Chapter

Shifting Wildfire Trends and Management Implications for the Wildland Urban Interface in the Twenty-first Century

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Abstract

Anthropogenic climate change is projected to impact a significant proportion of ecosystems throughout the world. These shifts in climate are already impacting a diversity of wildland and urban ecosystems, and they are projected to increase wildfire frequency and severity in many regions. This projected increase is the result of the interaction of altered drought, precipitation, and temperature regimes. Understanding shifts in wildfire regimes is critical for managers at the wildland-urban interface that work to protect structures and human life. This chapter will explore how ongoing and future shifts in climate will drive alterations to natural fire regimes in the United States, with focus on implications for the wildland-urban interface.

Keywords: climate change, fire regime, urban-natural interface, wildfire

1. Introduction

Fire is a global phenomenon that has historically maintained the structure and function of a range of ecosystems. Many ecosystems are adapted to periodic fire events, known as fire regimes, that describe the interval and severity of fire in a particular system. However, human influences in the twentieth century have changed the frequency and severity of wildfire in many forested ecosystems and understanding these shifts of fire regimes has been a major topic of investigation for the past several decades. This research has elucidated the numerous, complex, and interactive environmental factors driving shifts in wildfire regimes. Annually, 450 mHa of the Earth surface is burned due to wildfire [1], and the severity of wildland fires across the US has increased since the 1980s [2]. This is important because as the size, severity, and frequency of fires have changed, their influence on human infrastructure has become more damaging and costly.

The wildland-urban interface (WUI) is the boundary where human civilization and unmanaged lands meet. Currently, this interface occupies over 770,000 km^2 in the US, and increases in area classified as WUI are driven by ongoing development that pushes urban environments further into wildland areas [3]. Increasing development into the WUI puts increasing numbers of structures, mainly residential homes, and human lives at risk to damage or loss via wildfire. Further, the infrastructure required by the WUI presents an additional source of ignitions in areas that are primed to burn. While trees exhibit traits of fire resistance [4, 5], houses, in particular older structures, burn with greater intensity and speed. For example, the 2018 Camp Fire in the Sierra Nevada of California burned quickly through the town of Paradise while leaving many standing trees scorched but not completely burnt. While this fire had many complex causes [6], the quick spread of the fire through the town was a reason that escape was made difficult despite a populous aware and prepared for the danger.

While these changes in fire regimes have exacerbated the damage in WUI, anthropogenic climate change is expected to intensify the risk by fire to WUIs. Across the US, climate change in the next century is projected to drive increases in wildfire severity in some areas, and increased wildfire incidence in other areas [7]. Shifts in wildfire patterns will be driven by shifts in precipitation timing and amounts, vegetation, temperature regimes, and drought conditions [8–11]. While changing climate patterns have been reasonably well characterized, wildfire regimes are more complex to predict due to the interconnected nature of the drivers and heterogeneous nature of ignition sources. It is critical to understand and provide more accurate predictions for shifts in wildfire frequency and severity, due to the loss of life, economic damage, related catastrophic environmental events, such as flooding or water quality damage. This is particularly important as human development into the wildland areas, which are more prone to wildfires, has increased significantly over the past half century.

2. Shifting wildfire regimes

Fire regimes integrate the tendency of vegetation to burn and the climate conditions that promote fire in a metric that describes the spatial and temporal nature of fire in a particular region. While there are several ways to calculate these metrics [12] a general calculation includes a measure of how frequently a fire occurs at a location (i.e., the average fire return interval) and the effect that fire has on vegetation (i.e., the severity of the fire). Variability in fire regimes is driven by differences in elevation, vegetation life history, drought and precipitation patterns, land-use, among other ecosystem-specific parameters [13, 14]. Many animal and plant species have co-evolved with fire and are adapted to specific fire regimes [15]. Some denser-growing vegetation species are adapted to higher severity and stand-replacing burns, such as in the Northern Rockies, while other species are more adapted to lower and more moderate severity burns, such as in the southern Sierra Nevada.

The inherent complexity and spatial heterogeneity of fire regimes make it difficult to make general recommendations for fire management [15]. However, the implications of an expanding WUI and increasing trends of fire activity indicate a clear problem for fire management. This is compounded by the possibility that fire regimes may shift over time in response to anthropogenic driven changes in management, vegetation composition and density, and climate [16, 17].

2.1 History of fire regimes in the US

Historically, fire regimes were mostly driven by an ecosystem's vegetation, climate conditions, and human activities, which varied both spatially and temporally over the US. In the Northern Rocky Mountains, stand replacing fires are typical in pine forests of the region [18, 19]. Fires in this ecosystem occur at relatively low frequency (longer return intervals), but when they do occur, they can burn large areas of forest ecosystems at high severity, e.g., the Yellowstone fire in 1988 [20–22].

In contrast, low-intensity fires occurred more frequently in the southwestern forests of New Mexico and Arizona, due to the dry and warm semi-arid climate and tree species that exhibited resistance to fires (e.g., *Pinus ponderosa*). Much of the southeast was historically occupied by longleaf pine (*Pinus palustris*, **Figure 1A**), which thrives in high frequency, low burn severity fire regimes [23]. Pre-European settlement, longleaf pine forests were managed by Native American populations, and post-settlement there was a significant decline in the land area of these forests [24]. Currently, they are managed via frequent prescribed fire and are often grown to produce pine straw [25]. While wildfires have been major drivers of the American landscape, natural ecosystems are continually adapting to fire regimes over time in response to shifts in vegetation, management, and climate. However, human activities, management, and climate change are also driving the interaction between fire and vegetation over the past several centuries.

The shift in fire regimes in the Sierra Nevada is an example of the interactive effects of human management and climate change. Prior to Euro-American settlement, natural lighting strikes and fire activities by Native Americans were the main causes of fire ignitions in the Sierra Nevada [26]. Forests were burned with mixed-severity fires that included both light to moderate burning of understory and crown fires at the interval of a decade or two. The small trees and ground fuels were killed and cleaned in fires periodically, leaving patches of large, mature trees that are more resistant to wildfires due to thick bark that is hard to burn, preventing fire from spreading to the canopy [4, 5]. However, a combination of human influences changed the structure of these forests and made them more susceptible to frequent fires that spread through canopies. Early twentieth century logging practices preferentially selected for these larger trees, opening up space for denser thickets of small trees to colonize, leading to increases in forest density [27]. This change in structure was reinforced by widespread suppression of fires that historically cleared out undergrowth. Since the early twentieth century, fire suppression as a forest management technique was widely adopted after several large and severe wildfires

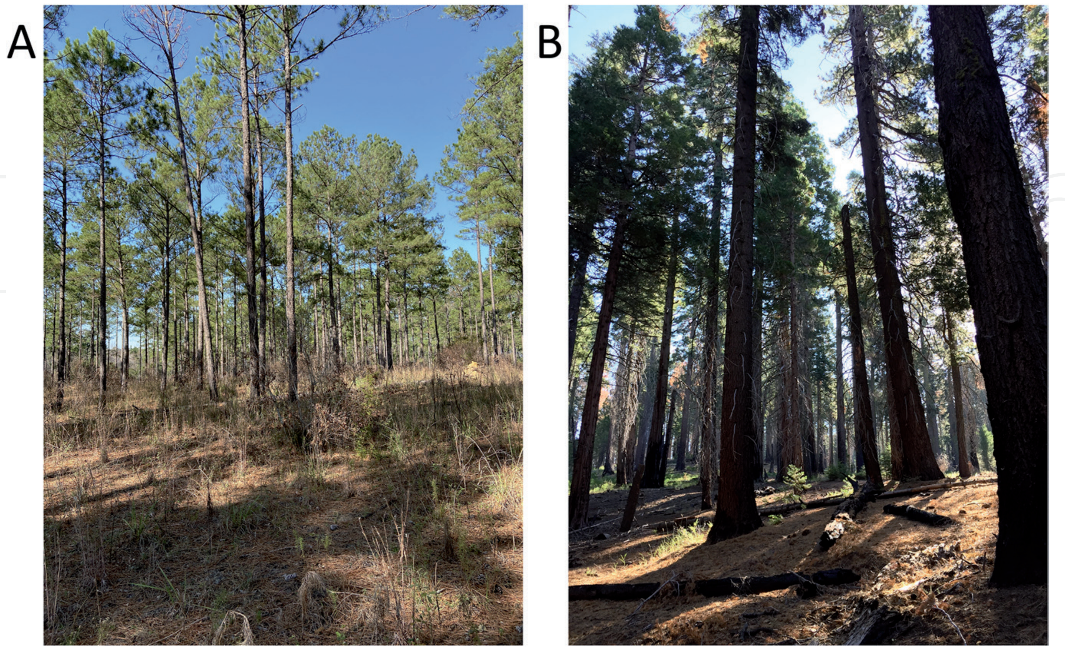

Figure 1.
*Fire severity is in part controlled by the density of the fuels and fire return interval. In photo A, loblolly pine (*Pinus palustris*) plantation in Georgia is managed for pulpwood production with prescribed fire approximately every 3 years. This low severity, high frequency fire regime maintains an open canopy and low-density fuels. In photo B, a conifer forest in Yosemite National Park one-year post recovery after the Rim Fire. All photos are © R. Abney.*

in the Northern Rockies that killed many and destroyed a number of settlements. The fire suppression efforts were successful in excluding low-severity fires, and this management strategy reduced the fire frequency to the lowest frequency measured in the past 3000 years [28]. Consequently, the accompanying densification of forests due to the fire deficit has contributed to increasing numbers of devastating fires in late twentieth and twenty-first centuries [29]. This shift in fire regimes is the result of combined factors including (1) the reduction of regular fire usage, which were regularly conducted by Native Americans to reduce fuel loads and to encourage culturally important vegetation [30]; (2) legacy of decades of fire-suppression that densified undergrowth which lead to increased spread of fire; (3) removal of large trees, which are resilient to low-to-medium fires, due to industrialized timber logging; (4) the disappearing of gaps among trees, which could have stopped fire from spreading, but were filled with smaller and denser trees that can easily act as continuous fuel sources and (5) species change from those with fire adverse traits, to shade-tolerant ones [31]. The current fire regime that includes more high-severity, large fire size, is a significant challenge to forest managers and is a critical risk to the safety of human life and development in the WUI.

2.2 Drivers of wildfire change

Drivers of wildfire include three main categories: regional climate, fuel availability and condition, and ignition sources. In areas of low fuel density, sources of ignition drive fire occurrence; however, in higher population density areas, such as the WUI, fuel availability drives fire occurrence [32]. Climate influences fire occurrence by the timing and amount of precipitation, temperature, and wind speed. Wildfire season starts when all these climate features reach their thresholds. The intensity of drought and strength of wind as well as the length of wildfire season is highly related to the severity and risk of wildfires. Westerling et al. [17] found that an extended fire season, resulting from earlier spring warming and extended drought in late fall, increased the fire frequency and severity in the Western US. This trend is predicted to continue as climate gets warmer and drier with ongoing climate change [7]. In the eastern US, precipitation and temperature patterns form a different climate, and thus different fire seasons than the western US. Southwestern forests are influenced by late-summer precipitation stemming from the North American monsoon that end fire-season earlier in the year. The pacific north-west and the Northern Rockies are routinely colder and wetter, thus interannual fire season lengths are short in general.

The available fuel load in part determines the extent of wildfire, including what and how much can be burned. In areas with limited fuel loads, such as the shrubland and grassland in Southwestern US, fires can occur frequently but are usually low-severity burns. High severity burns often occur in forests with large and dense biomass, which can provide plentiful fuel sources for wildfires. The spatial continuity of fuels also plays a critical role in shifts in fire regimes. The combination of large trees and clearings in forest floor vegetation in historical frequent-fire Western forests constrained the spread of crown fires. Examples of this are found in ponderosa or giant sequoia groves. However, effective fire suppression until the 1980s has reduced the number of surface fires that would have removed the ground and understory fuels periodically. Small trees and undergrowth filled the gaps between trunks and created continuous fuels that could carry flames to tree crowns, which has in part lead to higher severity and larger fires in the Western US that are currently observed [33] (**Figure 2**). Thus, forest and fire management can change fire regimes by changing the quantity and structure of fuels.

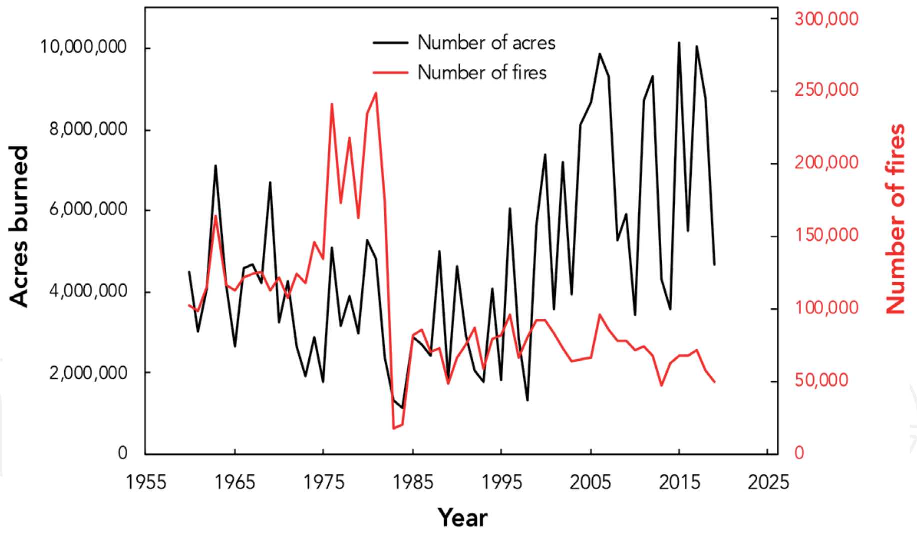

Figure 2.
The number of fires and land area burned in wildlands. Data are from the National Interagency Fire Center [2]. The number of fires has remained relatively constant since the 1980s, but the land area burned has increased, indicating that fires are becoming larger and more catastrophic.

Ignitions are a critical factor of wildfire regimes. Before the European settlement, lightning and Native American activities were the sources of ignition. As populations and permanent infrastructure expanded in the past century, sources of ignitions diversified, particularly in the WUI. While lightning is still an ignition source of large, severe wildfires in areas of lower population density such as in boreal forests and at higher latitudes [29], more fires are ignited by Anthropogenic sources, particularly as the WUI expands, such as sparks from power lines [34], accidental flares from camping fires [35], and deliberate arson [36].

The interactions among the three factors can change fire regimes in a positive feedback cycle. In areas with low population and human activities, sources of fire ignition increase fire occurrence, but in areas with high population density and frequent human activities, fuel availability drives the fire regime. In the meanwhile, shifts in climate can either increase or decrease the probability of fire occurrences in addition to the other two drivers.

2.3 Shifts in wildfire management

Prior to Native American settlement of North America, wildfires were unmanaged, and their severity and frequency were a result of the available fuel load and local climatic factors, namely precipitation, temperature, and drought conditions [37, 38]. North America was settled approximately 14,000 years ago [39], and there is considerable evidence for management of landscapes by Native Americans [40]. The exact magnitude of Native American burning is difficult to determine, due to methodological limitations in reconstructing historic fire frequencies [41], but the available evidence suggests that Native Americans utilized low severity burns in order to maintain prairie habitats and encourage growth of vegetation for cultural usage [40, 42]. The reconstructed fire record of the western US suggests that much of the pre-European settlement wildfire regime was primarily dictated by large-scale climate patterns, rather than via human influence [28].

Around the turn of the twenty-first century, policies were introduced to encourage fire suppression, mainly wildland firefighting, in part as a response to fires in the Northern Rockies in 1910 and as a means to protect timber resources and human

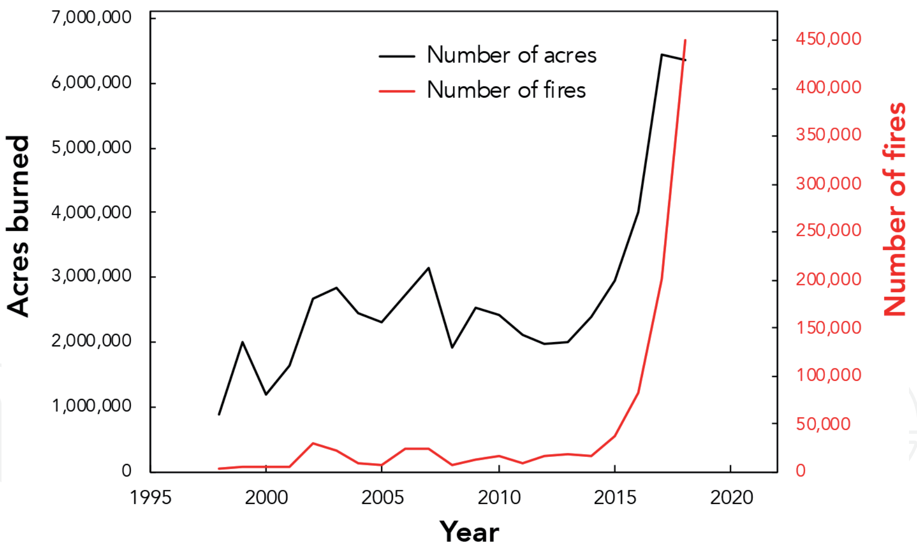

Figure 3.
Number of prescribed fires and acres burned in the United States from 1997 to 2018, data from the National Interagency Fire Center.

settlements [43, 44]. These policies generally did not consider fire suppression via other management strategies (e.g., fuel load reductions, prescribed burning), which led to a significant increase in the density of American forests [43].

In the past several decades, scientific research indicated the role that fires play in natural ecosystems in shaping ecosystem dynamics, but also to prevent the large fuel loading that results in larger, more severe wildfires. Following this research and shifts in political perspectives, recent changes in legislation, namely the Healthy Forests Initiative (2002) and the Healthy Forests Restoration Act (2003) [44], have allowed for more prescribed burning (**Figure 3**). This rapid increase in the use of prescribed fire across the US is likely to lead to a shift back towards a more natural fire regime in some areas, although it is unlikely that the magnitude of prescribed burning would approach the extent of what would naturally occur.

Prescribed burning has been widely adopted in the southeastern US, which in recent decades has led to a decrease in wildfires, with some exceptions in drought years [45]. In the western US, prescribed burning has been slower to be more widely adopted as a management strategy due to a number of factors, including the larger proportion of public lands, more restrictive legislation, and concerns about emissions and air quality [46]. Across the US, considerable public weariness of prescribed fire has also been a major barrier to its widespread use [46], due to concerns about control of the burns and air quality.

2.4 Predictions for future wildfire regimes

Projections for future wildfire regimes indicate that some areas of the US will experience larger and more severe wildfires, while other areas will experience fewer and less severe wildfires. The accuracy of these projections will in part depend upon management techniques within fire-prone ecosystems, including the use of prescribed burning vs. fire suppression [16]. In their recent study, Parks, Miller [16] project significant decreases in wildfire severity in the western US, which they attribute to changes in fuel loads into the twenty-first century and water deficit conditions. In the southeastern US, projections indicate a slight increase in area burned, with considerable variability across different states [47].

3. Wildfire in the wildland-urban interface

The major concerns of wildfire in the WUI are the risk to human life, structures, and economic productivity. The WUI comprises 9% of the land in the US, which equates to 39% of all housing units [48]. Prior development increased the proportion of land classified as a WUI from 1970 to 2000 by 52%, with future projections for ongoing increases in WUI lands [49].

One major consideration for management of wildfire risk at the WUI is understanding the drivers of shifts in wildfire regimes into the future. Some modeling work has predicted that shifts in fire regimes into the future will be more significant for wildfire occurrence at the WUI than expansion of WUI development [50]. However, with increasing areas classified as WUI, there are also increasing ignition sources for wildfires and developed lands that could suffer wildfire damage [3]. Some modeling work has shown that whether a residence has fire proofing, and the density of surrounding homes and vegetation all interact to control the severity and size of wildfire [51].

3.1 Current and shifting attitudes towards fire in the wildland-urban interface

Understanding attitudes concerning wildfire management at the WUI has drawn considerable research attention, because frequently public perception of the use of wildfire management techniques prevents their use [52–54]. Some of the major concerns are related to the cost of implementation of the management technique and direct impacts during implementation, such as decreased air quality during prescribed fire, and drawbacks of particular fire management techniques, including costs [53, 54]. Public attitudes towards wildfire management at the WUI also depend upon local factors, including previous wildfire management strategies employed, trust in local agencies responsible for managing wildfire risk, and individual attitudes towards the management techniques [53, 55, 56].

3.2 Public awareness of shifting climates at the wildland urban interface

As development has continued into the wildland-urban interface over the past several centuries, wildfire severity has increased [40]. Recent research has indicated that some populations are aware that future shifts in climate may lead to increased risk of wildfire and related property damage [57]. However, public perceptions of climate change have not significantly shifted in the past several decades, except along some partisan divides [58]. Regardless of public awareness of shifting wildfire risk into the future, areas of increased risk are facing increased insurance premiums and rates, as they already have in California [59].

4. Management of wildfire in the wildland-urban interface

4.1 Current strategies for managing wildfire at the wildland-urban interface

The main historic and current strategy to reduce the risk of wildfire has been fuel reduction [3, 54]. In wildlands, prescribed fire, allowing natural fires to burn within designated boundaries, and mechanical treatments, such as thinning or mastication, are the main strategies that have been successfully used to reduce wildfire frequency and severity [60]. There is a need to develop or re-develop the natural fire regime, or shift towards a more frequent, lower intensity fire regime, particularly in the Western US [40].

Land managers of ecosystems that are highly prone to wildfire at the WUI will likely need to undertake a proactive management approach to protect human safety and infrastructure in the WUI [40]. A commonly utilized strategy at the WUI is the establishment of a "defensible space" around residences and other properties, which reduces vegetation and other burn hazards adjacent and up to 30 m away from buildings [61]. Buildings can also be constructed of combustion-resistant materials, although this strategy is more effective when combined with defensible space [62].

4.2 Recommendations for strategies in consideration of future climate and fire regimes

While many strategies have been identified to manage forests at the wildland-urban interface, they have not been widely adopted due to a combination of factors, including lack of funding and political willpower [63]. Current research has indicated the effectiveness of utilizing prescribed fire to reduce the frequency and severity [45]. Expanded and more frequent use of prescribed fire and other fuel reduction techniques in the WUI can serve to protect infrastructure from more catastrophic wildfire and act to re-establish a historic wildfire regime.

One of the major barriers to increasing use of fuel reduction management strategies is public perception of both the use of these techniques and the increased risk of wildfire with ongoing climate change. Future management strategies should continue to include strategies for managing public perception to increase acceptance and participation in fuel management at the WUI and to increase understanding of the diverse factors involved in managing forests for both prescribed fire and wildfire events [64]. Additionally, these strategies should continue to focus on informing the public about the efficacy of defensible spaces and improve development planning to ensure greater accessibility, improved use of defensible space, and better building design [61].

4.3 Future research and ongoing uncertainty

There is considerable current and ongoing research focused on enhancing fire condition predictors and managing strategies related to reducing the severity and frequency of wildfires [16, 17, 65, 66]. Ongoing research in refining future climate predictions will generate considerably more certainty to predictions for future fire regimes. However, work in the area should focus more on the dynamics of wildfire at the WUI due to the critical resources that are at risk in those areas.

Many of the obstacles to implanting these management strategies are political in nature, with responsibility falling to local governments operating under limited funding and variable community support [63]. Some recent research has indicated that local differences in legal liability for prescribed burning lead to significant differences in the amount of land burned via prescribed fires [67]. While features of landscapes that make them prone to wildfire have been reasonably well-described, future research on mitigating the effects of wildfire in the WUI should consider the human dimension to management decision making [46]. Historically, human management has driven much of the increase in wildfire severity, and into the future, there will be a need for management strategies that reconcile natural fire regimes with protection of human life and property at the WUI.

5. Conclusions

Modern fire regimes are largely driven by anthropogenic activities and widely differ from pre-European and pre-Native American wildfire regimes. In the coming decades and century, projected climate shifts will drive corresponding shifts in wildfire occurrence and severity, with differing projections for different regions of the US. Development in the WUI needs to be informed for how to manage local shifts in wildfire regimes to mitigate the impacts of severe wildfire, and some of the ability of an area to respond is related to public perception of the risks of wildfire.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Randerson JT et al. Global burned area and biomass burning emissions from small fires. Journal of Geophysical Research – Biogeosciences. 2012;**117**:G04012. DOI: 10.1029/2012JG002128

[2] National Interagency Fire Center. National Report of Wildland Fires and Acres Burned by State. 2015. Available from: https://www.nifc.gov/fireInfo/fireInfo_statistics.html [cited 06 May 2015]

[3] Radeloff VC et al. Rapid growth of the US wildland-urban interface raises wildfire risk. Proceedings of the National Academy of Sciences. 2018;**115**(13):3314-3319

[4] Staver AC et al. Thinner bark increases sensitivity of wetter Amazonian tropical forests to fire. Ecology Letters. 2020;**23**(1):99-106

[5] Vines R. Heat transfer through bark, and the resistance of trees to fire. Australian Journal of Botany. 1968;**16**(3):499-514

[6] Melo RTM. We didn't start the fire... did we? Analyzing why California cannot seem to extinguish its worsening wildfire problem. Villanova Environmental Law Journal. 2020;**31**(1):5

[7] IPCC. In: Stocker TF, Qin D, editors. Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers. 2013

[8] Fried JS, Torn MS, Mills E. The impact of climate change on wildfire severity: A regional forecast for northern California. Climatic Change. 2004;**64**(1-2):169-191

[9] Harrison SP, Marlon JR, Bartlein PJ. Fire in the earth system. In: Changing Climates. Earth Systems and Society. Netherlands: Springer; 2010. pp. 21-48

[10] Marlon JR et al. Long-term perspective on wildfires in the Western USA. In: Proceedings of the National Academy of Science; 2012

[11] Torn MS, Mills E, Fried J. Will climate change spark more wildfire damage. Confronting Climate Change In California. Berkeley, CA: Lawrence Berkeley National Laboratory; 1998. LBNL-42592

[12] Gill AM, Allan G. Large fires, fire effects and the fire-regime concept. International Journal of Wildland Fire. 2009;**17**(6):688-695

[13] Swetnam TW, Baisan CH. Historical fire regime patterns in the southwestern United States since AD 1700. In: Fire Effects in Southwestern Forests: Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico; 1994

[14] Frost CC. Presettlement fire frequency regimes of the United States: A first approximation. In: Fire in Ecosystem Management: Shifting the Paradigm from Suppression to Prescription. Tall Timbers Fire Ecology Conference Proceedings; 1998

[15] Noss RF et al. Managing fire-prone forests in the western United States. Frontiers in Ecology and the Environment. 2006;**4**(9):481-487

[16] Parks SA et al. How will climate change affect wildland fire severity in the western US? Environmental Research Letters. 2016;**11**(3):035002

[17] Westerling AL et al. Warming and earlier spring increase western

US forest wildfire activity. Science. 2006;**313**(5789):940-943

[18] Hutto RL. Composition of bird communities following stand-replacement fires in northern Rocky Mountain (USA) conifer forests. Conservation Biology. 1995;**9**(5):1041-1058

[19] Arno SF. Forest fire history in the northern Rockies. Journal of Forestry. 1980;**78**(8):460-465

[20] Christensen NL et al. Interpreting the Yellowstone fires of 1988. Bioscience. 1989;**39**(10):678-685

[21] Elfring C. Yellowstone: Fire storm over fire management. Bioscience. 1989;**39**(10):667-673

[22] Romme WH, Despain DG. Historical perspective on the Yellowstone fires of 1988. Bioscience. 1989;**39**(10):695-699

[23] Frost C. History and future of the longleaf pine ecosystem. In: The Longleaf Pine Ecosystem. New York, NY: Springer; 2007. pp. 9-48

[24] Van Lear DH et al. History and restoration of the longleaf pine-grassland ecosystem: Implications for species at risk. Forest Ecology and Management. 2005;**211**(1-2):150-165

[25] Haywood JD. Influence of pine straw harvesting, prescribed fire, and fertilization on a Louisiana longleaf pine site. Southern Journal of Applied Forestry. 2009;**33**(3):115-120

[26] Pyne S, Vale TR. Fire, native peoples, and the natural landscape. Restoration Ecology: Book Review. 2003;**11**(2):257-259

[27] Naficy C et al. Interactive effects of historical logging and fire exclusion on ponderosa pine forest structure in the northern Rockies. Ecological Applications. 2010;**20**(7):1851-1864

[28] Marlon JR et al. Long-term perspective on wildfires in the western USA. Proceedings of the National Academy of Sciences. 2012;**109**(9):E535-E543

[29] National Interagency Fire Center. Prescribed Fires and Acres by Agency. 2018. Available from: https://www.nifc.gov/fireInfo/fireInfo_statistics.html [cited 28 August 2018]

[30] Stewart OC. Forgotten Fires: Native Americans and the Transient Wilderness. Norman, OK: University of Oklahoma Press; 2002

[31] Earles JM, North MP, Hurteau MD. Wildfire and drought dynamics destabilize carbon stores of fire-suppressed forests. Ecological Applications. 2014;**24**(4):732-740

[32] Guyette RP, Muzika R-M, Dey DC. Dynamics of an anthropogenic fire regime. Ecosystems. 2002;**5**(5):472-486

[33] Hurteau MD et al. Climate change, fire management, and ecological services in the southwestern US. Forest Ecology and Management. 2014;**327**:280-289

[34] Mitchell JW. Power lines and catastrophic wildland fire in southern California. In: Proceedings of the 11th International Conference on Fire and Materials. Citeseer; 2009

[35] Lydersen JM, North MP, Collins BM. Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. Forest Ecology and Management. 2014;**328**:326-334

[36] Prestemon JP, Butry DT. Wildland arson: A research assessment. In: Pye JM, Rauscher HM, Sands Y, Lee DC, Beatty JS, editors. Advances in Threat

Assessment and Their Application to Forest and Rangeland Management. Gen. Tech. Rep. PNW-GTR-802. Vol. 802. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest and Southern Research Stations; 2010. pp. 271-283

[37] Whitlock C, Shafer SL, Marlon J. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. Forest Ecology and Management. 2003;**178**(1-2):5-21

[38] Pausas JG, Paula S. Fuel shapes the fire–climate relationship: Evidence from Mediterranean ecosystems. Global Ecology and Biogeography. 2012;**21**(11):1074-1082

[39] Haynes G, Gary H. The Early Settlement of North America: The Clovis Era. Cambridge, England: Cambridge University Press; 2002

[40] Hessburg PF, Agee JK. An environmental narrative of inland Northwest United States forests, 1800-2000. Forest Ecology and Management. 2003;**178**(1-2):23-59

[41] Baker WL, Ehle D. Uncertainty in surface-fire history: The case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research. 2001;**31**(7):1205-1226

[42] Gruell GE. Fire on the early western landscape: An annotated record of wildland fires 1776-1900. Northwest Science. 1985;**59**(2):97-107

[43] Busenberg G. Wildfire management in the United States: The evolution of a policy failure. Review of Policy Research. 2004;**21**(2):145-156

[44] Johnson JF, Bengston DN, Fan DP. US policy response to the wildfire fuels management problem: An analysis of the news media debate about the Healthy Forests Initiative and the Healthy Forests Restoration Act. Journal of Environmental Policy & Planning. 2009;**11**(2):129-142

[45] Addington RN et al. Relationships among wildfire, prescribed fire, and drought in a fire-prone landscape in the South-Eastern United States. International Journal of Wildland Fire. 2015;**24**(6):778-783

[46] Ryan KC, Knapp EE, Varner JM. Prescribed fire in North American forests and woodlands: History, current practice, and challenges. Frontiers in Ecology and the Environment. 2013;**11**(s1):e15-e24

[47] Prestemon JP et al. Projecting wildfire area burned in the South-Eastern United States, 2011-60. International Journal of Wildland Fire. 2016;**25**(7):715-729

[48] Radeloff VC et al. The wildland–urban interface in the United States. Ecological Applications. 2005;**15**(3):799-805

[49] Theobald DM, Romme WH. Expansion of the US wildland–urban interface. Landscape and Urban Planning. 2007;**83**(4):340-354

[50] Liu Z et al. Climate change and wildfire risk in an expanding wildland–urban interface: A case study from the Colorado front range corridor. Landscape Ecology. 2015;**30**(10):1943-1957

[51] Spyratos V, Bourgeron PS, Ghil M. Development at the wildland–urban interface and the mitigation of forest-fire risk. Proceedings of the National Academy of Sciences. 2007;**104**(36):14272-14276

[52] Gill AM, Stephens SL. Scientific and social challenges for the management of fire-prone wildland–urban interfaces. Environmental Research Letters. 2009;**4**(3):034014

[53] Winter G, Fried JS. Homeowner perspectives on fire hazard, responsibility, and management strategies at the wildland-urban interface. Society & Natural Resources. 2000;**13**(1):33-49

[54] Winter GJ, Vogt C, Fried JS. Fuel treatments at the wildland-urban interface: Common concerns in diverse regions. Journal of Forestry. 2002;**100**(1):15-21

[55] Winter G, Vogt C, McCaffrey S. Residents Warming up to Fuels Management: Homeowners, Acceptance of Wildfire and Fuels Management in the Wildland-Urban Interface. The public and Wildland Fire Management: Social Science Findings for Managers. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station; 2006. pp. 19-32

[56] McCaffrey S et al. Social science research related to wildfire management: An overview of recent findings and future research needs. International Journal of Wildland Fire. 2013;**22**(1):15-24

[57] Schulte S, Miller KA. Wildfire risk and climate change: The influence on homeowner mitigation behavior in the wildland–urban interface. Society and Natural Resources. 2010;**23**(5):417-435

[58] Egan PJ, Mullin M. Climate change: US public opinion. Annual Review of Political Science. 2017;**20**:209-227

[59] Dixon LS. Insurance for Wildfire Risk in California. RAND; 2018. CT-499 Testimony presented before a joint meeting of the California State Assembly and California State Senate Committees on Insurance on October 30, 2018

[60] Mell WE et al. The wildland–urban interface fire problem–current approaches and research needs. International Journal of Wildland Fire. 2010;**19**(2):238-251

[61] Syphard AD, Brennan TJ, Keeley JE. The role of defensible space for residential structure protection during wildfires. International Journal of Wildland Fire. 2014;**23**(8):1165-1175

[62] Syphard AD, Brennan TJ, Keeley JE. The importance of building construction materials relative to other factors affecting structure survival during wildfire. International Journal of Disaster Risk Reduction. 2017;**21**:140-147

[63] Stephens SL et al. Managing forests and fire in changing climates. Science. 2013;**342**(6154):41-42

[64] Dupéy LN, Smith JW. An integrative review of empirical research on perceptions and behaviors related to prescribed burning and wildfire in the United States. Environmental Management. 2018;**61**(6):1002-1018

[65] Pechony O, Shindell DT. Driving forces of global wildfires over the past millennium and the forthcoming century. Proceedings of the National Academy of Sciences. 2010;**107**(45):19167-19170

[66] Stephens S, Moghaddas J. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management. 2005;**215**(1-3):21-36

[67] Wonkka CL, Rogers WE, Kreuter UP. Legal barriers to effective ecosystem management: Exploring linkages between liability, regulations, and prescribed fire. Ecological Applications. 2015;**25**(8):2382-2393