Targeted grazing and mechanical thinning enhance forest stand resilience under a narrow range of wildfire scenarios

V. M. Donovan

C. P. Roberts

D. T. Fogarty

David A. Wedin
University of Nebraska-Lincoln, dwedin1@unl.edu

D. Twidwell

Received: 24 June 2021 | Revised: 2 December 2021 | Accepted: 21 December 2021

DOI: 10.1002/ecs2.4061

ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

ARTICLE

Agroecosystems

Targeted grazing and mechanical thinning enhance forest stand resilience under a narrow range of wildfire scenarios

Victoria M. Donovan[1] | **Caleb P. Roberts**[1] | **Dillon T. Fogarty**[1] | **David A. Wedin**[2] | **Dirac Twidwell**[1]

[1]Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

[2]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

Correspondence
Victoria M. Donovan
Email: vdonovan2@unl.edu

Funding information
Institute of Agriculture and Natural Resources; USDA NIFA McIntire Stennis project, Grant/Award Number: 1008861; Nebraska Forest Service

Handling Editor: Justin duToit

Abstract

Increasing wildfire activity has spurred ecological resilience-based management that aims to reduce the vulnerability of forest stands to wildfire by reducing the probability of crown fire. Targeted grazing is increasingly being used to build forest resilience to wildfire, either on its own or in combination with treatments such as mechanical thinning; however, it is unclear how effective this method is at altering the probability of crown fire in forest stands. We use crown fire simulation models to quantify to what extent targeted grazing, mechanical thinning targeting the vertical fuel stratum, and a combination of both treatments alter eastern ponderosa pine savanna stand resilience to wildfire by modeling their relative impacts on the fuel stratum gap and subsequent crown fire occurrence under six different wildfire risk scenarios generated by altering wind and fuel moisture conditions. We then model changes in the probability of crown fire occurrence resulting from treatments across 75 field-sampled sites in the Pine Ridge region of Nebraska relative to predicted crown fire occurrence when sites are left untreated. We find that mechanical (vertical) thinning has the potential to alter the probability of crown fire in ponderosa pine stands to a much greater extent than targeted grazing. Combining both approaches had a slightly higher probability of reducing crown fire risk across the greatest range of wildfire risk scenarios. Across 75 sample sites, targeted grazing was only predicted to prevent crown fire occurrence at two sites expected to experience crown fire under observed stand conditions across all six of our wildfire risk scenarios. In contrast, targeted grazing combined with mechanical thinning was predicted to prevent crown fire at approximately half of the sites expected to experience crown fire under observed conditions for mild and moderate wildfire risk scenarios. Thus, targeted grazing should be combined with mechanical thinning to best enhance forest resilience to wildfire. No combination of targeted grazing or mechanical thinning was able to alter the probability of crown fire under wildfire risk scenarios most conducive to wildfire, confirming that relying solely on vertical thinning and targeted grazing is unlikely to sufficiently enhance resilience of forest stands to future wildfire conditions.

KEYWORDS
agroforestry, fuel management, fuel stratum gap, mechanical thinning, prescribed fire, pruning, resilience, targeted grazing, vertical thinning, wildfire

INTRODUCTION

Wildfire has been increasing across many regions of North America, leading to growing concern over the loss of ecosystem resources, human infrastructure, and lives (Busenberg, 2004; Dennison et al., 2014). The United States has appropriated billions of dollars for fuel management to enhance ecosystem resilience (the amount of disturbance a system can endure before transitioning to an alternative ecological regime or state; Holling, 1973) to wildfires (Bracmort, 2013). Increasing wildfire across rangelands and forests (Dennison et al., 2014; Donovan et al., 2017) has led to increasingly integrated management approaches. Two of the most used approaches are mechanical thinning and targeted grazing. Mechanical thinning can use a combination of methods, such as tree pruning and the removal of mature and small-diameter trees, to alter forest structure. Targeted grazing, a common practice in range management (Twidwell et al., 2013), is also applied in savanna and forest ecosystem management to help control surface fuel load and reduce the probability of crown fire (Brantly, 2014; Jain et al., 2012; Taylor Jr, 2006; Twidwell et al., 2013). Grazing is a primary focus in many regions because it is thought to achieve multiple economic objectives with a single management approach (cattle production and wildfire control; Gold & Hanover, 1987). However, the relative and integrated impacts of targeted grazing on enhancing savanna and forest resilience to wildfire are not well understood.

When fire shifts from surface to crown fire, it can lead to extensive stand mortality that can drive a transition to an alternative ecological state (Miller et al., 2019; Odion et al., 2010). Forest management has focused a great deal of effort on decreasing the probability of crown fire to boost stand resilience to wildfire by manipulating stand fuel structure (Lindenmayer et al., 2006). Historically in ponderosa pine (*Pinus ponderosa*) forests and savannas for instance, frequent low-severity surface fires promoted forest stand resilience to wildfire through altering stand structure both horizontally and vertically. Vertical alteration of fuels reduced the probability of crown fire by reducing surface and ladder fuels that promote fire spread from the ground into the tree crown and scorching the lower limbs of trees, thereby increasing the fuel stratum gap (the distance between surface and canopy fuels; Covington & Moore, 1994a, 1994b; Brown & Sieg, 1999). Horizontal alteration of fuels made stands less conducive to crown fire spread by killing individual trees within a stand that generated a more open stand structure (Brown & Sieg, 1999, Covington & Moore, 1994a, 1994b). The buildup of fuels resulting from the loss of this feedback with fire makes contemporary forests and savannas more susceptible to crown fire occurrence and spread and thus less resilient to wildfire (Dodge, 1972; Seidl et al., 2016).

Targeted grazing and mechanical thinning targeting vertical fuel distribution (hereafter referred to as mechanical thinning) alter the fuel stratum gap in different ways to reduce the probability of crown fire. Mechanical thinning alters the upper end of the fuel stratum gap by removing lower branches of trees using tree pruning and the lower end of the fuel stratum gap through the removal of ladder fuels such as small-diameter trees and shrubs that fall in the surface fuel layer (Agee & Skinner, 2005; Graham et al., 2004; Keeley et al., 2009). In contrast, targeted grazing alters surface fuel height by reducing herbaceous fuels and other understory vegetation. It is increasingly being used to control the height and load of live surface fuels to decrease the likelihood of fire spread from the surface into the tree crown (Gold & Hanover, 1987; Jain et al., 2012; Taylor Jr, 2006) and is of particular interest in forest–grassland ecotonal regions, where economic, ecological, and social objectives for grasslands and forests intersect. Targeted grazing has also been suggested as a more favorable option for controlling wildfire risk in the wildland–urban interface compared with mechanical thinning, herbicide use, or prescribed fire due to public perceptions of such treatments (Taylor Jr, 2006). While prescribed fire can be used as an alternative or supplemental technique to both these practices, a lack of cultural acceptance surrounding risk–benefit trade-offs means that it is generally underutilized (Kolden, 2019; McWethy et al., 2019).

In this paper, we determine the potential for targeted grazing and mechanical thinning to alter the probability and occurrence of crown fire within a forest stand through alteration of the vertical fuel stratum gap using the Pine Ridge region of Nebraska as a model system. Using on-the-ground data from a forest inventory and timber analysis across 75 sites in the Pine Ridge in combination with crown fire modeling software, we compare changes in crown fire probability and predicted occurrence in forest stands following (1) targeted grazing, (2) mechanical thinning, and (3) the combination of targeted grazing and mechanical thinning. We define mechanical thinning as crown pruning and seedling (trees <1.4 m in height) removal. We employed crown fire simulation using the Crown Fire Initiation Spread (CFIS) System (Cruz et al., 2004, 2005), which models crown fire initiation, occurrence, and rate of spread at the forest stand level to simulate the impacts of each management scenario. To assess under what context management scenarios would impact wildfire probability and occurrence, we use a bounded range of variation (BRV) framework (Moritz et al., 2013) to generate six wildfire risk scenarios that ranged from very low to extreme risk represented by varying wind speeds and fuel moisture contents.

METHODS

Study site

The Pine Ridge is a ~200,000-ha semiarid escarpment in northwest Nebraska typified by rocky ridges and steep canyons, with a mean elevation of ~1000 m. It is an ecotonal region of ponderosa pine forest interspersed with mixed-grass prairie (Schneider et al., 2011). The average annual rainfall is 43 cm (Schneider et al., 2011). The mean annual temperature is 16.3°C, while the annual low is 1°C (Schneider et al., 2011). Forests are dominated by ponderosa pine, although species such as American elm (*Ulmus americana*), box elder (*Acer negundo*), green ash (*Fraxinus pennsylvanica*), Rocky Mountain juniper (*Juniperus scopulorum*), and eastern red cedar (*Juniperus virginiana*) are also present in some locations (Donovan et al., 2019; Roberts et al., 2019). Forest understories are generally herbaceous (Figure 1). Common species in the herbaceous layer include little bluestem (*Schizachyrium scoparium*), needle-and-thread grass (*Hesperostipa comata*), western wheatgrass (*Elymus smithii*), blue grama (*Bouteloua gracilis*), and threadleaf sedge (*Carex filifolia*), as well as invasive species such as Kentucky bluegrass (*Poa pratensis*) and cheatgrass (*Bromus tectorum*) (Donovan et al., 2021). Eastern ponderosa pine forests such as the Pine Ridge historically experienced frequent fires, likely of low or mixed severity, that created sparse ponderosa pine with heterogenous structure (Brown & Sieg, 1999; Roberts et al., 2020). Presettlement fire return interval is estimated to have been between 6 and 12 years (Guyette et al., 2012). Active fire suppression has resulted in increasingly dense ponderosa pine stands over the last century. Multiple large, mixed-severity fires have burned through the Pine Ridge region in recent years (MTBS Project, 2019; Roberts et al., 2020).

FIGURE 1 Example of (a) the forest landscape and (b) understory structure of eastern ponderosa pine forests found in the Pine Ridge region of Nebraska

Following several consecutive large, mixed-severity fires in the early 2000s, fuel reduction treatments aimed at preventing high-severity wildfire have been implemented in the Pine Ridge by several organizations. The Nebraska Forest Service offers fuel reduction cost share to mechanically thin forests and remove ladder fuels (ground vegetation that creates continuity between surface fuels and tree crowns that allows fire to spread into the crown) in unburnt or burnt forests (Nebraska Forest Service, 2019; Nebraska Wildfire Control Act, 2013). The US Forest Service approved the implementation of mechanical treatments and targeted grazing in the burn area of the West Ash Fire of 2012 with the purpose of treating fuels to reduce wildfire hazards. The USDA Natural Resource Conservation Service and Nebraska Environmental Trust also manage and fund fuel reduction projects across the region. Grazing management via the US Forest Service allotment system is ongoing, and was occurring when sites were sampled during this study (2017; USDA Forest Service, 2019).

Estimating potential management outcomes in the Pine Ridge

We simulated management outcomes in eastern ponderosa pine landscapes based on stand structural conditions in the Pine Ridge of western Nebraska. To determine stand structural conditions, we used stand structural data collected across 75 sites during a 2017 forest resource inventory (Appendix S1: Figure S1; Renewable Resource Solutions LLC, 2018, available on request from the Nebraska Forest Service, University of Nebraska, Lincoln, NE). At each site, 15 plots with a radius of 3.5 m were installed in a 5-by-3 plot configuration (Appendix S1: Figure S1). Each plot within a cluster was spaced four chains (80.4 m) apart longitudinally, and six chains (120.6 m) apart latitudinally. Sample site distribution was focused on representing current forest stand conditions across the Pine Ridge. Sites were randomly selected across forested areas with adequate road access within the >200,000-ha region in both public and private lands where permission was granted. Sampling aimed to avoid burned areas; however, evidence of recent burning was recorded at three plots. Evidence of stand and crown thinning was recorded within at least one plot within 22 sample sites. Sporadic grazing occurred across the Pine Ridge at the time of sampling; however, the land was managed by private landowners, as well as state and federal agencies, meaning that grazing practices were not consistent across sample sites. Thus, field measures encompassed a wide range of stand conditions.

At each plot within each site, the basal area was measured using a prism with a basal area factor of 10. Live trees within each plot were counted, and tree diameter at breast height (dbh) and tree height were measured for each tree to determine stand height and density. Density was calculated for trees >11.4 cm dbh and large saplings >5 cm dbh. All conifer seedlings (designated as anything <1.4 m in height), regardless of species, were recorded and measured in height to the nearest 0.3 m (1 foot) within a 2-m radius around the center of each plot. The height of herbaceous vegetation was measured at the center of each plot to the nearest 0.3 m (1 foot). Detailed descriptions of sampling can be found in Renewable Resource Solutions, LLC (2018). Because fuel models assume homogenous stand conditions, we averaged plot-based measurements collected in the inventory to get a single measure per site ($n = 75$) that we used to represent the conditions of the forest stand (Appendix S1: Figure S2). These values were input into a Canopy Fuel Stratum Characteristics Calculator (Cruz et al., 2003) to generate stand-level estimates input into fire models (canopy base height and canopy bulk density). We also calculated the average stand conditions across sites to represent a typical stand in the Pine Ridge (Table 1).

The potential impact of targeted grazing on the fuel stratum gap was simulated by altering herbaceous fuel

TABLE 1 Mean, minimum, and maximum stand metrics recorded across 75 sample sites in the Pine Ridge region of Nebraska

Stand metric	Mean ± SE	Minimum	Maximum
Canopy base height (m)	5.28 ± 0.16	0.41	8.93
Canopy bulk density (kg/m^3)	0.09 ± 0.006	<0.01	0.24
Diameter at breast height (cm)	33.32 ± 0.48	23.14	43.26
Basal area (m^2/ha)	11.21 ± 0.61	0.61	22.96
Stand tree height (m)	11.70 ± 0.38	0.62	20.86
Herbaceous height (m)	0.58 ± 0.02	0.26	0.93
Seedling height (m)	0.43 ± 0.04	0.30	1.12
Fuel stratum gap (m)	4.38 ± 0.16	0	8.03

heights and seedling heights recorded at each site in the Pine Ridge. Our simulations were based on grazing by cattle, the primary livestock in the study region. In addition to herbaceous vegetation, high-intensity cattle grazing has been shown to largely reduce tree seedlings (Vandenberghe et al., 2007; Zimmerman & Neuenschwander, 1984). Because cattle do not target canopy fuels in ponderosa pine, we held canopy base height (the distance from the ground to the tree crown) constant.

We simulated mechanical thinning on the fuel stratum gap through the manipulation of both seedling height and canopy base height. Mechanical thinning in our study was modeled as crown pruning, used to remove lower branches of trees, and the removal of seedlings from the understory, which can act as ladder fuels (Figure 2). Thus, mechanical thinning had the potential to alter the fuel stratum gap through manipulation of both canopy and surface fuels (Figure 2). The maximum potential impact of mechanical thinning on canopy fuel reduction was estimated as a canopy base height of two thirds of tree height. Two thirds of tree height is the estimated maximum amount of canopy that can be removed from the tree crown before causing tree shock (Emmingham & Elwood, 1983). Assuming seedlings were removed during the thinning process, we then subtracted herbaceous height from this value to determine the post-thinning fuel stratum gap (Figure 2).

Crown fire simulations

We used the CFIS System to predict the probability of crown fire across a range of wildfire risk scenarios relative to different management scenarios (Cruz et al., 2004, 2005). The system uses a logistic model developed by Cruz et al. (2004) to predict crown fire probability using 10-m open wind speed (the wind speed 10 m above the top of the tree canopy), fuel stratum gap, estimated moisture content in fine dead fuels (estimated fine fuel moisture [EFFM]), and an estimate of surface fuel consumption ranging from <1 to >2 kg/m^2. CFIS outputs the probability of crown fire occurrence ($p_{\text{crownfire}}$) in a forest stand. To distinguish crown fire from surface fire, CFIS uses a threshold in the probability of crown fire at 0.5. If $p_{\text{crownfire}}$ value is <0.5, then surface fire is expected. If $p_{\text{crownfire}}$ value is ≥0.5, then crown fire behavior is expected. CFIS also calculates whether a crown fire is active or passive (following Cruz et al., 2005). Passive crown fire occurs when surface fire intensity is great enough to ignite the crown of a tree, but wind speed is not sufficient to support the propagation of crown fire from tree to tree. Active crown fire occurs when crown fire advances from tree to tree through surface and crown fire that are dependent on one another. These calculations integrate 10-m open wind speed, estimated fine fuel moisture content, and canopy bulk density to predict the active fire rate of spread. CFIS predicts active crown fire if the predicted spread rate is greater than the critical spread rate for active crown fire (Scott, 2006). Like other fire models, CFIS assumes homogenous stand conditions, so we used average stand conditions for model calculations and inputs (Alexander & Cruz, 2013; Cruz et al., 2003, 2004).

Wildfire risk scenarios

We created six wildfire risk scenarios based on the environmental inputs needed for CFIS simulations (wind speed and EFFM) to reflect the potential range of conditions that could occur in the Pine Ridge using a BRV framework, meant to assess boundaries corresponding to plausible upper and lower scenarios of change given the uncertainty of future conditions (Moritz et al., 2013). The

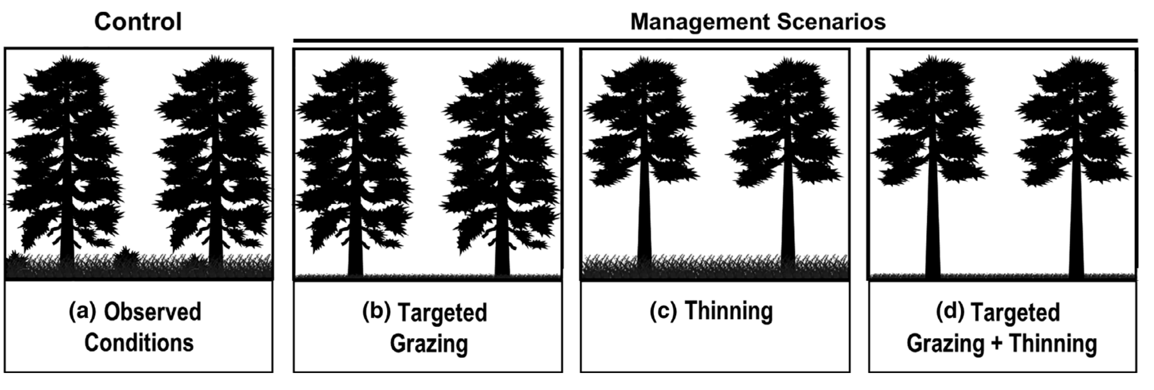

FIGURE 2 Diagrams of stand structural characteristics under (a) observed stand conditions (recorded conditions in the Pine Ridge, i.e., control) compared with three management scenarios: (b) targeted grazing, (c) thinning, and (d) targeted grazing combined with thinning

very low wildfire risk scenario was created to represent the least fire-conducive conditions possible, with minimum wind speed and very high fuel moisture (Table 2). Additional scenarios were built off this environmental scenario to create conditions that were increasingly more conducive to crown fire. The extreme wildfire risk scenario was created to represent the most fire-conducive conditions possible, using a high wind gust speed recorded in western Nebraska (77 km/h) and the minimum fuel moisture content possible in CFIS (2%), which falls within the lower range of fuel moisture contents recorded in the Pine Ridge (Abatzoglou, 2013; https://www.climatologylab.org/gridmet.html). Surface fuel consumption was held constant across all wildfire risk scenarios and treatment types at <1 kg/m^2, as this aligned with fuel consumption measured in other pine–grassland communities (Sparks et al., 2002).

Management potential to alter crown fire risk

We modeled a continuous range of fuel stratum gap sizes using the BRV framework to determine the potential for crown fire probability to be altered under different fuel management treatment types and wildfire risk scenarios. The maximum fuel stratum gap that can be modeled with CFIS is 12 m, which fits within the range of potential fuel stratum gaps possible in the Pine Ridge based on tree heights and the assumption that trees would survive with a crown that has two thirds of tree height removed (Emmingham & Elwood, 1983; Table 1). The lower limit was set to zero, the minimum fuel stratum gap recorded in the Pine Ridge. The potential influence of each treatment on the fuel stratum gap was used as the estimated range under which management could alter the probability of crown fire risk.

TABLE 2 Wildfire risk scenario input into models to assess changes in the probability of crown fire across different management scenarios

Wildfire risk scenario	Wind speed (km/h)	Estimated fine fuel moisture (%)	Surface fuel consumption (kg/m^2)
Very low	0.1	20	<1
Low	9	17	<1
Mild	18	15	<1
Moderate	26	12	<1
High	35	9	<1
Extreme	77	2	<1

We estimated potential grazing impact on the fuel stratum gap and the subsequent probability of crown fire using the average herbaceous height measured across the Pine Ridge (Table 1). Because grazing occurred sporadically across the Pine Ridge during sampling, we used the average value to represent the typical impact of grazing in the region (Figure 2). Targeted grazing can also reduce seedlings. However, because the average seedling height was lower than average herbaceous height across the Pine Ridge, average herbaceous height was used to set the potential distance over which targeted grazing could alter the fuel stratum gap.

We estimated the potential impacts of mechanical thinning (crown pruning and seedling removal) using average canopy base height measured across the Pine Ridge. Understories in the Pine Ridge are predominantly herbaceous (Figure 1). Because herbaceous fuels were taller than seedlings on average, the influence of mechanical thinning on surface fuels was negligible. The maximum potential impact of mechanical thinning on canopy base height was estimated as two thirds of the average tree height in the Pine Ridge. Two thirds of tree height is the estimated maximum canopy base height for a tree before causing tree shock (Emmingham & Elwood, 1983). We then subtracted the mean herbaceous height from this value to determine the fuel stratum gap (Figure 2).

Stand-level impacts of management on crown fire risk

We simulated management outcomes in eastern ponderosa landscapes at the stand level across our 75 sample sites in the Pine Ridge. Average stand height, basal area, and density were used to calculate canopy base height and canopy bulk density with the Canopy Fuel Stratum Characteristics Calculator (Alexander & Cruz, 2010) using regression equations developed by Cruz et al. (2003). We combined canopy base height calculated for each site with measured herbaceous and seedling heights from stand data to determine the fuel stratum gap based on four scenarios: observed conditions (recorded conditions in the Pine Ridge, i.e., the control), targeted grazing, mechanical thinning, and targeted grazing combined with mechanical thinning (Figure 2).

To determine the fuel stratum gap under observed conditions, we calculated surface fuel height by comparing average stand herbaceous fuel height and average stand seedling height at each site. We selected whichever was highest as the surface fuel height and subtracted that value from the calculated canopy base height for each stand to determine the fuel stratum gap.

To simulate the effects of targeted grazing, we used the minimum average herbaceous height found across the Pine Ridge sampling sites as the herbaceous height for all targeted grazing simulations. Because cattle grazing was occurring under different strategies at the time field measurements were taken, we assumed the minimum value represented the maximum potential ability of grazers to influence herbaceous height in the Pine Ridge region. Because seedlings can be largely reduced following high-intensity grazing (Vandenberghe et al., 2007; Zimmerman & Neuenschwander, 1984), we assumed they would not have escaped browsing. The minimum recorded herbaceous height was subtracted from the canopy base height recorded at each site to determine the fuel stratum gap that would exist under targeted grazing.

To simulate crown fire probability following mechanical thinning, we used mean herbaceous fuel height calculated for each site to set the surface fuel height, as seedlings would likely be damaged or removed as ladder fuels during thinning application in mechanical treatments (Fulé et al., 2002; Graham et al., 2004; Keeley et al., 2009). We set the canopy base height that could be created by mechanical thinning to two thirds of the recorded average tree height at each site (Emmingham & Elwood, 1983). We then subtracted the mean herbaceous height from the estimated canopy base height created by mechanical thinning at each site to determine the potential fuel stratum gap.

To calculate the combined impacts of mechanical thinning and targeted grazing, we subtracted the minimum herbaceous height recorded in the Pine Ridge (estimated to be the minimum height created by targeted grazing in the Pine Ridge) from the estimated canopy base height calculated in the mechanical thinning scenarios.

For each management scenario (observed conditions, targeted grazing, mechanical thinning, and targeted grazing + mechanical thinning), the calculated fuel stratum gap and canopy bulk density for each site were run in CFIS under each of our six environmental scenarios. In each case, we calculated whether fire was surface fire, passive crown fire, or active crown fire. We used generalized linear models with a binomial family to assess the impact of each treatment on the probability of crown fire occurrence. Statistical assessments were completed in R statistical software (R Core Team, 2021).

RESULTS

Management potential to alter crown fire risk

Observed stand structures varied greatly across the Pine Ridge (Table 1), with stand fuel stratum gaps ranging from 0 to 8 m (Table 1). Simulated targeted grazing was able to alter the fuel stratum gap an average of 0.58 m ± 0.02 SE (Table 1, Figure 3), with a maximum potential of up to 1.12 m based on maximum recorded seedling heights across stands (Table 1). This aligns with only slight changes in the probability of crown fire following targeted grazing under crown fire simulations (Figure 4a). Mechanical thinning altered the fuel stratum gap by an average of 7.32 m ± 0.24 SE (Figure 3), with a maximum potential of 13.22 m based on stand heights (Table 1). Based on crown fire simulations, thinning the vertical fuel stratum has a large potential to alter the probability of crown fire, particularly under mild and moderate fire risk conditions (Figure 4b). Combining thinning treatments and targeted grazing had the greatest potential to impact crown fire probability in the Pine Ridge by altering both surface and canopy fuels to increase the fuel stratum gap to an average of 7.49 ± 25 SE, with a maximum potential of 13.60 m (Figures 3 and 4c).

Stand-level impacts of management on crown fire risk

The effect of simulated management on crown fire occurrence across the Pine Ridge was negligible under all wildfire risk scenarios except the mild and moderate

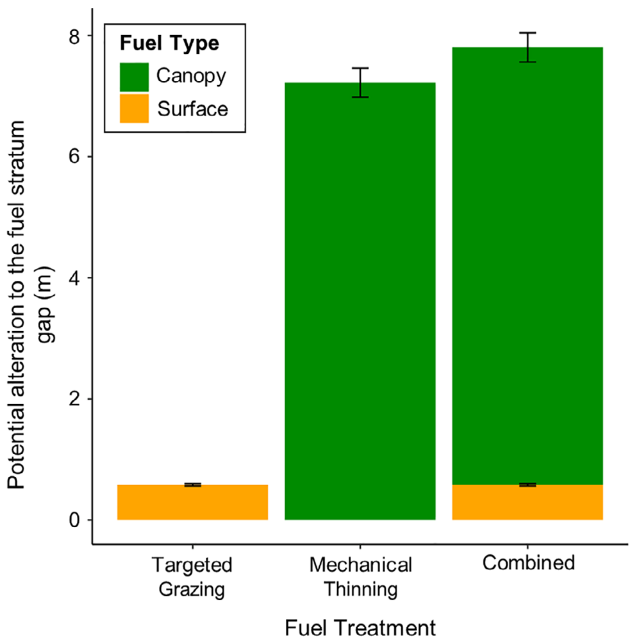

FIGURE 3 Potential for targeted grazing, thinning, and the combination of both mechanical thinning and targeted grazing to alter the fuel stratum gap in the Pine Ridge region of Nebraska based on average stand conditions across 75 sample sites. Error bars represent standard error

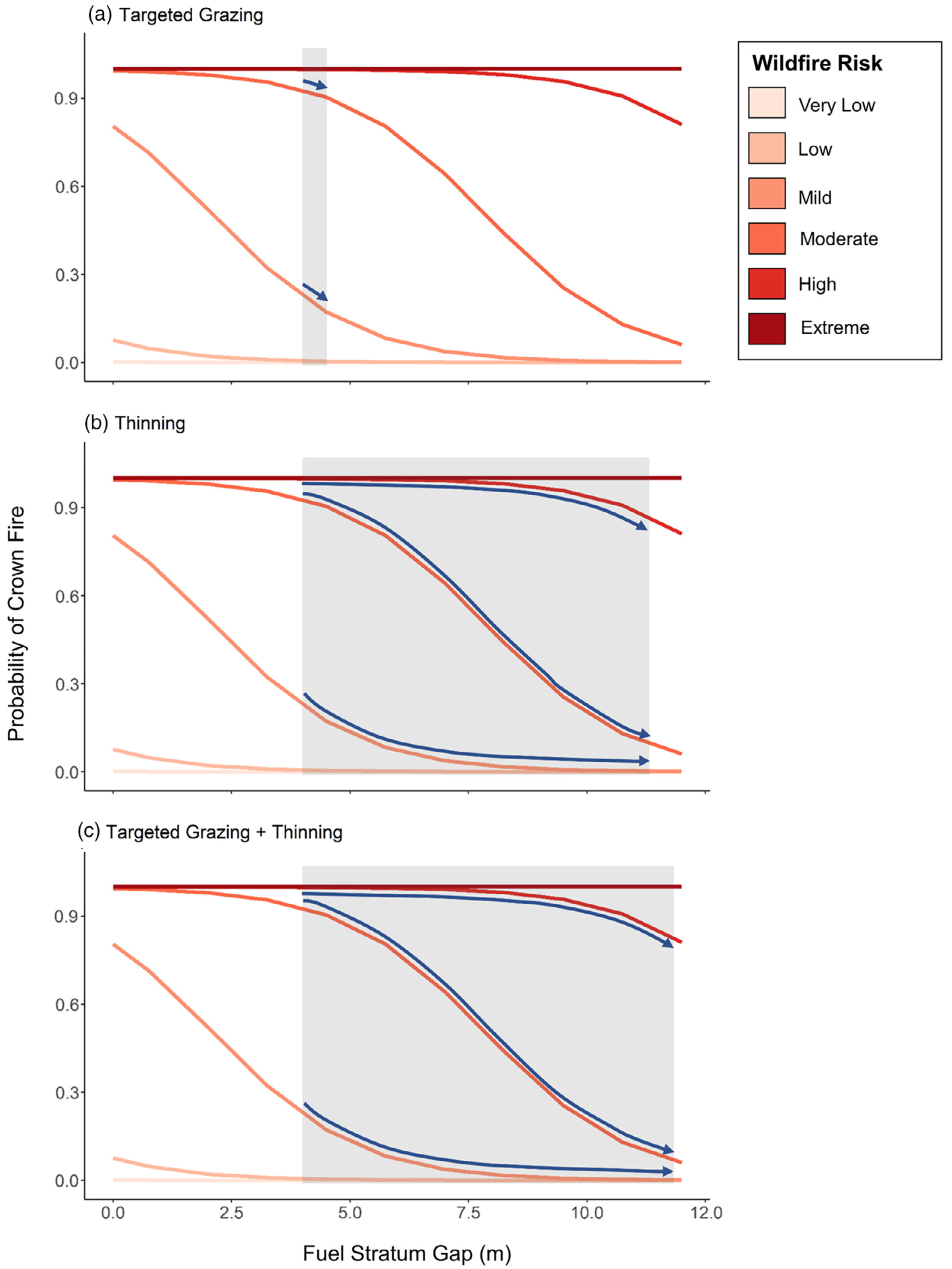

FIGURE 4 Ability of (a) targeted grazing, (b) thinning, and (c) targeted grazing combined with thinning to alter the probability of crown fire in the Pine Ridge across six wildfire risk scenarios, ranging from very-low-risk conditions for wildfire to extreme risk conditions for wildfire. Shaded sections represent the typical range under which each management type has the potential to alter the probability of crown fire, starting at a 4-m fuel stratum gap, the average fuel stratum gap in the Pine Ridge. Blue arrows emphasize the directionality of the change in the probability of crown fire with management application

scenarios (Figure 5). Under the observed stand conditions in the Pine Ridge, no sites will experience crown fire under very low and low wildfire risk scenarios. Similarly, current stands are largely resilient to crown fire under more mild wildfire risk scenarios; only 5 of the 75 sites assessed were predicted to experience passive crown fire

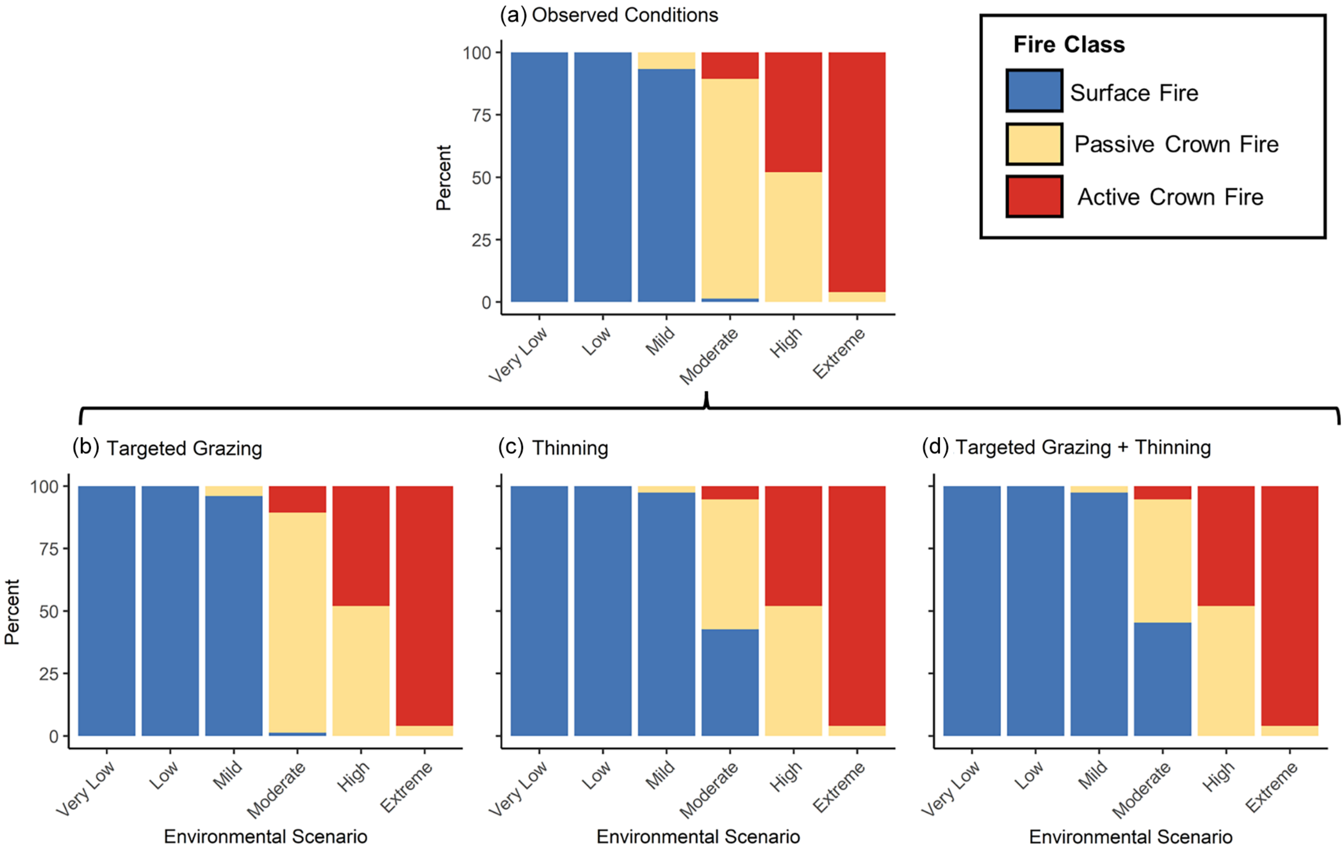

FIGURE 5 Percentage of sites ($n = 75$) predicted to experience surface (blue), passive crown (yellow), and active crown (red) fire in the eastern ponderosa pine forests in the Pine Ridge of Nebraska under different wildfire risk scenarios (very low–extreme). Plots show the percent of sites that would burn under (a) observed stand conditions (recorded stand conditions in the Pine Ridge, i.e., control) in comparison with scenarios where (b) targeted grazing, (c) thinning, and (d) targeted grazing combined with thinning were simulated

(Figure 5a). The fuel stratum gap was extremely low at these sites (<2 m). However, under the moderate wildfire risk scenario, all sites were predicted to experience passive crown fire except one (Figure 5a). This site had the highest recorded canopy base height (8.93 m) and fuel stratum gap (8.25 m) across all measured sites. No sites, regardless of the fuel stratum gap, were predicted to escape crown fire under high and extreme wildfire risk scenarios when sites were untreated (Figure 5a).

Targeted grazing alone had little impact on the probability of crown fire due to low canopy base heights in the Pine Ridge (Figure 5a). Targeted grazing was only predicted to influence crown fire occurrence under the mild wildfire risk scenario, though this was not significantly different from crown fire occurrence under observed conditions (estimate $= -0.30$, SE $= 0.78$, $p = 0.70$). Under the mild wildfire risk scenario, two of the five sites that experienced passive crown fire under observed stand conditions were predicted to experience surface fire when targeted grazing was applied (Figure 5a,b). The two sites where targeted grazing was predicted to be effective had the highest relative mean canopy base height (2.60 m $\pm$ 0.01 SE) and mean fuel stratum gap (1.71 m $\pm$ 0.18 SE) of these five sites under observed stand conditions. Sites where targeted grazing was not effective at eliminating passive crown fire under the mild wildfire risk scenario had the lowest canopy base height and fuel stratum gap of all 75 sites measured (mean canopy base height $= 1.44 \pm 0.54$ SE and mean fuel stratum gap $= 0.86 \pm 0.62$ SE). Implementing targeted grazing had no influence on the occurrence of crown fire under simulated moderate, high, and extreme wildfire risk scenarios at any site (Figure 5a,b).

Mechanical thinning was more effective at reducing crown fire under mild and moderate wildfire risk scenarios compared with targeted grazing, though this was only significant under the moderate wildfire risk scenario (mild wildfire risk: estimate $= -4.19$, SE $= 0.92$, $p = 0.97$; moderate wildfire risk: estimate $= -4.00$, SE $= 1.03$, $p \leq 0.01$). Under the mild wildfire risk scenario, three of the five sites that experienced passive crown fire under observed stand conditions were predicted to experience surface fire when mechanical thinning was applied. The two sites where crown fire was predicted following thinning under the mild wildfire risk scenario were young stands, with average stand heights of 1 and 4 m. Unlike targeted grazing, under the moderate wildfire risk scenario, thinning treatments were predicted to significantly decrease the probability of crown fire (estimate $= -4.01$, SE $= 1.03$, $p \leq 0.01$). Mechanical thinning treatments were able to shift 41% of sites that would experience crown fire without management intervention to surface fire. However, thinning was unable to alter predicted crown fire occurrence under the conditions most conducive to fire (high and extreme wildfire risk scenarios; Figure 5a,c).

Combining mechanical thinning and targeted grazing had the greatest impact on crown fire occurrence over either treatment alone in the Pine Ridge—but only by a small margin. The probability of crown fire was similar across sites that were treated with just thinning and those that combined targeted grazing and thinning management. Combining treatments shifted 44% of sites that experienced passive crown fire under observed stand conditions to surface fire under the moderate wildfire risk scenario, as compared to the 41% of sites under mechanical thinning treatments alone (Figure 5). However, these differences were not statistically significant (estimate $= 0.11$, SE $= 0.32$, $p = 0.98$).

DISCUSSION

Targeted grazing had a limited impact overall on the probability of crown fire in the Pine Ridge when used independently. While targeted grazing can hinder the ability of a forest to sustain surface fire (Zimmerman & Neuenschwander, 1984), we found that the ability of targeted grazing to directly hinder crown fire occurrence is limited because of the narrow contribution of surface fuels to the size of the fuel stratum gap relative to canopy base height. In contrast, we found that stand thinning treatments that increased fuel stratum gap by removing smaller trees and increasing canopy base height can hinder the ability of fire to spread from surface fuels into the tree crown under mild and moderate wildfire risk conditions. These results align with studies that have shown thinning can greatly reduce the severity of wildfire and crown fire occurrence (Lydersen et al., 2017; Pollet & Omi, 2002). While combining thinning with targeted grazing yielded the best results for improving stand resilience to wildfire in the Pine Ridge region, differences were not significant, only changing the probability of crown fire for a few stands.

Numerous studies have demonstrated the benefits of targeted grazing for wildfire management in rangelands. Herbaceous fuels have high potential reaction intensity and can support some of the highest rates of spread across fuel types (Rothermel, 1972). A study in the Great Basin demonstrated targeted grazing's ability to decrease flame lengths and rates of surface fire spread (Diamond et al., 2010). In the Pine Ridge, targeted grazing by cattle may provide a number of benefits tied to surface fire suppression potential and decreasing the probability of surface fire spread to forest areas less resilient to fire (factors not modeled in this study). However, there were only a few sites in the Pine Ridge with a small enough fuel stratum gap where grazing could impact the probability of crown fire. For targeted grazing to impact crown fire occurrence, sites needed to have a low enough canopy base height to be conducive to crown fire under the mild wildfire risk scenario, but a high enough canopy base height that the alteration of herbaceous fuel height would impact the fuel stratum gap. Thus, targeted grazing used independently is only effective at hindering crown fire occurrence in stands with relatively low canopy base height, high herbaceous fuel heights, and mild wildfire risk conditions. This practice needs to be applied under a very specific range of stand conditions to have an impact on forest stand resilience to crown fire. Altering stand structure through thinning has a much higher probability of affecting crown fire occurrence than targeted grazing.

No combination of stand management assessed in our study was able to alter the probability of crown fire under the conditions most conducive to wildfire. When wind speeds exceeded 26 km/h and EFFM was lower than 12%, crown fire was predicted to occur at all sites in the Pine Ridge, regardless of treatment type. These more severe wind speeds and lower EFFM are tied to high wildfire risk and are often the target for management treatments. Thus, stand-based management practices that targeted vertical fuel thinning are unlikely to be effective at reducing crown fire extent on their own under high wildfire risk conditions. Alternative management tactics can be adapted to promote forest stand resilience by reducing the probability of active crown fire within and among stands, particularly with changing global conditions and climate. Integrating concepts tied to spatial resilience (the contribution of spatial attributes to ecological resilience of a system; Allen et al., 2016) may provide opportunities to reduce crown fire over greater areas under more severe conditions by promoting stand structural mosaics similar to those that existed prior to widespread fire suppression (Larson & Churchill, 2012). Historically, mixed-severity fire would have impacted both horizontal and vertical fuel distribution across a range of scales, creating more heterogenous and discontinuous landscape structures that not only hindered crown fire initiation but also prevented the spread of active crown fire across larger scales (Baker, 2009; Odion et al., 2010; Spies et al., 2006; Williams & Baker, 2012). This heterogeneity is lost when wildfire is excluded from landscapes (Steel et al., 2018; Stevens et al., 2017), and is not addressed when using management practices that only target crown fire occurrence through vertical fuel distribution (tree pruning, ladder fuel removal). Increasing heterogeneity in forest fuel structure can increase fuel discontinuity, thereby reducing fire spread, area burned, and fire-driven tree mortality (Atchley et al., 2021; Koontz et al., 2020). Similarly, different within-stand clustering patterns can alter the net energy transferred from surface fuels to the tree crown (Ritter et al., 2020), though the impacts of forest stand structural variability on forest resilience can vary by region (Stephens et al., 2021). Increasing among-stand structural variability by harvesting or burning patches of trees in the Pine Ridge would decrease stand continuity across the landscape and recreate more resilient historical stand structures under more fire-conducive conditions (Kane et al., 2019). This becomes increasingly important as warmer and drier conditions associated with climate change are being linked to increasing wildfires in forest and savanna systems (Abatzoglou & Williams, 2016; Westerling et al., 2006). Future studies should integrate changes in within- and among-stand continuity in crown fire simulations in eastern ponderosa pine forests such as the Pine Ridge to determine their potential to increase forest stand resilience under high wildfire risk conditions. Because it has been argued that applying thinning treatments across large areas is unfeasible (Schoennagel et al., 2017) and that prescribed fire can be more effective than mechanical pruning at altering canopy fuel characteristics (Scott & Reinhardt, 2007), future studies could also compare the outcomes of thinning with mixed-severity prescribed fire for enhancing forest resilience.

There are several assumptions in our simulations that need to be considered. It is important to note that both mechanical thinning and targeted grazing can increase the amount of downed woody debris, a variable that can increase the probability of crown fire and that was not included in our analysis. Zimmerman and Neuenschwander (1984) found that areas grazed with cattle had higher amounts of downed woody debris than ungrazed stands in a mixed Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine forest. Coarse woody debris and snags were not accounted for in the forest resource inventory data collected for the Pine Ridge and consequently in our models. Thus, our simulations are likely more reflective of integrated management that incorporates techniques that reduce woody fuel accumulations (e.g., prescribed fire). Assumptions of fire simulation models also need to be considered when interpreting our results. For instance, spatial relationships that occur within a stand and among stands are not accounted for. Fuel complexes in fire models are assumed to be uniform and homogenous (Alexander & Cruz, 2013). Patterns in forest structure tied to variables such as topography are not reflected in our simulation models, yet can play an important role in shaping fire patterns (Heyerdahl et al., 2001; Kellogg et al., 2008; Stambaugh & Guyette, 2008). As fire simulation models continue to advance, we will be better able to encapsulate this complexity in quantifications of forest stand resilience to wildfire.

ACKNOWLEDGMENTS

This work was supported by the McIntire-Stennis Cooperative Forestry Program grant number NEB-38-107, project accession number 1008861 from the USDA National Institute of Food and Agriculture, the Nebraska Forest Service, and the University of Nebraska's Institute of Agriculture and Natural Resources. We thank Emma Keele for her assistance with preliminary data modeling.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Donovan et al., 2022) are available from Dryad: https://doi.org/10.5061/dryad.73n5tb2zp.

ORCID

Victoria M. Donovan https://orcid.org/0000-0002-2906-5268
Dillon T. Fogarty https://orcid.org/0000-0003-2541-4245

REFERENCES

Abatzoglou, J. T. 2013. "Development of Gridded Surface Meteorological Data for Ecological Applications and Modelling." *International Journal of Climatology* 33: 121–31.

Abatzoglou, J. T., and A. P. Williams. 2016. "Impact of Anthropogenic Climate Change on Wildfire across Western US Forests." *Proceedings of the National Academy of Sciences* 113: 11770–5.

Agee, J. K., and C. N. Skinner. 2005. "Basic Principles of Forest Fuel Reduction Treatments." *Forest Ecology and Management* 211: 83–96.

Alexander, M. E., and M. G. Cruz. 2010. "Introducing the Canopy Fuel Stratum Characteristics Calculator." In *Proceedings of 3rd Fire Behavior and Fuels Conference*, edited by D. D. Wade. Spokane, WA: International Association of Wildland Fire.

Alexander, M. E., and M. G. Cruz. 2013. "Limitations on the Accuracy of Model Predictions of Wildland Fire Behaviour: A State-of-the-Knowledge Overview." *The Forestry Chronicle* 89: 372–83.

Allen, C. R., D. G. Angeler, G. S. Cumming, C. Folke, D. Twidwell, and D. R. Uden. 2016. "Quantifying spatial resilience." *Journal of Applied Ecology* 53: 625–35.

Atchley, A. L., R. Linn, A. Jonko, C. Hoffman, J. D. Hyman, F. Pimont, C. Sieg, et al. 2021. “Effects of Fuel Spatial Distribution on Wildland Fire Behaviour.” *International Journal of Wildland Fire* 30: 179–89.

Baker, W. L. 2009. *Fire Ecology in Rocky Mountain Landscapes*. Washington, DC: Island Press.

Bracmort, K. 2013. *Wildfire Management: Federal Funding and Related Statistics. Report R43077*. Washington, DC: Congressional Research Service.

Brantly, S. 2014. *Forest Grazing, Silvopasture, and Turning Livestock into the Woods*. Lincoln, NE: USDA National Agroforestry Center.

Brown, P. M., and C. H. Sieg. 1999. “Historical Variability in Fire at the Ponderosa Pine—Northern Great Plains Prairie Ecotone, Southeastern Black Hills, South Dakota.” *Écoscience* 6: 539–47.

Busenberg, G. 2004. “Wildfire Management in the United States: The Evolution of a Policy Failure.” *Review of Policy Research* 21: 145–56.

Covington, W. W., and M. M. Moore. 1994a. “Southwestern Ponderosa Pine Forest Structure: Changes since Euro-American Settlement.” *Journal of Forestry* 92: 39–47.

Covington, W. W., and M. M. Moore. 1994b. “Postsettlement Changes in Natural Fire Regimes and Forest Structure.” *Journal of Sustainable Forestry* 2: 153–81.

Cruz, M. G., M. E. Alexander, and R. H. Wakimoto. 2003. “Assessing Canopy Fuel Stratum Characteristics in Crown Fire Prone Fuel Types of Western North America.” *International Journal of Wildland Fire* 12: 39–50.

Cruz, M. G., M. E. Alexander, and R. H. Wakimoto. 2004. “Modeling the Likelihood of Crown Fire Occurrence in Conifer Forest Stands.” *Forest Science* 50: 640–58.

Cruz, M. G., M. E. Alexander, and R. H. Wakimoto. 2005. “Development and Testing of Models for Predicting Crown Fire Rate of Spread in Conifer Forest Stands.” *Canadian Journal of Forest Research* 35: 1626–39.

Dennison, P. E., S. C. Brewer, J. D. Arnold, and M. A. Moritz. 2014. “Large Wildfire Trends in the Western United States, 1984–2011.” *Geophysical Research Letters* 41: 2014GL059576.

Diamond, J. M., C. A. Call, and N. Devoe. 2010. “Effects of Targeted Cattle Grazing on Fire Behavior of Cheatgrass-Dominated Rangeland in the Northern Great Basin, USA.” *International Journal of Wildland Fire* 18: 944–50.

Dodge, M. 1972. “Forest Fuel Accumulation—A Growing Problem.” *Science* 177: 139–42.

Donovan, V., C. Roberts, D. Fogarty, D. Wedin, and D. Twidwell. 2022. “Targeted Grazing and Mechanical Thinning Enhance Forest Stand Resilience under a Narrow Range of Wildfire Scenarios.” Dryad. Dataset. https://doi.org/10.5061/dryad.73n5tb2zp

Donovan, V., C. Roberts, C. Wonkka, D. Uden, D. Angeler, C. Allen, D. Wedin, R. Drijber, and D. Twidwell. 2021. “Collapse, Reorganization, and Regime Identity: Breaking Down Past Management Paradigms in a Forest-Grassland Ecotone.” *Ecology and Society* 26: 27.

Donovan, V. M., C. P. Roberts, C. L. Wonkka, D. A. Wedin, and D. Twidwell. 2019. “Ponderosa Pine Regeneration, Wildland Fuels Management, and Habitat Conservation: Identifying Trade-Offs Following Wildfire.” *Forests* 10: 286.

Donovan, V. M., C. L. Wonkka, and D. Twidwell. 2017. “Surging Wildfire Activity in a Grassland Biome.” *Geophysical Research Letters* 44: 2017GL072901.

Emmingham, W. H., and N. E. Elwood. 1983. *Thinning: An Important Timber Management Tool*. Corvallis, OR: Pacific Northwest Extension, Oregon State University, Washington State University, University of Idaho.

Fulé, P. Z., W. W. Covington, H. B. Smith, J. D. Springer, T. A. Heinlein, K. D. Huisinga, and M. M. Moore. 2002. “Comparing Ecological Restoration Alternatives: Grand Canyon, Arizona.” *Forest Ecology and Management* 170: 19–41.

Gold, M. A., and J. W. Hanover. 1987. “Agroforestry Systems for the Temperate Zone.” *Agroforestry Systems* 5: 109–21.

Graham, R. T., S. McCaffrey, and T. B. Jain. 2004. *Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Guyette, R. P., M. C. Stambaugh, D. C. Dey, and R.-M. Muzika. 2012. “Predicting Fire Frequency with Chemistry and Climate.” *Ecosystems* 15: 322–35.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2001. “Spatial Controls of Historical Fire Regimes: A Multiscale Example from the Interior West, USA.” *Ecology* 82: 660–78.

Holling, C. S. 1973. “Resilience and Stability of Ecological Systems.” *Annual Review of Ecology and Systematics* 4: 1–23.

Jain, T. B., M. A. Battaglia, H.-S. Han, R. T. Graham, C. R. Keyes, J. S. Fried, and J. E. Sandquist. 2012. *A Comprehensive Guide to Fuel Management Practices for Dry Mixed Conifer Forests in the Northwestern United States*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Kane, V. R., B. N. Bartl-Geller, M. P. North, J. T. Kane, J. M. Lydersen, S. M. A. Jeronimo, B. M. Collins, and L. Monika Moskal. 2019. “First-Entry Wildfires Can Create Opening and Tree Clump Patterns Characteristic of Resilient Forests.” *Forest Ecology and Management* 454: 117659.

Keeley, J. E., G. H. Aplet, N. L. Christensen, S. G. Conard, E. A. Johnson, P. N. Omi, D. L. Peterson, and T. W. Swetnam. 2009. *Ecological Foundations for Fire Management in North American Forest and Shrubland Ecosystems*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Kellogg, L.-K. B., D. McKenzie, D. L. Peterson, and A. E. Hessl. 2008. “Spatial Models for Inferring Topographic Controls on Historical Low-Severity Fire in the Eastern Cascade Range of Washington, USA.” *Landscape Ecology* 23: 227–40.

Kolden, C. A. 2019. “We’re Not Doing Enough Prescribed Fire in the Western United States to Mitigate Wildfire Risk.” *Fire* 2: 30.

Koontz, M. J., M. P. North, C. M. Werner, S. E. Fick, and A. M. Latimer. 2020. “Local Forest Structure Variability Increases Resilience to Wildfire in Dry Western U.S. Coniferous Forests.” *Ecology Letters* 23: 483–94.

Larson, A. J., and D. Churchill. 2012. “Tree Spatial Patterns in Fire-Frequent Forests of Western North America, Including Mechanisms of Pattern Formation and Implications for Designing Fuel Reduction and Restoration Treatments.” *Forest Ecology and Management* 267: 74–92.

Lindenmayer, D., J. Franklin, and J. Fischer. 2006. “General Management Principles and a Checklist of Strategies to Guide Forest Biodiversity Conservation.” *Biological Conservation* 131: 433–45.

Lydersen, J. M., B. M. Collins, M. L. Brooks, J. R. Matchett, K. L. Shive, N. A. Povak, V. R. Kane, and D. F. Smith. 2017.

"Evidence of Fuels Management and Fire Weather Influencing Fire Severity in an Extreme Fire Event." *Ecological Applications* 27: 2013–30.

McWethy, D. B., T. Schoennagel, P. E. Higuera, M. Krawchuk, B. J. Harvey, E. C. Metcalf, C. Schultz, C. Miller, A. L. Metcalf, and B. Buma. 2019. "Rethinking Resilience to Wildfire." *Nature Sustainability* 2: 797–804.

Miller, A. D., J. R. Thompson, A. J. Tepley, and K. J. Anderson-Teixeira. 2019. "Alternative Stable Equilibria and Critical Thresholds Created by Fire Regimes and Plant Responses in a Fire-Prone Community." *Ecography* 42: 55–66.

Moritz, M. A., M. D. Hurteau, K. N. Suding, and C. M. D'Antonio. 2013. "Bounded Ranges of Variation as a Framework for Future Conservation and Fire Management." *Annals of the New York Academy of Sciences* 1286: 92–107.

MTBS Project. 2019. "MTBS Data Access: National Geospatial Data." https://www.mtbs.gov/.

Nebraska Forest Service. 2019. "Fuels Reduction/Forest Restoration." https://nfs.unl.edu/fuels-assistance.

Nebraska Wildfire Control Act. 2013. Nebraska Act 81-828.

Odion, D. C., M. A. Moritz, and D. A. DellaSala. 2010. "Alternative Community States Maintained by Fire in the Klamath Mountains, USA." *Journal of Ecology* 98: 96–105.

Pollet, J., and P. N. Omi. 2002. "Effect of Thinning and Prescribed Burning on Crown Fire Severity in Ponderosa Pine Forests." *International Journal of Wildland Fire* 11: 1–10.

R Core Team. 2021. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Renewable Resource Solutions, LLC. 2018. *Western Nebraska Timber Supply Study Report*. Crystal Falls, MI: Renewable Resource Solutions, LLC.

Ritter, S. M., C. M. Hoffman, M. A. Battaglia, C. S. Stevens-Rumann, and W. E. Mell. 2020. "Fine-Scale Fire Patterns Mediate Forest Structure in Frequent-Fire Ecosystems." *Ecosphere* 11: e03177.

Roberts, C. P., V. M. Donovan, S. M. Nodskov, E. B. Keele, C. R. Allen, D. A. Wedin, and D. Twidwell. 2020. "Fire Legacies, Heterogeneity, and the Importance of Mixed-Severity Fire in Ponderosa Pine Savannas." *Forest Ecology and Management* 459: 117853.

Roberts, C. P., V. M. Donovan, C. L. Wonkka, L. A. Powell, C. R. Allen, D. G. Angeler, D. A. Wedin, and D. Twidwell. 2019. "Fire Legacies in Eastern Ponderosa Pine Forests." *Ecology and Evolution* 9: 1869–79.

Rothermel, R. C. 1972. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*. Ogden, UT: US Department of Agriculture, Intermountain Forest and Range Experiment Station.

Schneider, R., K. Stoner, G. Steinauer, M. Panella, and M. Humpert. 2011. *The Nebraska Natural Legacy Project: State Wildlife Action Plan*. Lincoln, NE: Nebraska Game and Parks Commission.

Schoennagel, T., J. K. Balch, H. Brenkert-Smith, P. E. Dennison, B. J. Harvey, M. A. Krawchuk, N. Mietkiewicz, et al. 2017. "Adapt to More Wildfire in Western North American Forests as Climate Changes." *Proceedings of the National Academy of Sciences* 114: 4582–90.

Scott, J. H. 2006. *Comparison of Crown Fire Modeling Systems Used in Three Fire Management Applications*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Scott, J. H., and E. D. Reinhardt. 2007. "Effects of Alternative Treatments on Canopy Fuel Characteristics in Five Conifer Stands." In *Restoring Fire-Adapted Ecosystems: Proceedings of the 2005 National Silviculture Workshop*. Gen. Tech. Rep. PSW-GTR-203, edited by R. F. Powers, 193–209. Albany, CA: Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

Seidl, R., T. A. Spies, D. L. Peterson, S. L. Stephens, and J. A. Hicke. 2016. "Searching for Resilience: Addressing the Impacts of Changing Disturbance Regimes on Forest Ecosystem Services." *Journal of Applied Ecology* 53: 120–9.

Sparks, J. C., R. E. Masters, D. M. Engle, and G. A. Bukenhofer. 2002. "Season of Burn Influences Fire Behavior and Fuel Consumption in Restored Shortleaf Pine–Grassland Communities." *Restoration Ecology* 10: 714–22.

Spies, T. A., M. A. Hemstrom, A. Youngblood, and S. Hummel. 2006. "Conserving Old-Growth Forest Diversity in Disturbance-Prone Landscapes." *Conservation Biology* 20: 351–62.

Stambaugh, M. C., and R. P. Guyette. 2008. "Predicting Spatio-Temporal Variability in Fire Return Intervals Using a Topographic Roughness Index." *Forest Ecology and Management* 254: 463–73.

Steel, Z. L., M. J. Koontz, and H. D. Safford. 2018. "The Changing Landscape of Wildfire: Burn Pattern Trends and Implications for California's Yellow Pine and Mixed Conifer Forests." *Landscape Ecology* 33: 1159–76.

Stephens, S. L., M. A. Battaglia, D. J. Churchill, B. M. Collins, M. Coppoletta, C. M. Hoffman, J. M. Lydersen, et al. 2021. "Forest Restoration and Fuels Reduction: Convergent or Divergent?" *Bioscience* 71: 85–101.

Stevens, J. T., B. M. Collins, J. D. Miller, M. P. North, and S. L. Stephens. 2017. "Changing Spatial Patterns of Stand-Replacing Fire in California Conifer Forests." *Forest Ecology and Management* 406: 28–36.

Taylor, C. A., Jr. 2006. "Targeted Grazing to Manage Fire Risk." In *Targeted Grazing: A Natural Approach to Vegetation Management and Landscape Enhancement*, edited by K. Launchbaugh, J. W. Walker, and R. L. Daines, 107–12. Englewood, CO: American Sheep Industry Association.

Twidwell, D., B. W. Allred, and S. D. Fuhlendorf. 2013. "National-Scale Assessment of Ecological Content in the World's Largest Land Management Framework." *Ecosphere* 4: 1–27.

USDA Forest Service. 2019. "Nebraska National Forest Project Archive." https://www.fs.usda.gov/wps/portal/fsinternet/cs/projects/nebraska/landmanagement/projects?archive=1&sortby=4.

Vandenberghe, C., F. Freléchoux, M.-A. Moravie, F. Gadallah, and A. Buttler. 2007. "Short-Term Effects of Cattle Browsing on Tree Sapling Growth in Mountain Wooded Pastures." *Plant Ecology* 188: 253–64.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. "Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity." *Science* 313: 940–3.

Williams, M. A., and W. L. Baker. 2012. "Spatially Extensive Reconstructions Show Variable-Severity Fire and Heterogeneous Structure in Historical Western United States Dry Forests." *Global Ecology and Biogeography* 21: 1042–52.

Zimmerman, G. T., and L. Neuenschwander. 1984. “Livestock Grazing Influences on Community Structure, Fire Intensity, and Fire Frequency within the Douglas-Fir/Ninebark Habitat Type.” *Journal of Range Management* 37(2): 104–10.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher’s website.

How to cite this article: Donovan, Victoria M., Caleb P. Roberts, Dillon T. Fogarty, David A. Wedin, and Dirac Twidwell. 2022. “Targeted Grazing and Mechanical Thinning Enhance Forest Stand Resilience under a Narrow Range of Wildfire Scenarios.” *Ecosphere* 13(5): e4061. https://doi.org/10.1002/ecs2.4061