Journal of Forestry, 2024, **XX**, 1–17
https://doi.org/10.1093/jofore/fvae012
Advance access publication 13 May 2024
Research Article - fire & fuels management

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Constraints on Mechanical Fuel Reduction Treatments in United States Forest Service Wildfire Crisis Strategy Priority Landscapes

George A. Woolsey,[1] Wade T. Tinkham,[2,*] Mike A. Battaglia,[2] and Chad M. Hoffman[1]

[1]Department of Forest and Rangeland Stewardship, Warner College of Natural Resources, Colorado State University, Fort Collins, CO 80523, USA.
[2]USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO 80523, USA.
*Corresponding author e-mail: Wade.Tinkham@usda.gov

Abstract

The USDA Forest Service recently launched a Wildfire Crisis Strategy outlining objectives to safeguard communities and other values at risk by substantially increasing the pace and scale of fuel reduction treatment. This analysis quantified layered operational constraints to mechanical fuel reduction treatments, including existing vegetation, protected areas, steep slopes, and administrative boundaries in twenty-one prioritized landscapes. Results suggest that achieving the objective to treat 20%–40% of high-risk area is unlikely in most landscapes under a business-as-usual approach to mechanical fuel reduction treatments. Increased investment in steep-slope systems and expanded road access opens sufficient acreage to meet treatment objectives in eighteen of twenty-one priority landscapes. Achieving treatment objectives in the remaining three landscapes will require both increased investment to overcome physical constraints and navigating administrative complexities within reserved land allocations to implement fuels treatments at the pace and scale needed to moderate fire risk to communities.

Study Implications: Legal, operational, and administrative factors have hindered the implementation of proposed wildland fire risk reduction management actions. Investing in steep-slope systems, expanding use of temporary roads, and revising administrative rules to allow for appropriately tailored mechanical thinning in special conservation areas are possible ways to meet fuel reduction treatment objectives of the USDA Forest Service Wildfire Crisis Strategy in twenty-one landscapes across the western United States. Broadening the land base available for mechanical treatment allows for flexibility to develop treatment plans that optimize across the multiple dimensions of effective landscape-scale fuel treatment design and restore fire as a key ecosystem process.

Keywords: forest planning, risk management, forest policy

Despite broad agreement in scientific and policy arenas that proactive management actions are needed to foster fire- and climate-adapted forests in the western United States ([US]; Hessburg et al. 2021), the pace and scale of treatments has been inadequate to address the immense management challenge (Prichard et al. 2021). In response, the USDA Forest Service (Forest Service) recently launched a Wildfire Crisis Strategy (USFS 2022b), hereafter called the Strategy, with the goal to substantially increase the rate and extent of risk reduction fuel treatments over the next decade. The Strategy proposes to implement treatments on up to 20.2 million ha (50 million ac) over 10 years using an "all-lands" approach to manage wildfire risk across property boundaries and ownership types (public, private, tribal) in the western US (e.g., Charnley et al. 2020). To meet the goals of the Strategy, the US federal government appropriated just over $5 billion through the Infrastructure Investment and Jobs Act of 2021 (P.L. 117-58[1]) and an additional $1.8 billion in funding for fuels treatments via the Inflation Reduction Act of 2022 (P.L. 117-169[2]). The Forest Service has suggested that this proactive approach is a paradigm shift in their management from a reactive approach centered on aggressive wildfire suppression, which cost the agency over $1.9 billion per year from 2016 to 2020 (USFS 2022b).

The Strategy prioritizes twenty-one landscapes for initial investment in fuels treatment projects across ten western states targeting federal, state, tribal, and private lands where wildfire ignitions will potentially affect communities (figure 1). The twenty-one landscapes include forest and shrubland systems across the western US where increases in wildfire frequency, area burned, and area burned at high severity have been observed in recent decades (Hagmann et al. 2021; Parks and Abatzoglou 2020; Singleton et al. 2019; Syphard et al. 2018). The selection criteria for these twenty-one priority landscapes included potential wildfire exposure to buildings, infrastructure, and critical watersheds with additional consideration for underserved communities, indigenous peoples and lands, fish and wildlife habitat, and other values (USFS 2023a). Areas with ongoing projects that could be scaled in their extent while operating under existing authorities were prioritized to maximize the area of impact (USFS 2023a). The boundaries of the twenty-one priority landscapes roughly

Received: January 9, 2024. **Accepted:** April 18, 2024.

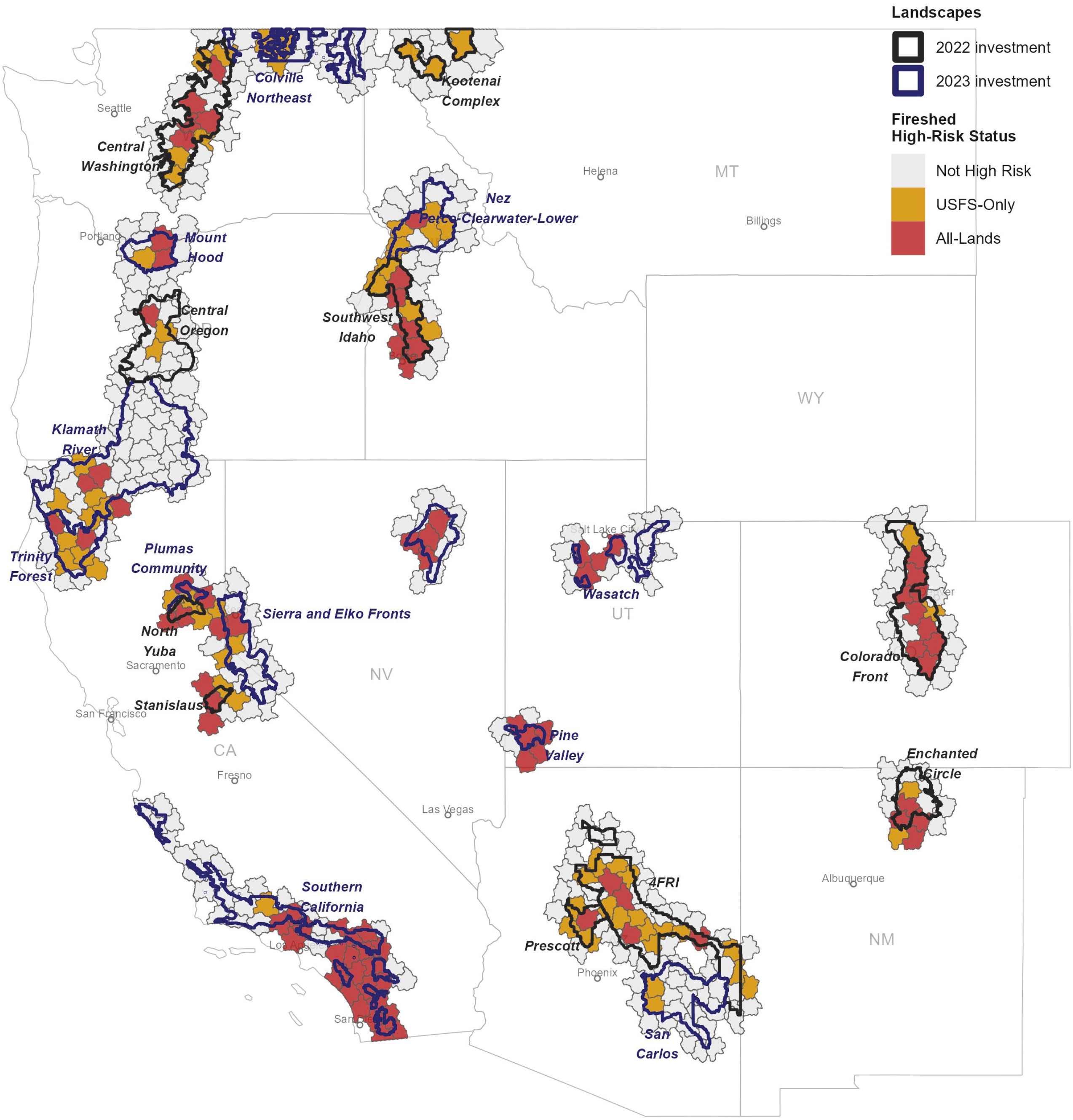

Figure 1 2022 USDA, Forest Service Wildfire Crisis Strategy 21 landscapes prioritized for fuel reduction treatments in Arizona, California, Colorado, Idaho, Nevada, New Mexico, Montana, Oregon, Utah, and Washington. Ten landscapes outlined in black and 11 outlined in navy blue represent 2022 and 2023 Strategy investments, respectively. Firesheds intersecting priority landscapes are shaded by risk to communities with the highest risk firesheds identified in the Strategy shaded red (multiple ownerships) and orange (Forest Service ownership only). Firesheds shaded in gray are still at-risk to potential wildfire impacts but were not classified as high-risk by the Strategy.

follow the boundaries of "firesheds" prioritized to reduce wildfire transmission to developed areas (figure 1). Firesheds are geographic delineations averaging approximately 100,000 ha (250,000 ac) that were created to organize the landscape into units for managing wildfire risk to communities. Wildfire simulation data from the national FSim library (Short et al. 2020) was intersected with building locations to quantify source of fire risk to communities at the fireshed level (Ager et al. 2021a). Nested within firesheds are project areas of approximately 10,000 ha (25,000 ac) in size that represent the geographic unit at which vegetation and fuel management projects are planned. The full process for delineating fireshed boundaries and determining risk across the continental US is described in detail in Ager et al. (2021a).

The size of each priority landscape does not represent total planned treatment acres. Rather, the Strategy has set a goal to treat 20%–40% of "high-risk" fireshed areas within the twenty-one priority landscapes where community exposure to potential wildfire is the greatest (USFS 2022c, p. 4; USFS 2022d, p. 10). The 20%–40% treatment level follows science showing that fuels reduction at this scale can effectively reduce fire size and severity (Collins and Skinner 2014; Lydersen et al. 2017). The total area of the twenty-one priority landscapes is approximately 19 million ha (47 million ac), of which 9.6 million ha (23.7 million ac) are in high-risk firesheds; an objective of treating 20%–40% would indicate the need to treat 1.9 to 3.8 million ha (4.7 to 9.5 million ac). The Forest Service notes that meeting Strategy objectives may require increasing fuels and forest health treatments by up to four times current treatment levels in some areas of the western US (USFS 2022b). Fuels reduction treatments are implemented with the intent to "alter the fuel complex in such a way as to modify fire behavior and thereby minimize the potential negative impacts of future wildfires on ecosystem goods and services, cultural resources, and human communities" (Hoffman et al. 2020, p. 1160). Land managers consider landscape condition, ecology, and objectives to design fuel treatments that typically include mechanical thinning of trees prioritizing the removal of small-diameter trees and fire-sensitive species, mastication of woody material, prescribed fire, managed wildfire, grazing, or herbicide to reduce herbaceous fuels, or a combination of approaches (Agee and Skinner 2005; Jain et al. 2012; Miller et al. 2019; Monsen et al. 2004).

Prior research evaluating fuel treatment effectiveness at achieving desired outcomes provides guidance on how to design and implement treatments at broad spatial scales (Collins et al. 2010). Recent reviews of fuel treatment effectiveness at the landscape scale (McKinney et al 2022; Ott et al. 2023; Urza et al 2023) have found positive relationships between effectiveness and (1) the amount of area treated (i.e., treatment extent), (2) the size of individual treatment units, (3) use of a placement prioritization scheme (e.g., based on fire threat) or optimization algorithm (e.g., treatment optimization model [Finney et al. 2007]), and (4) recency of treatment. This research indicates that effectiveness of fuel treatments at the landscape scale is affected by interacting dimensions of treatment design rather than extent (e.g., 20%–40% of a landscape) alone. However, maximizing the effectiveness of fuel treatments across a landscape is hindered by a complex web of regulations and other constraints that limit the extent, intensity, and location of treatment application (Lydersen et al. 2019; North et al. 2015; Van Deusen et al. 2012). Although increased use of managed fire (i.e., prescribed burning and managed wildfires) has been touted as a strategy for increasing treatment pace and scale (e.g., Kolden 2019), its use is significantly limited by risk-related concerns (air quality, liability, safety), resources (workforce), and regulations (Miller et al. 2020; Ryan et al. 2013). Fuel reduction via mechanical means represents an alternative; however, financial, legal (e.g., wilderness and roadless areas), operational (e.g., steep slopes, distance to roads), and administrative (e.g., sensitive species habitat, riparian buffers) factors alone or in combination affect whether mechanical equipment is practical or allowed in different areas (North et al. 2015). Prior work considering layered legal, operational, and administrative constraints found that only 25% of the total land area and 44% of productive forest area was available for mechanical treatment on Forest Service land across the Sierra Nevada bioregion (North et al. 2015). By contrast, in the area spanning the Four Forest Restoration Initiative (4FRI) in northern Arizona, Hampton et al. (2011) estimated that 74% of ponderosa pine (*Pinus ponderosa*) forest was available for mechanical thinning after removing acreage due to regulations and guidelines related to wildlife, soils, hydrologic, and other factors. The national forestland in the Sierra Nevada analyzed by North et al. (2015) overlaps with portions of four Strategy priority landscapes in this region, but the Strategy landscape boundaries do not follow national forest boundaries and include other land ownerships excluded in previous analysis. The area in northern Arizona analyzed by Hampton et al. (2011) is nearly identical to the 4FRI priority landscape. Even with substantial funding allocated to complete the fuels reduction work needed, these studies indicate that there could be major challenges to completing the proposed work on some landscapes, whereas meeting treatment objectives may be more feasible on others. To support development of the Strategy, Ager et al. (2021b) used the strategic planning model ForSys (Ager et al. 2019) to prioritize areas for treatment on the 58 million ha (143 million ac) of the seventy-six Forest Service-managed national forests in fifteen western and central US states (Forest Service regions 1–6) and found that protected areas, including wilderness and roadless areas where mechanical equipment is either legally prohibited or infeasible, made up 50% of the total area (Ager et al. 2021b). Although this strategic planning addressed some coarse-scale restrictions to implementing mechanical treatments (i.e., protected areas), a more granular identification of constraints (*sensu* Hampton et al. 2011; North et al. 2015) is needed to address the feasibility of implementing treatment in areas prioritized by the Strategy (Ager et al. 2021b).

The objective of this study is to spatially identify the mechanically treatable area and the constraints on management activities in the twenty-one priority landscapes outlined in the Forest Service Wildfire Crisis Strategy to inform plan implementation and future policy-making efforts. We took a tiered approach to understand the constraints to mechanical treatment. Specifically, at the scale of each of the twenty-one landscapes, we asked the following questions: (1) What is the spatial extent of the landscape on which ground-based equipment is allowed and operationally feasible? (2) Which constraining factor(s)—legal, operational, administrative—is most limiting to mechanical fuel reduction treatment? To characterize the spatial arrangement of mechanically available land we used the nested spatial framework for firesheds and asked the questions (3) How are fireshed project areas distributed based on level of mechanical constraint? (4) Is 20%–40% of high-risk fireshed area mechanically available in moderately and lightly constrained fireshed project areas? and (5) Are lightly constrained fireshed project areas spatially aggregated such that extensive treatments could be implemented using primarily mechanical methods? To address these questions, three scenarios of operational constraints were analyzed to represent a range of management alternatives under current standards for implementing mechanical treatment.

Methods

This study combines readily available datasets in a Google Earth Engine workflow to quantify the amount and spatial arrangement of land available for mechanical risk reduction fuel treatments after considering operational constraints within the twenty-one landscapes prioritized in the Forest Service Wildfire Crisis Strategy. A hierarchy of constraints that affect mechanical operability (figure 2) starting with more inflexible limitations and progressing to less rigid

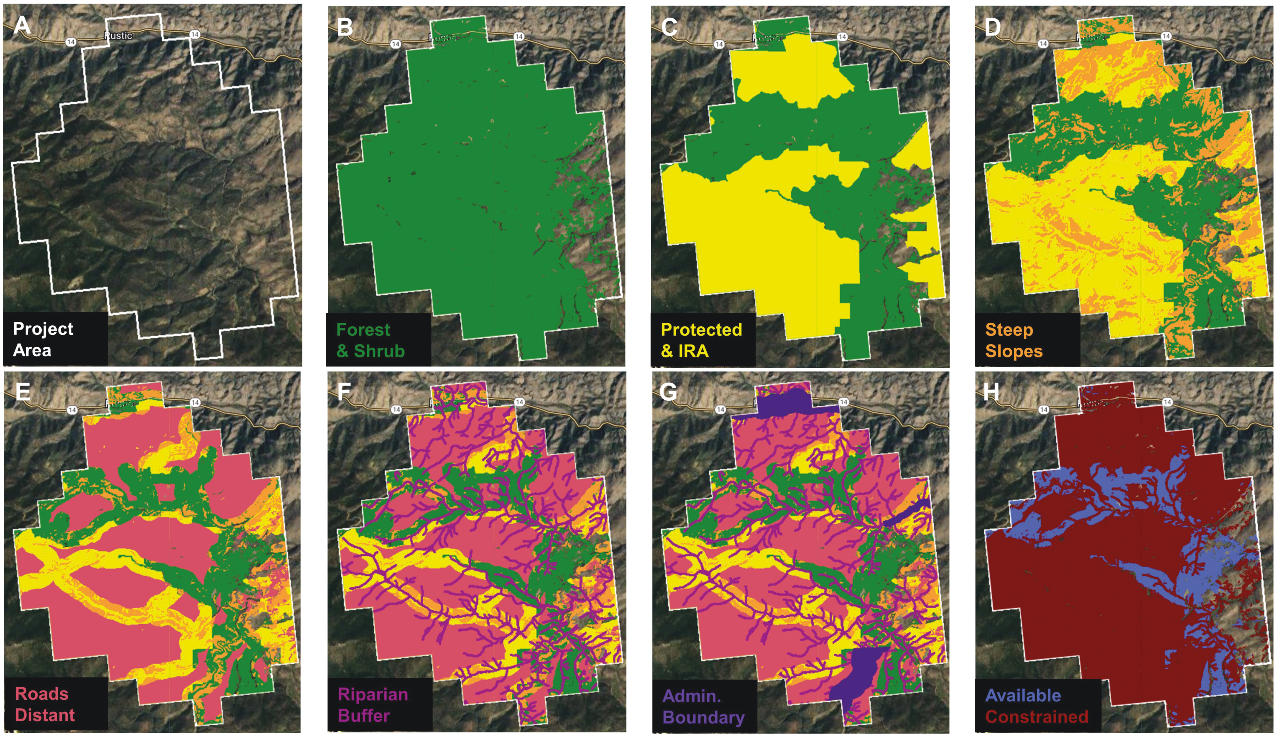

Figure 2 Workflow used to quantify the amount of land available for mechanical forest health and risk reduction fuel treatments by considering layered operational constraints. This example illustrates scenario 2 for a (A) 10,252 ha (25,000 ac) fireshed project area near Rustic, Colorado in the Colorado Front Range priority landscape. The analysis identifies (B) all forest and shrubland areas, (C) removes protected and inventoried roadless areas, (D) classifies land as mechanically operable based on terrain slope, (E) buffers existing roads according to equipment haul distances, (F) removes areas within riparian buffers, (G) removes areas within administrative boundaries, and (H) determines what land is mechanically available or constrained and by what factor.

constraints was implemented in a manner similar to North et al. (2015). To answer questions 1 and 2 of the present study, we used this hierarchical approach to classify the area within the boundary of each of the twenty-one priority landscapes as either mechanically available or mechanically constrained. To reflect the emerging increase in willingness to invest in fuel reduction treatments, our approach expands on North et al. (2015) by allowing mechanical access regardless of timber value across all scenarios, by expanding slope access up to 60% (compared with 50% slopes to access only the most valuable timber), and by considering a scenario that allows for treatment within administratively designated lands.

After identifying the area available for mechanical operations, we used the nested spatial framework delineating firesheds developed by Ager et al. (2021a) and described above to characterize the spatial arrangement of mechanically available land within the twenty-one priority landscapes (figure 3). The level of analysis used for questions 3–5 in our study was the fireshed project area approximately 10,000 ha (25,000 ac) in size, which represents the area at which planning and implementation of vegetation and fuel management treatments typically occurs. Fireshed project areas were included for analysis if 25% or more of the project area was within the boundary of a priority landscape (figure 3B).

Management Scenarios Used to Quantify Mechanically Available Acreage

As a first-level constraint, areas within the boundary of each priority landscape that were not classified as forest or shrubland based on the 2019 National Land Cover Database ([NLCD]; Dewitz and USGS 2021) were removed from consideration for mechanical treatment (figure 2B). The remaining area represented the total acreage available for treatment given no constraints. We chose to analyze the feasibility of implementing mechanical operations on combined forest and shrubland acreage because the Strategy makes no distinction between treatment objectives under different land cover conditions, high-risk firesheds span both cover types, and research identifies mechanical treatment as an alternative in both systems. With combined forest and shrubland area as the base layer, protected areas such as wilderness and inventoried roadless areas were identified and removed (figure 2C) using Gap Analysis Project (GAP) Status Code 1 areas and inventoried roadless area (IRA) designation in the US Geological Survey Protected Areas Database ([PAD-US]; USGS 2018). Mechanized equipment is prohibited in wilderness areas (Wilderness Act, P.L. 88-57716[3]), whereas roadless rules ("Special Areas; Roadless Area Conservation," 66 Federal Register 3244, January 12, 2001[4]) prohibit road construction and timber harvest but allow for the removal of small-diameter trees to reduce the likelihood of uncharacteristic wildfire. These restrictions were also used by Ager et al. (2021b) in support of Strategy development.

To account for various operability constraints for mechanical equipment, we developed three scenarios (Table 1) prior to analysis to represent a gradient in funding, policy, and management options based on four constraining factors to mechanical operability: slope, road access, riparian buffers, and administrative designation (Table 1). Scenario 1 reflects a status quo approach to mechanical fuel reduction treatments

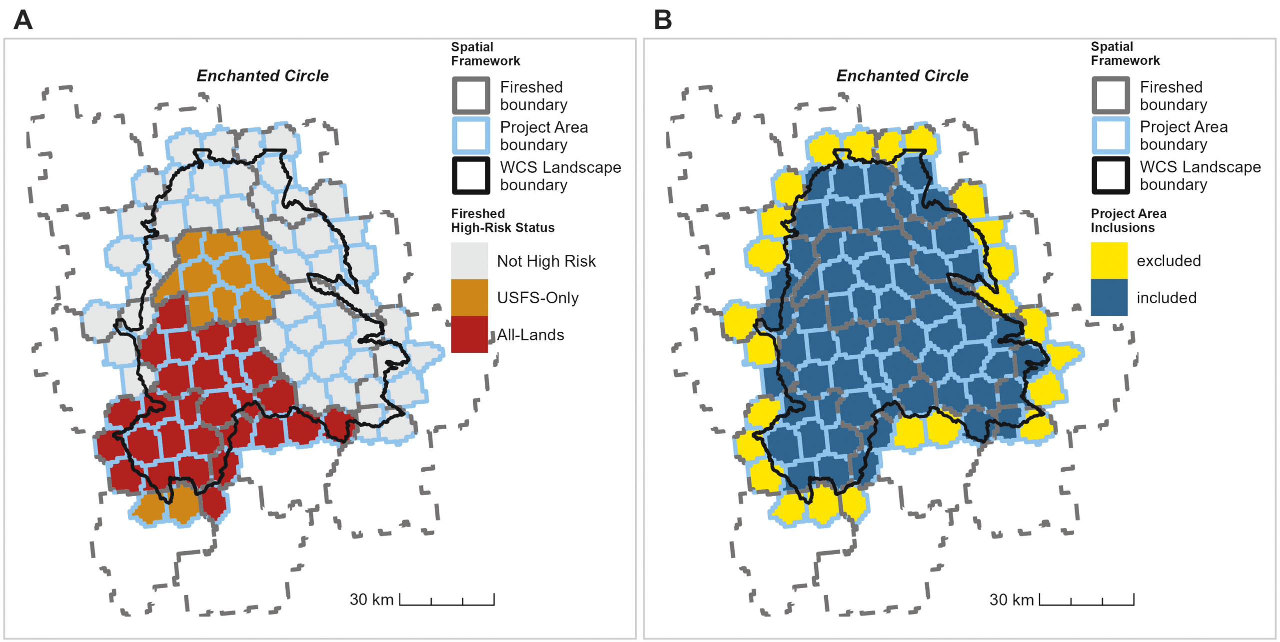

Figure 3 (A) Nested spatial framework of the Enchanted Circle priority landscape (New Mexico; black outline) delineating firesheds (gray dashed outline) approximately 100,000 ha (250,000 ac) in size which are the broad scale unit of prioritization and nested fireshed project acreas (light blue outline) approximately 10,000 ha (25,000 ac) in size which are used for planning and conducting fuel management projects. Fireshed project areas are shaded by risk to communities of the parent fireshed with the highest risk firesheds as determined by the Strategy shaded red (multiple ownerships) and orange (Forest Service ownership only). (B) Fireshed project areas that did not have at least 25% of area within the boundary of the Strategy priority landscape were excluded (shaded yellow) from the analysis.

Table 1. Hierarchy of constraints used to determine whether mechanical equipment was allowed and operationally feasible for this analysis, where spatial analysis was overlaid from L1 through L5 to attribute the cause of constraint.

	Constraint type	Scenario 1 most constrained	Scenario 2	Scenario 3 least constrained
L0:	NLCD cover type	Forest or shrubland	Forest or shrubland	Forest or shrubland
L1:	Protected or IRA status	Not protected	Not protected	Not protected
L2:	Slope	<40%	<60%	<60%
L3:	Distance to nearest road	<1,000 ft <305 m	<2,000 ft <610 m	<2,000 ft <610 m
L4:	Riparian buffer	>100 ft >30 m	>100 ft >30 m	>50 ft >15 m
L5:	Administrative designation	No designation	No designation	Any designation

based on Forest Service operations in recent years (North et al. 2015) where mechanical treatments occur on slopes <40% within 1,000 feet (305 m) of existing road infrastructure and are excluded within 100 ft (30 m) of waterways and all specialty administrative designations (e.g., sensitive species habitat, conservation areas, wildlife refuges). Scenario 2 represents a management approach characterized by increased investment to overcome physical constraints by working on steeper slopes up to 60% and increasing the use of temporary roads by extending the distance to existing roads to 2,000 feet (610 m), with no changes to riparian buffers and administrative designations. This scenario emphasizes utilizing recent innovations in mechanized harvesting systems, such as tethered or cable-assisted equipment, that have been designed to operate on steep slopes (e.g., 40%–70%) and may extend mechanical management opportunities to previously inoperable areas (Belart et al. 2019; Sessions et al. 2016). Although there are steep-slope systems that can operate on slopes over 60%, we chose 60% slope as the maximum slope considered mechanically accessible in our analysis based on prior research showing that accessing slopes > 65% using tethered equipment significantly increases operational cost due to decreased maneuverability and payload (West et al. 2022). Scenario 3 is the least restrictive scenario considered in this analysis and builds on scenario 2 by expanding treatment near riparian areas and within administratively designated areas. Management scenario 3 represents a treatment approach that is characterized by both increased investment to overcome physical constraints (as in scenario 2) and reduced administrative hurdles to implement treatment within reserved lands (Charnley et al. 2015; Gosnell et al. 2020; Stephens and Ruth 2005). We acknowledge that all of the constraints to mechanical fuel reduction treatments considered in our analysis can potentially be overcome via policy changes, technological innovation, increased funding, or a combination thereof. However, we chose to analyze opportunities to expand fuel reduction via mechanical means using constraint thresholds that were set based on levels represented in the published literature, which were established through consultation with regional managers (Holland et al. 2022; North et al. 2015, 2021).

Slope constraints to mechanically treatable areas were calculated using 3D Elevation Program ([3-DEP]; USGS 2020) data at 10 m resolution (figure 2D). Remote areas distant from existing road infrastructure were removed using the US Census Bureau TIGER/Line road dataset (USCB 2016) and the Forest Service Forest Activity Tracking System database ([FACTS]; USFS 2023b) tables, including the motor vehicle use map for trails and roads and the national forest system trail and road map (figure 2E). Administrative boundaries were removed from the treatable area (figure 2F and G) using GAP Status Code 2 in PAD-US, the US Fish and Wildlife Survey Threatened and Endangered Species Active Critical Habitat Report (USFWS 2023), and riparian buffers were identified using the National Hydrography Dataset ([NHD]; USGS 2022). After each constraint was added, we calculated the reduction in forest and shrubland area (hectares) and the reduction percentage in each landscape by comparing this value with the total area remaining after the cumulative reduction from prior constraints.

Spatial Arrangement of Mechanically Available Land

Distribution of Fireshed Project Areas by Level of Mechanical Constraint (Question 3)

For each fireshed project area included in this analysis, the entire project area, including area outside of the priority landscape boundary, was used to calculate the percentage of forest and shrubland mechanically available. The fireshed project areas were then divided into three classes of mechanical constraint: high (81%–100% constrained; 0%–19% available for mechanical treatment), medium (60%–80% constrained; 20%–40% available), and low (0%–59% constrained; 41%–100% available). Our fireshed project area classification was based on the methodology outlined for subwatersheds by North et al. (2015), who used slightly different cutoff levels: high (85%–100% constrained), medium (65%–84% constrained), and low (0%–64% constrained). We chose these levels to align with Strategy objectives and science showing that fuels treatments are more effective as the percentage of the landscape treated progressively increases. We then calculated the proportion of fireshed project areas in each of these mechanical constraint classes for each priority landscape.

Mechanically Available Acreage to Meet Treatment Area Objective of 20%–40% (Question 4)

We assumed that priority landscapes with greater proportions of spatially clustered treatable acreage are more likely to achieve the Strategy objective to treat 20%–40% of high-risk acreage. Using our classification of fireshed project areas by level of mechanical constraint, landscapes where mechanical methods are lightly constrained across a majority of project areas will likely be able to plan fewer, larger individual treatments given that available acreage is spatially clustered, whereas moderately constrained project areas could provide supplemental treatment acreage to meet objectives. To assess the 20%–40% objective, the amount of mechanically available area within low and medium constraint high-risk fireshed planning areas was aggregated and compared against the total area of high-risk fireshed planning areas included for analysis (figure 3). Fireshed project areas were classified as high-risk based on the parent fireshed in the Strategy (figures 1 and 3A). This methodology captures three of the five dimensions of fuel treatment design found to positively influence landscape-scale effectiveness (Ott et al. 2023): (1) treatment areas are prioritized based on classification as high-risk under the Strategy, (2) the potential treatment area is spatially clustered to allow for increasing individual treatment unit size, and (3) the extent determined available for treatment is evaluated compared with the Strategy objective level of 20%–40%.

Spatial Aggregation of Fireshed Project Areas by Level of Mechanical Constraint (Question 5)

To quantify the spatial aggregation of fireshed project areas by level of mechanical constraint, we created patch boundaries by combining spatially connected fireshed project areas of the same class of mechanical constraint until all other adjacent project areas were of a different class (accomplished by performing a geometric union by constraint class). For each landscape, we then selected the largest patch of interconnected fireshed project areas by constraint class and calculated the proportion of the total area of all project areas represented by this patch (i.e., largest patch index). Although there are alternative landscape metrics that quantify connectivity and dominance, we chose the largest patch index based on its intuitive interpretation. Extensive patches with little mechanical constraint represent opportunities for land managers to design plans that incorporate the principles of effective landscape-scale fuel treatments (Collins et al. 2010).

Results

Mechanically Available Acreage in the Strategy's Priority Landscapes

The total area of the twenty-one priority landscapes selected in the Forest Service Wildfire Crisis Strategy is approximately 19 million ha (48 million ac) of which 16.1 million ha (39.8 million ac) is classified as forest or shrubland (83%; Table 2). The Central Washington Initiative landscape has the lowest proportion of combined forest and shrubland cover at 70% and the North Yuba (California) landscape has the highest proportion of forest and shrubland cover at 97% (Table SA1). Four landscapes have a majority of area that is classified as shrubland—Prescott (Arizona), San Carlos Apache Tribal Forest Protection (Arizona), Southern California Fireshed Risk Reduction Strategy, and Sierra and Elko Fronts (Nevada)—whereas the remaining seventeen landscapes are primarily forested (Figure SA1).

On the combined forest and shrub area across all twenty-one priority landscapes, 29% is available to mechanical treatment under status quo (scenario 1) constraints, 42% is available under scenario 2 constraints, and 53% is available under scenario 3 constraints (Table 2). Mechanically available forest and shrubland acreage at the individual landscape level ranged from a low of 10% to a high of 60% under scenario 1, 20% to 70% under scenario 2, and 24% to 83% under scenario 3 (Table SA1; Figure SA2). A detailed report of the data describing the extent of mechanically available acreage within the boundary of each priority landscape by scenario and the reductions by constraining factor is presented in supplementary Appendix A online.

Table 2. Combined forest and shrubland area across the twenty-one priority landscapes and the percentage reduction of different types of constraints on mechanical treatment based on the three scenarios of operational constraints considered in this analysis.

			Constraint						
			Least flexible to most flexible						
	Forest and shrub (ha)	Forest and shrub (%)	Protected and IRA	Slope steepness	Road distance	Riparian buffer	Administrative boundary	Mechanically available (ha)	Mechanically available (%)
Overall landscape area									
Scenario 1	16.1 M	82.9%	-22.0%	-16.9%	-19.8%	-7.0%	-5.6%	4.6 M	28.7%
Scenario 2	16.1 M	82.9%	-22.0%	-5.2%	-12.0%	-10.5%	-8.4%	6.8 M	41.9%
Scenario 3	16.1 M	82.9%	-22.0%	-5.2%	-12.0%	-7.5%	0.0%	8.6 M	53.3%

Scenario 1 represents the status quo with mechanical fuel reduction treatments occurring on slopes <40% within 1,000 feet (305 m) of existing road infrastructure and are excluded within 100 ft (30 m) of waterways and all specialty administrative designations. Scenario 2 allows working on slopes up to 60% and use of temporary roads to allow operation within 2,000 feet (610 m) of existing roads. Scenario 3 expands on Scenario 2 by allowing mechanical treatment near riparian areas and within administratively designated areas.

Spatial Arrangement of Mechanically Available Land

Distribution of Fireshed Project Areas by Level of Mechanical Constraint (Question 3)

Under the status quo (scenario 1), mechanical fuel reduction treatments were highly constrained (0%–19% available for mechanical treatment) on 42% of project areas ($n = 896$), moderately constrained (20%–40% available) on 29% of project areas ($n = 622$), and lightly constrained (41–%100% available) on 29% of project areas ($n = 613$) (figure 4B). Relaxing steep slope constraints and expanding temporary road construction in scenario 2 increased the proportion of lightly constrained project areas across all landscapes from 29% to 53% and from 28% to 58% within high-risk firesheds (figure 4B). Our scenario 3, which expands treatment in riparian and administratively designated areas, further increased the proportion of lightly mechanically constrained fireshed project areas to 68% of all fireshed project areas and to 76% of high-risk firesheds (figure 4B).

Under the operational constraints represented by scenario 1, project areas lightly constrained to mechanical access accounted for the highest proportion of area on four of twenty-one landscapes, whereas eight landscapes had a greater proportion of project areas highly constrained to mechanical access (figure SB1). Allowing mechanical operations on steeper slopes and expanding the use of temporary roads using scenario 2 resulted in all but seven priority landscapes (i.e., fourteen landscapes) having a majority (>50%) of project areas classified as lightly constrained (figure B1). Relaxing constraints to mechanical operations in administratively designated areas (scenario 3) in addition to operating on steeper slopes and further away from existing roads resulted in all but three priority landscapes—San Carlos Apache Tribal Forest Protection (Arizona), Southern California Fireshed Risk Reduction Strategy, and Pine Valley (Utah)—or eighteen landscapes having a majority (>50%) of project areas classified as lightly constrained (figure B1).

Mechanically Available Acreage to Meet Treatment Area Objective of 20%–40% (Question 4)

Under the status quo approach to mechanical fuels reduction treatment (scenario 1), there are four priority landscapes where over 20% of high-risk acreage is mechanically available in lightly constrained project areas, whereas an additional ten landscapes may meet the 20% minimum target of high-risk acreage by pooling low and medium constraint areas (figure 5; Table SB1). However, seven landscapes have less than 20% of high-risk area mechanically available in combined low and medium constraint planning areas based on scenario 1 operational constraints. Increasing slope and road access under scenario 2 resulted in fifteen priority landscapes with over 20% of high-risk acreage mechanically available in lightly constrained areas and an additional three landscapes with over 20% of high-risk acreage mechanically available in combined low and medium constraint areas (figure 5; Table SB1). Under scenario 2 operational constraints, there are only three landscapes with less than 20% of high-risk area mechanically available in combined low and medium constraint planning areas: Central Washington Initiative (Washington; 13.2% available), Trinity Forest Health and Fire-Resilient Rural Communities (California; 17.1% available), and Mount Hood Forest Health and Fire-Resilient Communities (Oregon; 19.9% available). Under the most comprehensive approach to fuel reduction work considered in this analysis (scenario 3), the combined impact of operating on steep slopes, expanding the use of temporary roads, and allowing treatment near riparian areas and within administratively designated areas resulted in all twenty-one priority landscapes with sufficient available acreage in lightly constrained areas to meet the objective of treating over 20% of high-risk acreage using mechanical methods alone (figure 5; Table SB1).

Spatial Aggregation of Fireshed Project Areas by Level of Mechanical Constraint (Question 5)

Examination of a map of project areas shaded by constraint level under scenario 2 (figures 4A and 6A, Figures SB3–SB22) reveals that mechanically constrained and mechanically available areas tend to be clustered. For example, in the Central Washington Initiative (figure 6A) landscape under scenario 2 constraints, fireshed planning areas in the western portion of the landscape are mostly highly constrained, whereas fireshed planning areas in the eastern portion are mostly lightly constrained. The largest patch of fireshed project areas classified as lightly constrained covered between 10% and 20% of the total landscape for most priority landscapes (i.e., eleven of twenty-one) under scenario 1 (figure SB2). Three landscapes had a significant proportion of total area covered by the largest lightly constrained patch in which managers would have

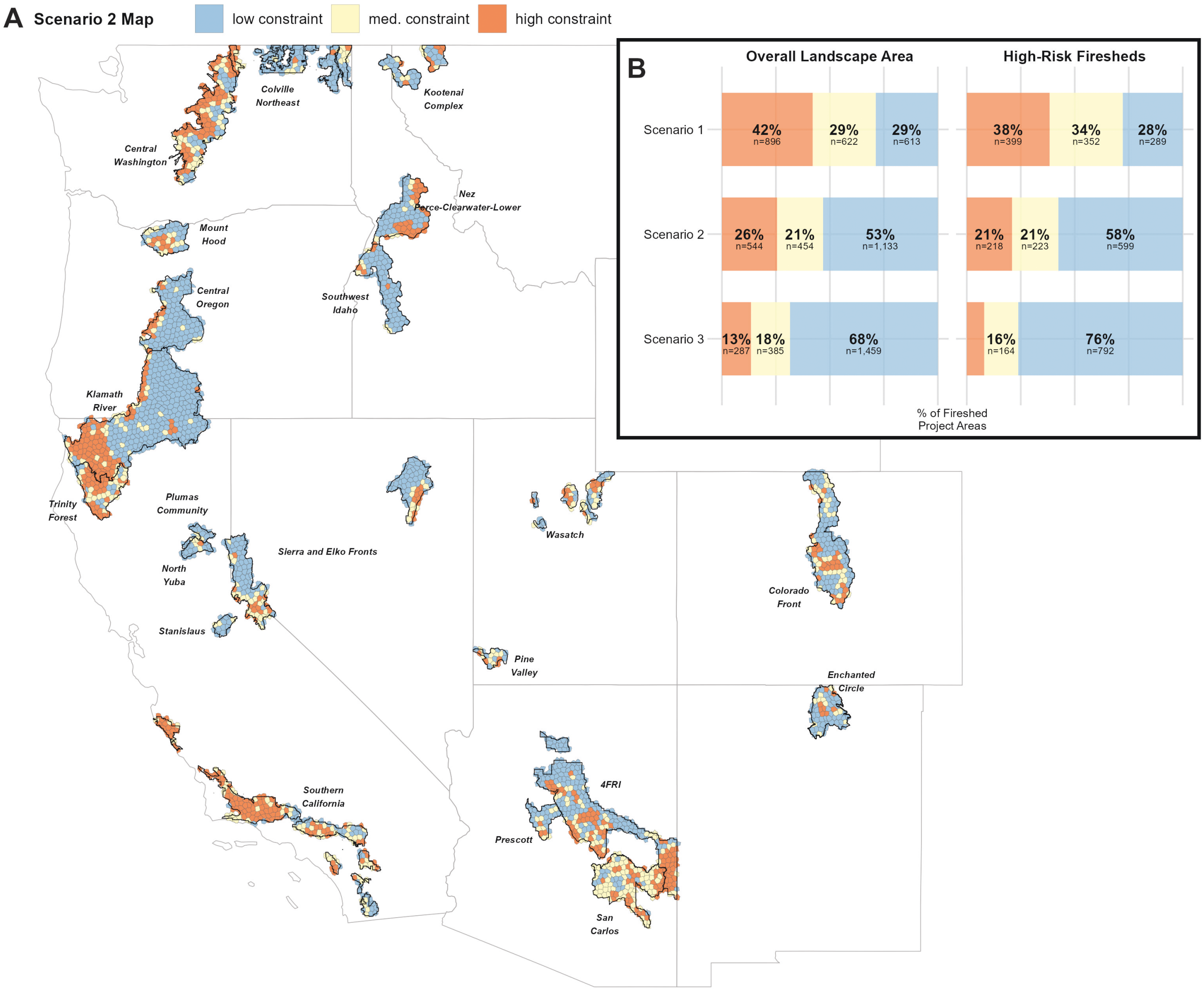

Figure 4 Fireshed project areas were divided into three classes of mechanical constraint: high (81%–100% constrained; 0%–19% available for mechanical treatment), medium (60%–80% constrained; 20%–40% available), and low (0%–59% constrained; 41%–100% available). (A) Fireshed project areas in Forest Service Wildfire Crisis Strategy priority landscapes were mapped and shaded by level of constraint with this example representing scenario 2 mechanical constraints. (B) The distribution of fireshed project areas by level of constraint was determined within the overall landscape area and within high-risk firesheds only.

broad flexibility to optimize fuel treatment design: Central Oregon (73%), Southwest Idaho (60%), and Klamath River Basin (Oregon; 47%). Allowing access to steeper slopes and areas more distant from existing roads under scenario 2 increased the proportion of the total landscape covered by the largest patch of lightly constrained area to 25% or greater in fifteen of the twenty-one priority landscapes (figure B2). Under the most thorough approach we considered for expanding fuel reduction treatments, scenario 3, the largest lightly mechanically constrained patch comprised 35% or greater of the total landscape in all but four priority landscapes (i.e., seventeen landscapes; figure B2). The Southern California Fireshed Risk Reduction Strategy and San Carlos Apache Tribal Forest Protection (Arizona) landscapes were among the priority landscapes with the lowest proportion of total landscape acreage covered by the largest lightly mechanically constrained patch under all three mechanical constraint scenarios considered. On the Southern California Fireshed Risk Reduction Strategy landscape, the proportion of total landscape area composed of the largest patch of lightly mechanically constrained project areas was 1% for scenario 1, 6% in scenario 2, and 8% under scenario 3 (Figures SB2 and SB8). Conversely, on this priority landscape, the proportion of total landscape area composed of the largest patch of highly mechanically constrained project areas was 39% under scenario 1, 24% under scenario 2, and 20% under scenario 3 (Figures SB2 and SB8).

Discussion

Constraints on Meeting Strategy Objectives using Mechanical Methods

The Forest Service Wildfire Crisis Strategy plan prioritizes twenty-one landscapes across ten states in the western US for initial funding to accomplish fuels reduction treatments on 20%–40% of high-risk acreage where community exposure to potential wildfire is the greatest (USFS 2022b, 2022c, 2023a). The Strategy highlights the use of mechanical treatment as a primary tool for fuels reduction treatments, yet mechanical operability is limited by factors

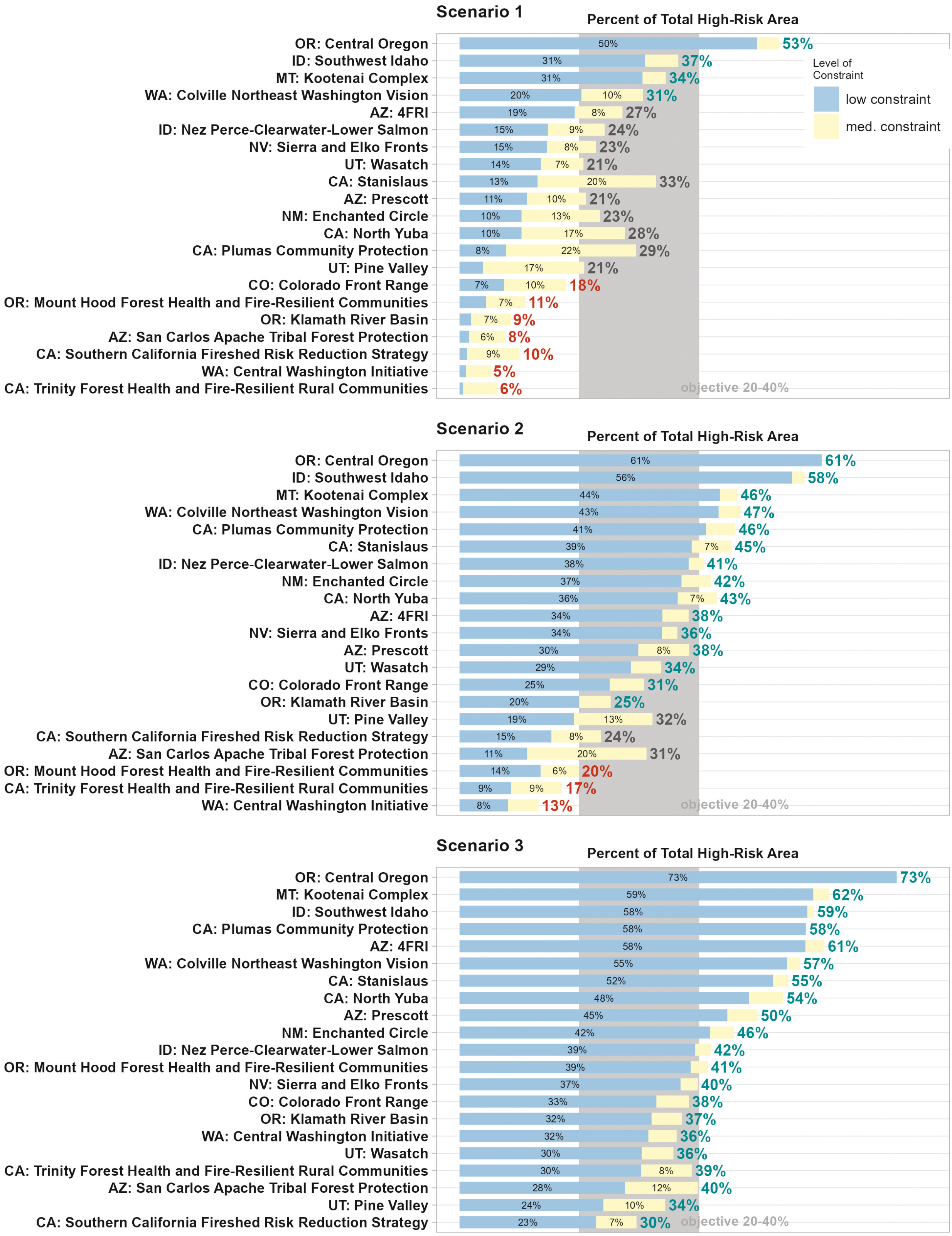

Figure 5 Percent of total area within high-risk firesheds where there exists the ability to create effective, extensive fuels treatments by mechanical methods alone (low constraint areas: 0%–59% constrained; 41%–100% available for mechanical treatment) or in combination with managed fire (medium constraint areas: 60%–80% constrained; 20%–40% available). The gray area in the plot represents the Strategy objective of treating 20%–40% of high-risk fireshed acreage.

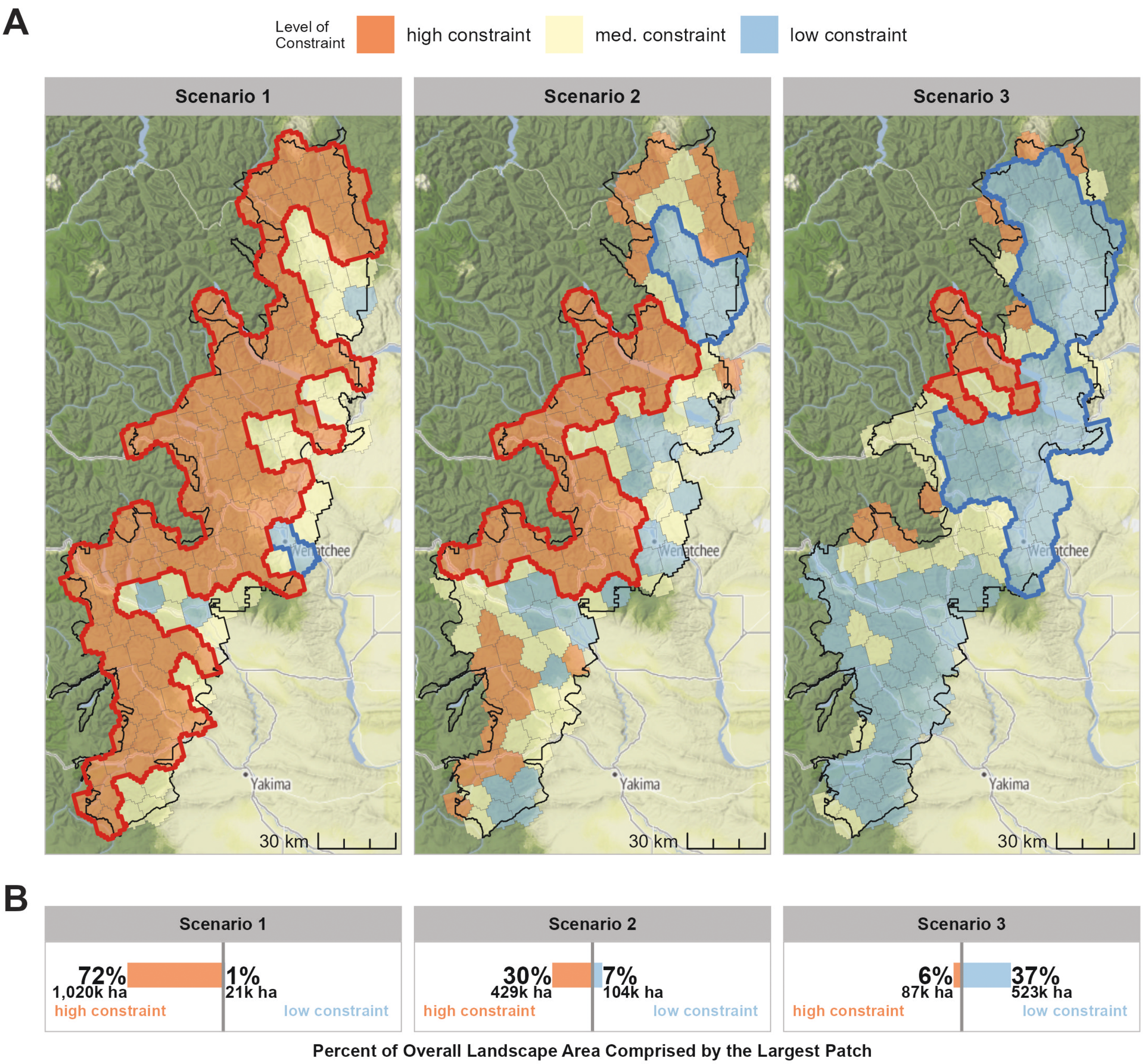

Figure 6 (A) Central Washington Initiative (Washington) priority landscape divided into fireshed project areas. Shadings indicate percentage of the total combined forest and shrubland acres that are available for mechanical treatment: high (81%–100% constrained; 0%–19% available for mechanical treatment), medium (60%–80% constrained; 20%–40% available), and low (0%–59% constrained; 41%–100% available). The largest patch of interconnected fireshed project areas classified as highly and lightly constrained are outlined. (B) Proportion of the total area of the overall landscape comprised by the largest patch of interconnected fireshed project areas of similar levels of mechanical constraint. Comparison is made between the largest patch of project areas classified as high constraint and the largest patch of project areas classified as low constraint. Breakdowns of patch size under each scenario is available for all landscapes in Supplemental Appendix B online.

including legal, operational, and administrative constraints (North et al. 2015). Our analysis suggests the status quo approach to mechanical fuel reduction treatments based on Forest Service operations in recent years (scenario 1) could prevent attainment of Strategy objectives in seven of the twenty-one priority landscapes (figure 5; Table SB1). By working on steeper slopes (up to 60%) and increasing the use of temporary roads (scenario 2), operations under the Strategy have an opportunity to mechanically treat 20%–40% of high-risk acreage on all but three of the twenty-one priority landscapes (figure 5; Table SB1). To ensure success in treating over 20% of high-risk acreage using mechanical methods alone on the remaining three priority landscapes may require support navigating administrative complexities within reserved land allocations in addition to increasing slope and road access (scenario 3).

Although construction of temporary roads and operations on steep slopes (e.g., 40%–60%) have potential to broaden the land base available for treatment and enhance manager flexibility to ensure landscape objectives are met, there are a number of concerns and challenges with implementation. Steep slope operations using tethered mechanized harvesting systems, for example, can increase the cost of treatment compared with operations on gentle slopes using untethered equipment (Petitmermet et al. 2019), and there is little science on the effectiveness of these treatments to reduce fire hazard on steep slopes (Chang et al. 2023; Pittman et al. 2023). A recent study of tether-equipped systems used for fuel reduction treatment in the Klamath Basin in southern Oregon and northern California found that operation costs were about 1.47 times the cost of nontethered operations (Petitmermet et al. 2019), and a wildfire simulation study found only modest reductions in fire behavior and severity from fuel treatments on 60% slopes regardless of surface fuel treatment compared with untreated conditions (Pittman et al. 2023). This suggests that more studies are likely needed to support implementing and designing effective and efficient fuel reduction treatments on steep terrain. Despite these uncertainties, there are benefits to these newer technologies, as tethered mechanization improves operator safety and reduces costs compared with manual chainsaw labor typically used for treatments on steep slopes (Visser and Stampfer 2015), and soil impacts are reduced when compared to nontethered systems (Green et al. 2020). There are also concerns with expanding the use of temporary roads, which can negatively affect aquatic and riparian ecosystems by accelerating erosion, increasing sediment deposition, altering stream temperatures, and creating barriers to aquatic organism movement (Reeves et al. 2018). However, there are trade-offs associated with increasing temporary road usage as the benefits of reducing the risk of high-severity fire, and associated negative impacts to water resources (e.g., erosion, sediment deposition, increased flooding susceptibility) may potentially outweigh the ecological risks (Gannon et al. 2019).

The most comprehensive approach to mechanical fuel reduction work considered in this analysis (scenario 3) included expanding mechanical treatment within administrative boundaries (e.g., sensitive species habitat and riparian zones), which allowed for sufficient opportunity to achieve Strategy objectives of treating 20%–40% of high-risk fireshed area using mechanical methods alone on all twenty-one priority landscapes (figure 5; Table SB1). Although administrative designations such as sensitive species habitat, conservation areas, and riparian buffers do not prohibit mechanical treatment by law, in practice these areas are commonly left untreated by land managers who wish to avoid administrative hurdles and litigation concerns (Charnley et al. 2015; Gosnell et al. 2020; Stephens and Ruth 2005). Although administrative reserves are core to conservation efforts under climate change (Watson et al. 2014), focusing management on iconic landscapes and wildlife can lead to a tunnel vision that discounts diversity in socioecological systems and limits management flexibility in the face of emerging threats (Spies et al. 2019; Stephens et al. 2016). If specific values are to be maintained, it is likely that more active management will be required to facilitate ecosystem adaptation to climate change, altered disturbance regimes, and invasive species (Keenan 2015; Lindenmayer et al. 2000; Millar et al. 2007; Seidl et al. 2016). Proactive management within reserved lands that includes mechanical thinning and prescribed fire promotes resilience to future disturbance and aligns with conservation objectives, especially in seasonally dry and fire-adapted landscapes (Jones et al. 2022; Spies et al. 2019). Proposals for creating new protected areas and enhancing protective measures in existing administrative reserves such as those under consideration for mature and old-growth forests (Executive Order No. 14072, 2022) would most effectively meet conservation and policy goals if designed and actively managed to account for these threats (Spies et al. 2006; Steel et al. 2023). In the case of riparian reserves and buffers, the potential for tree removal to alter the microclimate (e.g., increased stream temperature) is a frequently cited management concern; however, habitat heterogeneity generated by disturbance can facilitate aquatic species adaptation and productivity under a wide range of conditions (Reeves et al. 2018).

Broadening the Treatment Land Base to Enhance Management Flexibility

Previous research on maximizing the effectiveness of landscape-scale fuel treatments highlights five dimensions of fuel treatment design: extent, placement, size, prescription, and timing (Collins et al. 2010; Ott et al. 2023). This research suggests that meeting the 20%–40% treatment objective of the Strategy may be insufficient to mitigate undesirable wildfire effects if those treatments are suboptimally arranged. Extensive patches of spatially connected land available for mechanical treatment represent opportunities for land managers to design broad-scale treatment plans that optimize across these dimensions by expanding the total area treated, adjusting the size of individual treatment units, using placement prioritization schemes, and maintaining treatment effectiveness over time (Collins et al. 2010). Our analysis indicates that when mechanical treatments are limited to modest slopes near existing roads outside of administratively designated areas (scenario 1), contiguous patches where operations may effectively create extensive fuels treatments by mechanical methods alone are uncommon on the majority of the twenty-one priority landscapes (figure SB2). Under our management scenarios 2 and 3, results show that broadening the land base available for treatment enables flexibility for land managers by creating extensive, spatially aggregated areas on the majority of priority landscapes (figure 6; figure B2). Operating under less rigid constraints will facilitate treatment planning that integrates local knowledge and accounts for constraints not considered in this analysis. Flexibility in the design of landscape-scale management strategy has been identified as key to achieving convergence of the objective to mitigate negative impacts of potential wildfire to human communities with the objective to restore ecosystem resilience to future disturbance by promoting heterogeneity in forest and shrubland structure (Stephens et al. 2021).

Climate models suggest that wildfire activity will likely continue to increase under hotter and drier conditions (Bowman et al. 2020; Krawchuk et al. 2009; Moritz et al. 2012) and that the reintroduction of fire as a key ecosystem process is essential to create wildfire-resilient landscapes (Churchill et al. 2013; Larson and Churchill 2012; North et al. 2012). This analysis focused on mechanical fuel treatments which, when implemented alone, have been shown to effectively mitigate negative wildfire effects (e.g., Prichard and Kennedy 2014; Prichard et al. 2020). However, an approach that combines mechanical thinning with prescribed fire may be most effective, especially in seasonally dry pine and mixed-conifer forests common across the western US (Fulé et al. 2012; Kalies and Kent 2016; Vorster et al. 2024). Strengthening engagement with tribal partners is listed as a primary Strategy objective (USFS 2022a) and mechanically thinning dense forests to reintroduce cultural burning could extend socioecological benefits to tribal communities while recovering opportunities for tribal engagement in resource management in ancestral lands across all jurisdictions (Lake et al. 2017; Long et al. 2018). To meet Strategy objectives of substantially increasing the pace and scale of fuel treatments over the next decade, North et al. (2021) suggest a "pyrosilviculture" approach, which strategically implements mechanical thinning operations to (1) create fuel-reduced anchors from which to expand prescribed fire and managed wildfire operations, (2) precisely execute fuel-reduction work in areas where sensitive resources and assets (e.g., wildlife habitat and homes) are at risk, and (3) generate revenue from forest products to support jobs and economic returns. York et al. (2021) also promote a pyrosilviculture approach to facilitate more widespread use of fire as a management tool, whereby mechanical thinning is implemented with the explicit aim to enable future prescribed fire to meet objectives such as reducing hazardous fuels. Strategic implementation of mechanical thinning to create fuel-reduced anchors could also facilitate the management of naturally ignited wildfires to meet restoration objectives (Huffman et al. 2020), an approach highlighted by the Strategy (USFS 2022a). The range of mechanical fuel reduction constraint across the twenty-one priority landscapes identified in our analysis supports this combined-strategy approach to create extensive networks of fuel-reduced conditions resilient to future wildfires and climate conditions. Our results show that no single management tool will be sufficient to reduce community wildfire exposure and enhance landscape resilience across a broad landscape. Management options are determined within a context of interacting physical and social factors (see Prichard et al. 2021) highlighting the importance of place-based knowledge and collaboration for developing and implementing management actions that effectively reduce fire hazard while also meeting local objectives.

Implications for Management Strategies

This analysis identified a gradient of feasibility to implementing mechanical fuel reduction treatments across the twenty-one priority landscapes selected in the Forest Service Wildfire Crisis Strategy. The business-as-usual approach to mechanical fuel reduction treatments will likely need to be expanded to provide opportunities for land managers to design and implement effective large-scale management strategies. On the majority of Strategy landscapes, this will allow for planning that meets risk-reduction goals, considers tradeoffs to meet multiple objectives, incorporates indigenous and local knowledge, and extends opportunities to reintroduce fire where ecologically and socially appropriate. However, even after expanding the area available to ground-based equipment, we found that management challenges may persist on some landscapes. For example, many landscapes include project areas with high levels of mechanical constraint across all scenarios considered in this analysis that are directly adjacent to urban areas, such as Salt Lake County, Utah, and Orange and Ventura Counties, California (Figures SB21 and SB8). In these areas, it will be challenging to incorporate prescribed fire fuel reduction treatments as an alternative due to air quality, liability and safety concerns, and other regulations (Miller et al. 2020; Ryan et al. 2013). Instead, managers and policymakers will likely need to consider alternative means to reduce community wildfire exposure, including strategic fuel breaks (Gannon et al. 2023; Massada et al. 2011), defensible space measures (Cohen 2000; Syphard et al. 2014, 2017), and sustainable land-use planning (Calkin et al. 2014; Gill and Stephens 2009; Keeley and Syphard 2019; Moritz et al. 2014; Stephens et al. 2009).

Comparison with Prior Research

Our results are in line with those reported in prior work considering layered legal, operational, and administrative constraints in areas overlapping the Strategy priority landscapes. Hampton et al. (2011) estimated that 74% of ponderosa pine forest acreage was available for mechanical thinning in the 4FRI landscape after removing acreage due to regulations and guidelines related to wildlife, soils, hydrologic, and other factors. The primary differences between our methods and those used by Hampton et al. (2011) are that we include areas distant from existing roads as constrained whereas they make no adjustments for road access, and we include all Mexican spotted owl (*Strix occidentalis lucida*) critical habitat (USFWS 2004) as constrained in scenarios 1 and 2 whereas they include only owl activity centers as constrained. Thus, the most appropriate comparison of our results to Hampton et al. (2011) would be to pool our scenario 1 mechanically available area with areas distant from roads and our administratively constrained areas (Table SA1) for an estimated total landscape proportion of 70% which is in line with their 74% estimate. Scenario C by North et al. (2015) is more mechanically restrictive than our scenario 2, with them estimating 43% and 39% of the productive acreage in the Plumas and Stanislaus National Forests, respectively, as being available. Although the Strategy priority landscape boundaries deviate from national forest boundaries, our scenario 2 estimates are comparable at 50% and 46% in the Plumas and Stanislaus landscapes, respectively, being available for mechanical thinning (Table SA1).

Study Limitations

Although our analysis utilized methods that have been used in recent western national forest plan revisions and prior research (North et al. 2021), several limitations still exist. This analysis spans the broad extent of ten western US states and required simplifying assumptions about the conditions and factors that constrain mechanical treatment, which may not apply given locality differences. For example, soil conditions are not equally suitable for ground-based equipment at a given slope steepness across all areas (Belart et al. 2019; Robitaille et al. 2015). Coordinating land management practices across multiple ownerships and jurisdictions with differing values and perceptions about managing the wildfire crisis (Charnley et al. 2015; Gill and Stephens 2009; Kooistra et al. 2022) also presents unique challenges that were not considered in this analysis. A "shared stewardship" approach (Kooistra et al. 2022; USFS 2018) has been suggested to achieve land management objectives across boundaries and jurisdictions as communities aim to build socioecological resilience for adapting to changing climate and socioeconomic conditions (McWethy et al. 2019). Additionally, this analysis did not consider economic constraints to mechanical treatment given the substantial congressional funding for fuels reduction work available through the Strategy in these areas. Economic constraints including funding for treatment, workforce capacity (Hartsough et al. 2008), and the net economic benefit of mechanical thinning or harvesting based on the value of potential forest products, and the costs of harvesting and transporting those products (e.g., Prestemon et al. 2012) pose significant challenges to risk reduction fuel treatments in the western US. Fuel reduction projects often remove small-diameter trees and produce biomass residue, yet infrastructure is lacking in many regions to process this material and barriers exist to the creation of long-term economically sustainable markets (Han et al. 2004; Hjerpe et al. 2009; Nicholls et al. 2018).

Our analysis identified four of the Strategy priority landscapes as having a majority of area classified as shrubland (Figure SA1). Although mechanical treatments (e.g., chaining, cutting, mowing, and mastication) are among the most commonly implemented fuel reduction treatments in shrublands (Miller et al. 2019; Monsen et al. 2004), with mastication requiring a carrier machine, cutting head, and mounting system similar to forest harvesting systems (Jain et al. 2018), this analysis did not consider how mechanical treatments in shrublands might differ from treatments in forests. Research on fuel reduction treatments in shrublands, including mechanical-only, fire-only, and combined mechanical and prescribed fire treatments, has identified trade-offs between wildfire risk reduction and promoting ecological integrity (Miller et al. 2019). In warmer and drier shrubland sites, fire-only and mechanical-only treatments can decrease surface fire behavior (Ellsworth et al. 2022), but in areas where these treatments have been implemented to address woodland encroachment and promote desired shrubs and herbaceous vegetation, modeled fire behavior increased posttreatment (Williams et al. 2023). Mechanical, prescribed fire, and combined mechanical-fire fuel reduction treatments in shrublands have been associated with decreased live woody fuels and associated crown fire potential, but research has identified increases in exotic annual grasses following these treatments, which may lead to increased potential for quicker moving surface fires (Brennan and Keeley 2015, 2017; Coop et al. 2017; Martorano et al. 2021; Wilkin et al. 2017). Under moderate burning conditions, these surface fires may be easier to control than crown fires from a fire suppression perspective; however, Keeley and Syphard (2019) provide evidence that recent destructive shrubland fires in California were primarily driven by extreme winds and that landscape-level fuel treatments alone would have had minimal impact on fire control. Future research on the constraints to implementing fuel reduction treatments at a landscape scale could consider partitioning analysis based on different land cover classifications.

Supplementary Material

Supplementary material is available at *Journal of Forestry* online.

Acknowledgments

The authors would like to thank Matthew Ross, Yu Wei, Michelle Day, and two anonymous reviewers for their thoughtful feedback and insights while reviewing the manuscript. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or US government determination or policy. This paper was written and prepared by a US government employee on official time, and therefore, it is in the public domain and not subject to copyright.

Conflict of Interest

None declared.

Data Availability

Source code used to generate the datasets and perform analysis for this project has been published to the public domain at: https://github.com/georgewoolsey/wcs_mechanical_constraints

Endnotes

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