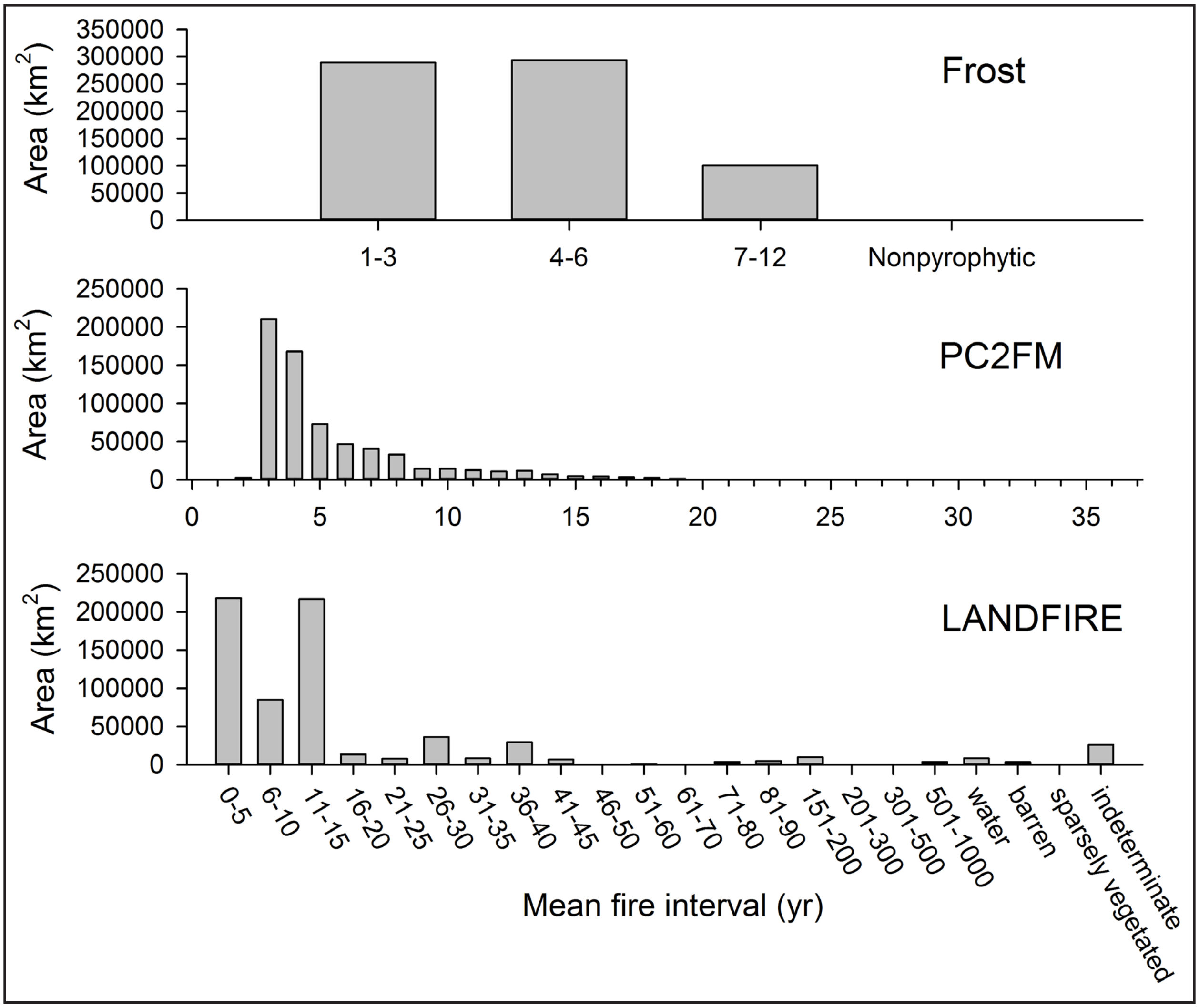

Figure 2. Bar charts of area covered by different mean fire intervals according to estimates by Frost, the PC2FM (Guyette *et al.* 2012), and LANDFIRE (Keane *et al.* 2002). Each estimate has a unique mean fire interval categorization.

fire return intervals of 1 yr to 5 yr (Mattoon 1922, Christensen 1981, Frost 2006). The majority of the longleaf pine communities in Texas are longleaf pine-bluestem (*Schizachyrium scoparium* [Michx.] Nash) savanna types; however, smaller areas of longleaf pine-shortleaf pine (*P. echinata* Mill.)-loblolly pine (*P. taeda* L.)-hardwoods transition types also occur (Frost 2006). A fire scar history study in a longleaf pine-bluestem savanna of south-central Louisiana indicated a mean fire return interval of 3.3 years for the pre-EAS period (1650 to 1793; Stambaugh *et al.* 2011*a*). In this study, fire scar evidence suggested a majority of late growing season fires with unique occasional biannual burning (i.e., two fires in one calendar year). Other longleaf pine fire scar studies from the Coastal Plain of Florida and Appalachian Mountains of Alabama indicate similarly short fire return intervals (Henderson 2006, Bale 2009).

The mixed-pine hardwood forest subregion primarily consists of shortleaf pine, loblolly pine, longleaf pine, and planted slash pine (*P. elliottii* Engelm.). Fire was an important historic disturbance to this region considering the presence of fire-adapted shortleaf and longleaf pines (Keeley and Zedler 1998). No studies describe historical fire regimes for the mixed pine-hardwood forest region and the nearest fire histories in pine-hardwood forests are in the Ozark Highlands of Arkansas and Oklahoma where fire return intervals were as short as 3 yr to 7 yr (Guyette *et al.* 2006, Stambaugh *et al.* 2013). In these studies, the majority of fires occurred during the dormant season. Considering the more southerly position and less topographically rough landscape of the mixed pine-hardwood forests in Texas, it can probably be assumed that fire frequencies were equally or more frequent than those in the Ozarks. More recent examinations of fire scars from the southern Ouachita Mountains of Oklahoma suggest a higher proportion of late-growing season fires than has been observed in the Ozarks (Stambaugh *et al.*, University of Missouri, Columbia, USA, unpublished data).

Oak Woods and Prairies. In the Oak Woodlands subregion, a recent fire scar history study at Purtis Creek State Park showed a historically frequent fire regime (Stambaugh *et al.* 2011*b*). From 1681 to 2005 (325 years), the MFI was 6.9 years. Prior to 1850, fire intervals ranged from 2 to 16 years with a MFI of 5.9 years. Based on tree demographics, there was no evidence of stand-replacing fire events during the period of record. Relatively severe fires, defined as those scarring >25 % of trees, occurred twice during the pre-1850 period. During the Civil War era, fire return intervals increased and coincided with a pulse of successful oak regeneration. Nearly all fires recorded at the site occurred when trees were dormant.

Currently, no quantitative information exists regarding the pre-EAS fire frequency in the Eastern and Western Cross Timbers subregion; however, frequent fire is considered an important agent to maintaining the Cross Timbers ecosystem (Engle *et al.* 1996), which extends from southeastern Kansas to central Texas (Francaviglia 2000). Dyksterhuis (1948) stated that early settlers of the Jacksboro vicinity recalled no shrubby undergrowth in the Western Cross Timbers, but instead a grassy understory that commonly burned during dry periods. They also stated that when the first white settlers arrived in the Western Cross Timbers fringe, Native Americans regularly burned the grass and had done so for years, perhaps even learning the practice from early Spanish settlers. Dyksterhuis (1948) described the uncertainty as to the pre-settlement fire regime of the Cross Timbers, but several early traveler accounts mentioned the incursion of adjacent prairie fires into the Cross Timbers as the mechanism for grassy understories and branch formations of the trees. A 1942 survey report conducted in the Trinity River watershed used fire scars to show that periodic fires were still occurring through the mid-twentieth century (Dyksterhuis 1948). Recently, several studies have described fire regimes in the Cross Timbers region of Oklahoma (Clark *et al.* 2007; Stambaugh *et al.* 2009, 2014; DeSantis *et al.* 2010; Allen and Palmer 2011) and all of these documented relatively frequent pre-EAS fire frequencies (3.3 to 12.3 years) and a preponderance of dormant season fire events. Stambaugh *et al.* (2014) indicated a greater potential for extensive and higher severity fires in historic versus modern times.

Blackland Prairies. As the southernmost extension of the tallgrass prairie, the Blackland Prairie subregion probably had a similar fire regime to other tallgrass prairie regions; however, the Blackland Prairie experiences higher temperatures (~10 ˚C higher annual average) and a longer growing season than the rest of the tallgrass prairie ecosystem, and its fire regime may have reflected these environmental differences (Smeins 1972). The Texas Parks and Wildlife Department[1] stated:

[1] Available at http://www.tpwd.state.tx.us/landwater/land/habitats/post_oak/

> *The Blackland Prairie and Post Oak Savannah landscapes were formed and maintained by two major forces: frequent fire and grazing of bison. Recurrent fires ignited either by lightning or humans (American Indian) were the major force that molded the prairie and savannah landscapes. These fires were typically very large in scale and would traverse the countryside until they reached landforms or conditions that would contain them (rivers, creek bottoms, soil change, topographical change, climatic change, or fuel change). Fire maintained these plant communities by suppressing invading woody species and stimulating growth of prairie grasses and forbs. Large herds of bison, sometimes as large as 1,000 animals, ranged the prairies and savannahs, where they would consume large quantities of grasses, trample organic matter, and then distribute seed into the disturbed soil. The grazing pressure was not continuous, however, and the large herds would move on allowing the range time to recover.*

Smeins (2004) cites two 1840s reports (Gregg 1844, Kendall 1845) that assert that frequent fires and large grazing animals were the primary influences on vegetation in the Grand Prairie and Cross Timbers regions in pre-settlement times. Considering the Blackland and Grand Prairie's positions between the oak-dominated Cross Timbers and Oak Woodlands, it is likely that their fire regimes are strongly related. Like the Cross Timbers and Oak Woodlands, it is likely that these large prairie subregions burned at least every 3 to 7 years and, with a dominance of grass surface fuels, the potential annual burning window of the prairies was likely larger, leading to an increased fire frequency.

Gulf Coast Prairies and Marshes. No quantitative information describing the historical frequency of fire was found for this region and subregions, though depictions of fire from historical accounts reveal information related to ignition source, fire use, and fire frequency. Pioneers and early explorers described large and frequent fires across the Texas Coastal Plain, and the cessation of fire has been suspected as the primary cause of woody plant expansion (Box *et al.* 1967). Alvar Nuñez Cabeza de Vaca, shipwrecked on Galveston Island in 1528, lived among the Native Americans and traveled throughout southeastern Texas. He reported that the Native Americans burned the coastal prairies for game management and insect control (Lehmann 1965). Lehmann (1965) compiled several early written accounts of fire in the coastal plains and prairies[2]. Numerous early travelers recounted Native American use of fire for game management, hunting purposes, insect control, warfare, and to discourage settlement of their hunting grounds (Bandalier 1905). Other expeditions recorded evidence of burnt-over landscapes. No specific frequency of fire was given for these early historical mentions of fire in the region, although it is generally inferred to be frequent. More is known about the early EAS era (early to mid-1800s), when prairies reportedly were burned twice per year (summer and winter) to improve forage for livestock or for other reasons (e.g., insect control, vandalism). Ilkin (1841) broadly stated that the "long dry grass of the prairies is twice a year (summer and winter) set on fire". Burning of the prairies is documented for longer than four centuries, and continued until fire exclusion policies began in the 1940s. Only suppositions can be made to distinguish how fire regimes may have differed between upland coastal prairies, dunes, and the estuarine zone. Within these areas, it is likely that fire frequency generally decreased with decreases in vege-

[2] Lehmann's (1965) research also applies to portions of the Brush Country region.

tation continuity, decreases in fuel production, and within permanently flooded sites.

Coastal Sand Plains. No quantitative information describing the historical frequency of fire was found for this region.

South Texas Brush Country. While no historical fire frequency was given, Johnston (1963) was able to confirm through early descriptions that the grasslands of Brush Country have experienced an increase in woody vegetation since pre-settlement times, and believed that removal of periodic fire was the most likely reason for the change. No quantitative information describing the historic frequency of fire was found for the Bordas Escarpment or Subtropical Zone subregions.

Edwards Plateau. Although little quantitative data exists of pre-settlement fire frequency, it is generally believed that frequent fires maintained the grasslands of the Edwards Plateau, specifically in the Live Oak-Mesquite (*Quercus virginiana* Mill.-*Prosopis* L.) Savanna (Humphrey 1962, Smeins *et al.* 1997). Humphrey (1962) cites several early observers (e.g., Bowman 1914, Bray 1904, Buechner 1944, Foster *et al.* 1917) who corroborate that the Edwards Plateau was maintained by periodic burning, and that woody species invasion occurred with fire cessation. Foster (1917) and Buechner (1944) specifically mention Native American burning as maintaining the Edwards Plateau as a treeless plain, although this description as "treeless" is contradictory to other early observations (Diamond 1997). Wright (1978) speculated that fires may have occurred in the Edwards Plateau at 20- to 30-year intervals based on the fire frequency that would prevent large Ashe juniper (*Juniperus ashei* J. Buchholz) trees from surviving. Other researchers have estimated that fires were more frequent, occurring at 10-year intervals or less (Wright and Bailey 1982, Wright 1988, Frost 1998, Paysen *et al.* 2000;). High variability in fire intervals is expected given the region's diverse topographic and edaphic-geological formations (Stambaugh and Guyette 2008). Fires were most common during late winter (February to March) and late summer (July to September) when grasses were either dormant or dry and lightning strike frequency is increased (Paysen *et al.* 2000).

In the Balcones Canyonlands subregion, pollen records from the last glacial maximum (18.6 24 k yr BP to 24 k yr BP) at Friesenhahn Cave indicate a dominance of grassland vegetation that lacked *Artemisia* spp. (Hall and Valastro 1995). Compared to modern shortgrass and tallgrass prairies, the Edwards Plateau also had less tree pollen (*Pinus, Juniperus, Quercus*) during these times. Amos and Gehlbach (1988) supposed fire may have been the most important, non-edaphic factor controlling vegetation patterns. Based on the ecology of Ashe juniper, Diamond *et al.* (1995) surmised that the exclusion of the species in pre-EAS times required relatively frequent surface fires with few crown fires. Although the authors provided information about the relative fire frequency and type during pre-EAS times (Table 1), no numbers were given. Drought may be as significant as fire with respect to influencing vegetation of the Edwards Plateau. During the severe and widespread 1949 to 1954 drought, tree mortality rates were elevated for many species (e.g., post oak [*Quercus stellata* Wangenh.], Nuttall oak [*Q. texana* Buckley, also known as Spanish oak], shinnery oak [*Q. havardii Rydb.*], Ashe juniper, and elms [*Ulmus* spp.]; Young 1956).

No mention of a fire regime specific to the Lampasas Cut Plains subregion was found; however, it is generally believed that the region was historically a grassland-open savanna and has changed post-EAS due to overgrazing by livestock and elimination of natural fires (Dillard *et al.* 2006). Reemts and Hansen (2008), working at Fort Hood within the Lampasas Cut Plains, state that the area was historically a complex of several vegetation communities, some fire dependent (e.g., prairies, oak savannas, oak-juniper woodlands) and others fire sensitive (e.g., riparian woodlands, floodplain forests).

Llano Uplift. No quantitative information describing the historical frequency of fire was found for this region.

Rolling Plains. Based on early descriptions of the "mesquite timber" and the known fire adaptive traits of honey mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*), it is clear that the Rolling Plains (i.e., Mesquite Plains) were affected by fire before EAS (Wright and Bailey 1982). Wright (1978) speculated that fires historically occurred every 20 to 30 years in the Rolling Plains. This estimate was based on historical documentation of the presence of large mesquite trees. This frequency was also supported by the findings of Steuter (1982), who showed that young redberry juniper (*Juniperus pinchotii* Sudw.), the primary woody invader of these grasslands, is fire intolerant for as long as 20 years under some conditions.

Fire scar history data from the Wichita Mountains in southwestern Oklahoma (Stambaugh *et al.* 2014) likely represent the closest quantitative source of historical fire information. Here, fire scars on post oaks resulted in historical (pre-1850) MFIs that varied from 6.3 to 12.3 years across four 1 km^2 study areas. Higher severity fires occurred during drought years and increased fire frequency corresponded with the Civil War period. Ninety-seven percent of the fire scars occurred during the dormant season, indicating that fires burned between the fall and spring seasons. No quantitative information describing the historic frequency of fire was found for the Escarpment Breaks or Canadian Breaks subregions.

High Plains. Pollen records from White Lake during the last glacial maximum indicated an *Artemisia*-dominated grassland with a high importance of composites (Hall and Valastro 1995). Based on early written descriptions of the High Plains and the high fire tolerance of honey mesquite, Wright and Bailey (1982) postulated that, before EAS, honey mesquite occurred frequently but with a low-growth form. Mesquite occurring in a shrubby growth form due to frequent burning was also described by Bartlett (1854) in his southwest borderlands explorations. This growth form was likely the result of the combined effects of fire, drought, grass competition, wildlife activity, and firewood collection. Despite conflicting historical accounts of exactly how prevalent mesquite was prior to EAS, it is accepted that it was a natural component of rangeland vegetation, and that densities have increased following cessation of fire (Paysen *et al.* 2000). Historically, wildfires in the High Plains were often large in size due to abundant and continuous fuels, conducive fire weather, and a lack of man-made fire breaks (Wright and Bailey 1982). Courtwright (2007) presents an in-depth review of historical fire accounts in the Great Plains, including those of west Texas, presumably the High Plains. Here, fires were frequent and largely caused by human ignitions prior to, during, and following EAS.

Trans Pecos. The Trans Pecos region is complex with regard to topography and natural subregions because mountain ranges express distinct assemblages of plants and animals. Historical fire regime characteristics of mountains may be comparable to those of "sky islands," whereby lightning ignitions are common and lower elevation desert lands act as fire breaks that isolate mountain range fire regimes, causing each to be unique (Swetnam *et al.* 2001). In the Mountain Ranges subregion, fire scars on Mexican piñons (*Pinus cembroides* Zucc.) at Big Bend National Park (Moir 1982) suggested that fires burned during intervals of approximately 11 to 71 years during the period 1800 to 1914. In a more recent study, piñon pine fire scar records from an approximate 4.5 km^2 area in Big Bend National Park indicated historical fire intervals ranged between 5 and 74 years (Poulos *et al.* 2009). The MFI for all fire scars was 19.4 years for the period between 1786 and 1913. In the same study, in a 35 km^2 area in the Davis Mountains, piñon pine fire scars revealed fire intervals that ranged from 4 to 27 years during the same period (Poulos *et al.* 2009). The MFI for all fire scars was 11.2 years. For both sites combined, 76.5 % of fire scars occurred in the dormant season. Piñon pine recruitment occurred during wet phases, particularly when fire occurrence was relatively low. In a more detailed report of these findings that also includes a site in Coahuila, Mexico, Camp *et al.* (2006) stated that MFIs prior to fire exclusion ranged from 7.2 to 7.7 years for fires that scarred ≥10 % of sample trees.

Fire scars from southwestern white pine (*Pinus strobiformis* Engelm.) (n = 119) and ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson) (n = 14) at Guadalupe Mountains National Park revealed a MFI of 4 years (range = 1 yr to 54 yr) for the period 1530 to 1990 (Sakulich and Taylor 2007). During the pre-EAS period (1700 to 1879), fires occurred on average every 2.7 years (range = 1 yr to 15 yr); this was followed by a lengthened MFI of 8.4 years (range = 5 yr to 13 yr) during the EAS period (1880 to 1922). The study found that fire occurrence was greatly reduced with the onset of ranching in the area around 1922. Fire scars indicated that most fires (91 %) occurred early in the growing season. Forest age structure and fire scar data also indicated that, historically, most fires were low or moderate in severity. Three distinct fire regimes were identified by the study: a regime of frequent, small fires before 1800; less frequent, larger fires after 1800; and, no fires after 1922. The shift in the fire regime circa 1800 may be explained by declines in Native American populations, land use changes such as grazing, or by climate change. Cessation of fire after 1922 coincided with the introduction of livestock grazing. The authors documented a shifting forest composition at the site, with higher density and greater presence of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) following the introduction of livestock grazing around 1922. They attributed recent high severity wildfires to this increase in forest density.

The Trans Pecos region lies within Bailey's (1996) larger Chihuahuan Semidesert Province where Kaib (1998) conducted extensive fire scar history investigations paired with human history and cultural fire use documentation in the Southwest Borderlands of Arizona and Mexico. According to Kaib (1998), from 1650 to 1880, riparian canyon pine-oak forests of the Southwest Borderlands had MFIs ranging from 3.1 to 4.6 years, upper-elevation mixed-conifer forests had MFIs ranging from 2.9 to 3.6 years, and desert grasslands had MFIs as frequent as 1.4 years. Within Texas, no written accounts of fire were found, and it is generally concluded that fires did occur but not as frequently as in other southwestern states. Wright (1980), in examining the effects of fire on semidesert grass-shrub vegetation, did not identify a pre-EAS fire frequency for southwestern Texas (i.e., Desert Grasslands subregion), but suggested that the desert grasslands burned less frequently than every 10 years. Generally, vegetation was mostly controlled by interactions among periodic droughts, grazing, wildlife activity, and fire. In a review of North American grasslands, Anderson (1990) concluded that the semidesert shrub grasslands were historically less frequently burned than other grassland types. While they did experience periodic fires, woody species were likely controlled by the interaction between fire, drought, and browsing animals, and recent expansion of woody species is due to both overgrazing by cattle and fire suppression.

No quantitative information describing the historical frequency of fire was found for the Desert Scrub, Salt Basin, Sand Hills, or Stockton Plateau subregions. Based on the sparsely vegetated conditions of these lands in comparison to adjacent grasslands, it is generally thought that fire disturbances were historically very infrequent or non-existent due to the non-pyrophytic landscape (Frost 1998).

Maps and Geodatabases

Pre-settlement fire frequency regimes of the United States. Frost (1998) classified the majority of natural regions of Texas as having MFIs dominated by 1 to 12 years (Figure 2). The southern portions of the Edwards Plateau (i.e., Balcones Canyonlands) and much of the Trans Pecos region had the most infrequent fire occurrence (MFI = 7 yr to 12 yr), while central and eastern Texas had the most frequent fire occurrence (MFI = 1 yr to 3 yr) (Table 1). Portions of west Texas (e.g., High Plains, Rolling Plains) and the Gulf Coast (e.g., southern Piney Woods, Gulf Coast Prairies and Marshes, Coastal Sand Plains) were also considered to have frequent fire regimes (i.e., MFI = 1 yr to 3 yr; Table 1, Figure 1). MFIs of regions at higher elevations (e.g., Trans Pecos, Llano Uplift, southern Edwards Plateau) are relatively infrequent.

Physical Chemistry Fire Frequency Model (PC2FM). Similar to Frost's map, the PC2FM depicted MFIs increasing from east to west (Table 1, Figure 1). The area covered by MFIs decreased exponentially with increasing MFI length (Figure 2). The shortest MFIs were predicted for the Blackland Prairies, Gulf Coast Prairies and Marshes, and Brush Country, while the longest intervals occurred in the Trans Pecos region (Desert Grassland, Desert Scrub, Salt Basin subregions). Because this model does not consider vegetation conditions in predictions, some areas that are sparsely vegetated were still predicted to have MFIs (i.e., burnable), whereas Frost's map and LANDFIRE may have used unburnable classifications (e.g., nonpyrophytic, indeterminate; Table 1) for these same areas. Similar to Frost's map, the PC2FM predicts relatively frequent MFIs (<10 yr) for the majority of the state (Figure 2).

LANDFIRE. The LANDFIRE National MFI map depicts frequent fire intervals (0 to 5 years) for large areas of the Blackland Prairies and Gulf Coast Prairies and Marshes regions (Table 1, Figure 2). Because of the finer resolution data, longer fire intervals are found within regions with a majority of frequent intervals (Table 1). LANDFIRE depicts much longer MFIs than the other sources in large areas of the southern Trans Pecos region (e.g., Mountain Ranges, Desert Scrub, Stockton Plateau; MFIs up to 501 to 1000 years). Overall, a wide range of MFIs is depicted in the Trans Pecos region. LANDFIRE, similar to Frost's map and the PC2FM, predicts the majority of the state to have MFIs of <16 yr (Figure 2).

DISCUSSION

As is common throughout much of the world, quantitative fire history data is limited. Because of this, in the future, it is likely that greater reliance will be placed on comparable data, maps, and geodatabases to obtain more complete and continuous spatial representation of fire regimes. For this reason, obtaining additional fire history data and conducting syntheses of multiple lines of evidence are valuable to validation and improvement of map and model estimates. Based on the existing fire scar chronologies in Texas and regions with comparable vegetation, much potential likely exists for obtaining fire history data in the Piney Woods, Oak Woods and Prairies, and forested mountain ranges of the Trans Pecos region. Even longer-term fire history information may be inferred from pollen and charcoal in sediments (Albert 2007). The former two regions have perhaps a heightened need for fire regime characterization as they correspond with the most densely populated portions of the state where fire risk can be high (e.g., 2011 Bastrop Complex Fire).

Both literature and maps suggest that the full range of fire frequencies found in North America occur in Texas. Some areas burned annually, some very infrequently, and a few arid areas nearly barren of fuel were devoid of fire. While quantitative data documenting Texas' historical fire regimes are severely limited (N = 4 studies), multiple sources of information indicate that, prior to EAS, the majority of lands in Texas burned at mean fire intervals of 1 to 12 years. In summary, work towards synthesizing fire regime information has resulted in a new comprehensive picture of Texas' (and many other regions) historical fire environment where fire was a primary environmental parameter, shaping a complex mosaic of natural communities from the Gulf Coast to the interior mountains.

Historically, fire intervals varied spatially and temporally as forced by climate and weather, ignitions, humans, and environmental conditions (e.g., fuels and topography) (Morgan *et al.* 2001). In addition to MFIs, scientists and land managers agree that variability in fire intervals is equally important to understanding fire regimes, fire effects, ecosystem responses, and fire management (Bergeron *et al.* 1998, Keane *et al.* 2009). Qualitative historical accounts of fire and vegetation in Texas provide observations of this complex variability and have strengths and limitations as descriptors of historical fire regimes (Swetnam *et al.* 1999, Ruffner 2006). Like historical accounts, quantitative fire interval maps and models, such as those reviewed here, also have limitations such as inability to display temporal variability, or too coarse to predict or simulate spatio-temporal variability. Regardless, models and maps of fire regimes have high utility and land managers find qualitative and quantitative fire regime information as a useful reference for many reasons (Morgan *et al.* 2001). Data that quantitatively can describe both spatial and temporal variability in fire (e.g., annual resolution fire event records across landscapes) are likely of highest value to managers who need to translate historical fire information into management contexts and adapt to different site conditions and constraints.

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