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Wildfire Risk and Hazardous Fuel Reduction Treatments Along the US-Mexico Border: A Review of the Science (1986-2019)

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ABSTRACT: The ecosystems along the border between the United States and Mexico are at increasing risk to wildfire due to interactions among climate, land-use, and fuel loads. A wide range of fuel treatments have been implemented to mitigate wildfire and its threats to valued resources, yet we have little information about treatment effectiveness. To fill critical knowledge gaps, we reviewed wildfire risk and fuel treatment studies that were conducted near the US-Mexico border and published in the peer-reviewed literature between 1986 and 2019. The number of studies has grown during this time in warm desert to forest ecosystems on primarily federal lands. The most common study topics included fire effects on native species, the role of invasive species and woody encroachment on wildfire risk, historical fire regimes, and remote sensing and modeling to study wildfire risk across the landscape. A majority of fuel treatment studies focused on prescribed burns, and fuel treatments collectively had mixed effects on mitigating future wildfire risk and threats to ecosystems depending on vegetation and fire characteristics. The diversity of ecosystems and land ownership along the US-Mexico border present unique challenges for understanding and managing wildfire risk, and also create opportunities for collaboration and cross-site studies to promote knowledge across broad environmental gradients.

KEYWORDS: Arid lands, invasive species, mechanical treatments, prescribed fire, southwestern United States, woody encroachment

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Introduction

The border region between the United States and Mexico contains desert scrub to montane forest ecosystems with different wildfire histories due to variation in their climates, topographic features, fuel loads, and land-uses.[1,2] Over the past several decades, fire suppression, woody plant encroachment, spread of non-native invasive species, and aridification have interacted to increase wildfire frequency and severity.[3-5] High fuel loads and catastrophic wildfire threaten human life and infrastructure, degrade wildlife habitat, and imperil natural and cultural resources.[6] Fuel treatments that include prescribed fire, managed wildfire, mechanical fuel reduction, herbicide application, and livestock grazing have been historically implemented throughout the border region to reduce wildfire risk, improve ecosystem condition, and increase the safety and security of border operations. A recent example of these efforts is the Southern Border Fuels Management Initiative, which was initiated in 2017 to conduct fuel treatments across 1,300 kilometers of Department of the Interior (DOI) lands along the US-Mexico border.[7]

Despite large investments in fuel treatments, our knowledge about the effectiveness of treatments to reduce fuel loads, mitigate wildfire risk, and improve ecosystem health remains limited. Enhanced understanding about treatment effectiveness and resulting changes to wildfire risk and ecosystem condition can improve future efforts in face of a growing wildfire threat in the coming decades. We addressed this important information gap by conducting a literature review of fuel treatment and wildfire risk studies in ecosystems that occur along the US-Mexico border over the past 34 years. The goal of our review was to determine (1) when and where along the border wildfire and fuel treatment studies have taken place, and (2) the current state of knowledge on wildfire and fuel treatments along the border and important information gaps that can be filled with future research.

Methods

In January 2020, the lead author searched the Web of Science Core Collection from the years 1986 to 2019 using a combination of terms that included locations and ecosystems near the US-Mexico border, along with keywords such as "fire" and "risk." While the US-Mexico border region is often defined by an area that covers 100 km in either direction from the international border,[8] we included studies if they occurred within an ecosystem that fell within this area, but the study site was geographically further away. To find studies that examined fuel treatments, keywords such as "fuel* treatment*," "prescribed fire," "mechanical thinning," "mastication," and "herbicide" were included. Studies were excluded if they were conducted in regions outside the southwestern United States and northern Mexico or if their focus was not on relevant ecosystems or fire-related topics. Sixty different keyword searches were initially performed, but only 19 searches returned 90 useable studies published in peer-reviewed papers selected for this review.

Selected studies were categorized by the year of publication, location, ecoregion, land ownership, topic of study, and fuel treatments used where the study took place. We mapped the locations of the studies using information available from coordinates, figures, or written descriptions. We calculated the number of studies in each category relative to the total number of studies and summed the number of publications that occurred in 5-year intervals from 1986 to 2019. We extracted and summarized relevant information from the studies by topic, which fell under the wildfire risk and fuel treatment theme of the review.

Results and Discussion

The number of publications on wildfire risk and fuel treatments in ecosystems that occur along the US-Mexico border has increased over the last 34 years from 5 studies (6% of the total number of 90 selected studies) published between 1986 and 1999 to 30 (33% of total) published between 2015 and 2019 (Figure 1). Forty-two percent of the 90 selected studies focused on wildfire risk and fuel treatments in ecosystems along the US-Mexico border were conducted in Arizona, 18% in New Mexico, 10% in California, 5% in Texas, and 1% in Mexico, whereas 20% took place across multiple states, and 4% were conducted in nonborder states within ecosystems that extend to the border region (ie, the Mojave Desert in southern Nevada) (Figures 2 and 3A). Twenty-four percent of the selected studies were conducted in the Chihuahuan Desert, 21% were based in the Sonoran Desert, 17% were in the Mojave Desert, 25% were in the Madrean Archipelago (Sky Island mountain ecoregion of southeastern Arizona and southwestern New Mexico) and other forested ecoregions of the Southwest, and 13% were conducted in other ecoregions or across multiple ecoregions (Figure 3B). Most studies were conducted on federal lands (85%), and of those federal studies, 43% were conducted on DOI lands, 25% occurred on US Department of Agriculture lands, 5% were on lands managed by the Department of Defense, and 12% were conducted on lands managed by multiple or other agencies (Figure 3C). Thirty-four studies addressed fuel treatments, and within these studies, 65% examined prescribed fire, 12% looked at mechanical treatments (thinning, pile and burn, hand-pulling of invasive

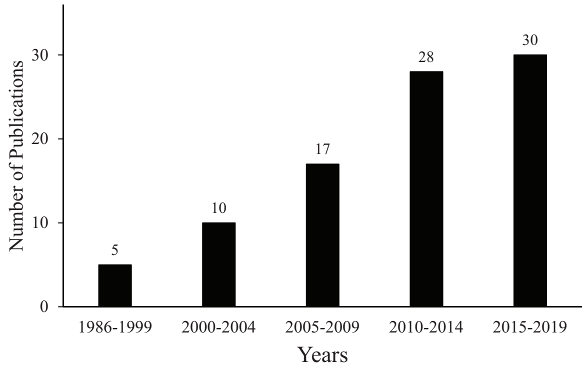

Figure 1. The number of studies that address wildfire risk and fuel reduction treatments along the US-Mexico border through time.

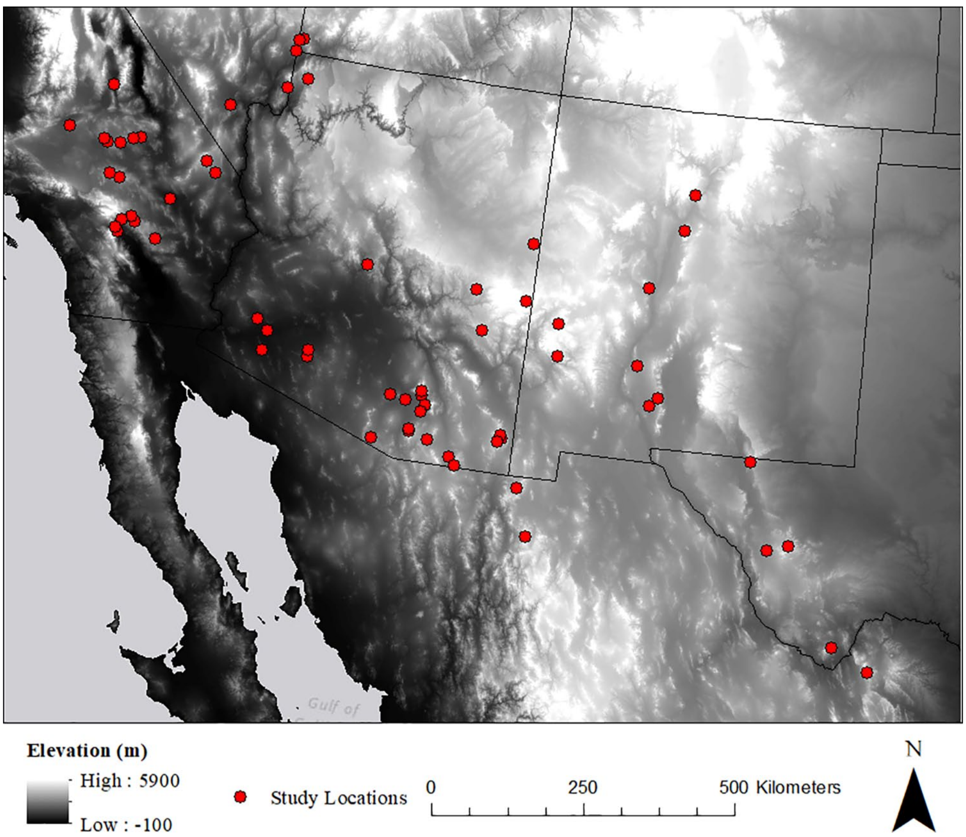

Figure 2. Locations of studies in ecosystems that occur along the US-Mexico border that address wildfire risk and fuel reduction treatments.

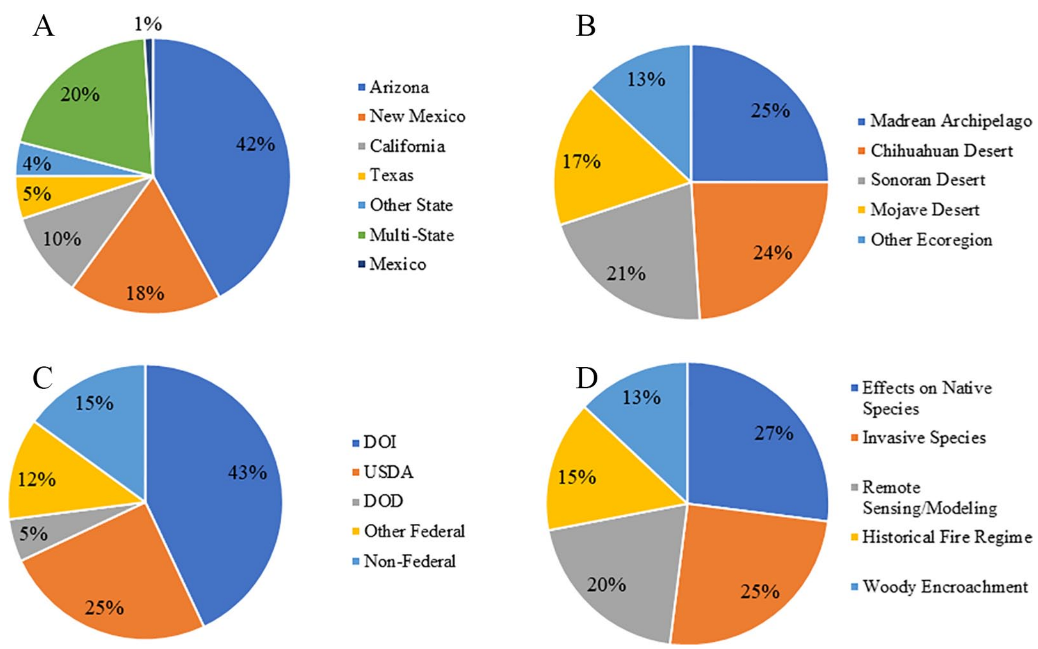

Figure 3. Studies that address wildfire risk and fuel reduction treatments along the US-Mexico border by (A) state and country, (B) ecoregion, (C) land ownership, and (D) topic.

species), 3% explored livestock grazing, and 20% considered multiple combinations of these treatments. Herbicide application was a secondary treatment examined in these studies but was not studied independently of other treatments. Studies that addressed both fuel treatments and wildfire risk could be divided into the primary topics of fire effects on native species (27%), invasive species (25%), woody encroachment (13%), historical fire regimes (15%), and remote sensing and modeling (20%) (Figure 3D).

Studies that addressed fire effects on native species found that fire can both increase[9] and decrease[10,11] the growth and productivity of native species. Several studies found mixed effects on plant species that depended on plant traits, fire characteristics, and pre-fire treatments.[12-17] Woody plants were often negatively affected by fire, whereas grasses and forb species often experienced post-fire increases in abundance.[13,18] However, rapid-reproducing woody species fared better following fire than poor recruiters,[15,16] and some perennial grasses that invested heavily in above ground compared with below ground production did not respond well to fire.[12] Negative responses to fire were further exacerbated by low soil nutrient[19] and water availability[20] conditions. Fire changed the spatial patterning of native vegetation[21] and leaf litter decomposition,[22] and enhanced soil erosion by decreasing native perennial vegetation cover.[23] Similar to the large variation in the responses of native plant species, native wildlife species had both positive and negative responses to fire.[10,24] Forest-dwelling species responded positively to fires that created intermediate heterogeneity in vegetation structure.[25,26] Importantly, preexisting fuel treatments including livestock grazing,[27] prescribed fire alone,[28] or prescribed fire in combination with mechanical treatments[20,29-33] reduced subsequent wildfire severity, associated declines in productivity and mortality of native species, and enhanced post-wildfire recovery.[30] Long-term fuel treatment effects on native species were assessed by Havstad and James,[34] who found that native vegetation cover was not influenced by prescribed fire 13 years after the burn treatment application, and by Strom and Fulé,[29] who projected that fuel treatments had multidecadal effects on native vegetation structure. These contrasting results can be explained by the recovery time of the species and ecosystems studied.

Studies on invasive species tended to focus on the grasses red brome (*Bromus rubens*) and schismus (*Schismus* spp.) in the Mojave Desert, buffelgrass (*Pennisetum ciliare*) in the Sonoran Desert, and Lehmann lovegrass (*Eragrostis lehmanniana*) in the Sonoran and Chihuahuan deserts. Studies on these non-native flammable species found that fire promoted their spread, leading to increased fire frequency and thereby supporting a positive feedback loop between fire and the invasive species.[35-41] The change in invasive species following wildfire can depend on fire frequency and severity[39] and soil type.[42] Although some studies found that the cover of invasive species did not increase after fire,[42-44] all studies generally agreed that invasive species increased wildfire risk.[45-52] Some of the factors these papers discussed as leading to the propagation of invasive species, and therefore the rise of wildfire risk, included high precipitation[42,43,51,52] and high soil nitrogen.[48,51] Fuel treatments caused a reduction,[49,53] as well as no changes to invasive species abundance.[42,43,47,54,55]

Similar to invasive species, woody plant species have increased in abundance along the US-Mexico border over the past several decades, including in areas previously occupied by grasslands.[56,57] Woody plant encroachment can increase the risk of a high severity fire, and several studies addressed treatments to reverse this pattern and help restore a low-severity fire regime. These studies found reduced woody plant abundance following prescribed burns in most cases,[55,58-60] but woody regeneration and interactions with grass species were variable depending on the fire season, fire return interval, and the degree of livestock grazing.[21,34,61-63] Fire rather than livestock grazing may have a larger role in maintaining grass dominance in the border region, although the mechanisms behind the balance of woody plants and grasses remain controversial.[56] Reductions in woody plant cover had a positive effect on wildlife species requiring more open and grass-dominated habitat, but negative effects on wildlife species requiring a higher density of woody vegetation.[64] Despite strong effects on wildlife, many woody plant species including mesquite recovered quickly following treatments.[65]

Historical wildfire regimes have been the topic of multiple studies that typically assess wildfire frequency, size, and severity. Many of these studies examined the relationship between fire characteristics and topographic attributes,[66-69] or fire characteristics and climate—specifically how wildfire risk can increase after antecedent wet years that increase fuel loads, followed by dry fire years.[68,70-72] Historical fire regimes along the border interact with land-use and associated characteristics—including livestock grazing,[73-75] land ownership,[76] and the degree of remoteness and historical management practices.[2] Larger fires were found to historically occur within the United States compared with Mexico, likely due to higher levels of fire exclusion and resulting fuel buildup.[2]

Much of the research on the topic of remote sensing and modeling was conducted across different plant communities including desert scrub, woodland, and forest of the Madrean Archipelago. Many studies focused on fuel types and biomass to assess wildfire risk[77-84] or used spectral vegetation indices to measure impacts of previous fires.[83,85] In addition, remote sensing was commonly used with the goal of modeling the spread of invasive grasses because of their role in increasing wildfire risk.[3,86,87] Using environmental characteristics to predict wildfire likelihood and severity was an approach found in several studies using slope, elevation, and climate.[88-90]

Soil was not a major topic of border studies included in our review despite its inclusion in searches. However, the influence of soils on wildfire and the effect of wildfire on soils were secondarily addressed in the literature. Wildfire frequency was enhanced with increasing elevation and soil moisture[69] and in shallow and fine-textured soils compared with deep and coarse-textured soils.[89] Brooks,[45] Allred and Snyder,[9] and Ladwig et al[19] all found an increase in soil nitrogen after fire, which has been shown to cause higher growth of invasive plants, increasing the risk of potential fires.[37,46,48,51,91] Multiple studies documented that fire promotes the redistribution of sediment and soil nutrients from under woody plant canopies to areas between woody plants, which can promote increases in perennial grass cover and reductions in woody encroachment.[58-60,92] Fire increased soil bulk density, runoff, sediment yield, and channelization while reducing water infiltration in ecosystems along the US-Mexico border.[23,93] In addition to increased susceptibility to water erosion, post-fire soils were exposed to elevated wind erosion, which could be further amplified by land-use that reduces perennial vegetation.[94,95]

Knowledge Gaps and Future Research

Our review highlights the state of knowledge of wildfire and fuel treatments in ecosystems that occur along the US-Mexico border and reveals several knowledge gaps and avenues for future research. Although invasive grasses in the southwestern United States and northern Mexico typically increase wildfire risk, more work is needed to better link the effects of different invasive species, including research, on fire-related traits in invasive species compared with native species and how these traits interact with environmental conditions to influence wildfire risk. The suppression of invasive species and promotion of native species are now occurring at large spatial scales, yet we know little about how these efforts are influencing wildfire risk and ecosystem recovery across broad management units. The importance of climate effects on wildfire and related invasive species abundance, together with forecasts of increasing aridity along the US-Mexico border,[96] suggests a growing need for studies that project how future climate will influence wildfire and the associated spread of invasive species. While future warming is likely to extend the fire season length and increase fuel flammability,[4] previous research in the US-Mexico border region has revealed the importance of antecedent wet conditions in promoting fine fuel production necessary to increase wildfire activity.[72] Villarreal et al[97] report in this special collection that recent fires deviate from historical fire regimes for most ecosystems along the border, especially at extreme ends of bioclimatic gradients. These results point out the need to experimentally impose climate extremes through rainfall or temperature manipulation[98] in conjunction with fire to determine important interactions that affect ecosystem condition. Research will have added value for future decision-making if connections are made between past fire-environment relationships and how fires might respond to future conditions.

More recently occurring wildfires have been used to understand how historical fuel treatments have affected fire behavior, and this research avenue is likely to be increasingly helpful for fire mitigation as the frequency and severity of wildfires are expected to intensify.[3,4] Pairing post-fire ecosystem monitoring with measurements that took place in the same area before the wildfire occurred offers a promising method to understand recovery patterns and opportunities for management intervention. Most of the fuel treatment studies we reviewed examined changes to wildfire risk over relatively short periods of time, but long-term monitoring is necessary to assess how the risk profile changes through time and when treatments need to be repeated.[99] Studies that assess post-fire linkages between vegetation and wildlife are especially helpful to understand ecosystem-level effects, yet are not abundant in the literature. Prescribed burning was the primary fuel treatment found in this review, but studies on the potential for fuel breaks and different treatment combinations and frequencies could help determine other effective prevention measures.

The variable topography, soils, and vegetation of the US-Mexico border not only present unique challenges for understanding wildfire activity, but also present opportunities for studies that employ environmental gradients, cross-site comparisons, and networked experiments to expand our knowledge. Similarly, the patchwork of land-uses and ownership along the border creates incentive to further explore how these factors influence wildfire activity and invites new research that crosses jurisdictional boundaries, including across the international border. Indeed, Villarreal et al[2,97] emphasize the need for continued collaboration and shared data sets from both sides of the border to adequately learn from historical fire regimes and understand the potential of future changes. Connectivity of fuels and related fire hazards across the US-Mexico border makes collaborative resource management increasingly important to reduce the risk of transboundary wildfire transmission and to improve ecosystem health.[100,101]

Studies were less common on the Mexico side of the border where much of the land is privately or communally *(ejidos)* held, and government-sponsored fire suppression and fuel management strategies often exist alongside local traditional burning practices and communal fire management.[102] Intentional fuel treatments in the Mexican borderlands are uncommon, but recently Mexican state and federal government agencies, universities, and local communities have collaborated on prescribed burns along the border,[103] with the objectives of reducing fuels, studying treatment effectiveness, and providing training on fuel management. Within the United States, studies in this review were particularly lacking on Native American lands and in Texas (Figure 1). The increasing number of studies on wildfire risk and fuel treatments along the US-Mexico border signifies a growing body of knowledge to inform land management decision-making in the region. Continued studies along the border, particularly research that fills important knowledge gaps, will help protect ecosystems and human populations that are at risk of negative fire impacts and will expand the knowledge needed to prepare for future wildfire regimes.

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Author Contributions

This review was conceived by SMM. KML performed the literature search. KML and SMM wrote the paper with contributions from MLV.

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