How much is enough?

Fostering resilience to high-severity fire through fuel treatments

Andreas Wion, Zander Evans, Cody Dems. Forest Stewards Guild (2026).

Healthy forests are resilient - able to resist, recover, and reorganize following disturbances like fires or drought. Resilience is a cornerstone of ecological forestry. Here, we address a simple question with a complex answer – how much work does it take to rekindle forest ecosystem resilience? We borrow the definition of forest ecosystem resilience from D. Falk et al. (2022):

> *Resilience describes the tendency of a system to return to its prior state following a perturbation. Ecological resilience manifests itself through traits that promote recovery and resistance at the organismal level, the long-term persistence of populations, and the continuity of community assembly through repeated disturbances.*

Fuel Reduction Treatments

In many dry mixed conifer forests of the western US, low-intensity surface-fires were a commonplace occurrence prior to 1900 (Allen et al. 2002). Active policies of fire suppression and erasure of indigenous stewardship have fundamentally altered the composition, structure, and distribution of many dry forests in the western US, leading to the collapse of this surface fire regime (Covington and Moore 1994, Hagmann et al. 2021). Accelerating rates of uncharacteristic stand-replacing fires (i.e., high-severity) in surface-fire adapted forests requires action to prevent long-term and irreversible forest loss (Hessburg et al. 2020, Parks et al. 2025).

Managers retain one important lever through which they can restore resilience to dry conifer forests – **fuel reduction treatments** involve removing younger and small diameter trees through thinning and burning the biomass (Agee and Skinner 2005, Evans et al. 2011). Ideally, this is accompanied by maintaining a program of repeated broadcast burning, the combination of which has been demonstrated to be highly effective at reducing the occurrence and severity of subsequent wildfires, increasing forest resilience to fire and drought, and restoring historical pattern and process (Davis et al. 2024, Kalies and Yocom-Kent 2016, Fule et al. 2012). Decades of observation, experimentation, and simulations indicate that treatments significantly impact wildfire behavior, specifically altering ignition probability and reducing crown fire potential, overstory canopy loss, and crown scorch - even under extreme weather conditions (Lydersen et al. 2017, Beckmann et al. 2025, Prichard et al. 2020). Treatments that include both thinning and surface fuel reduction are the most effective at moderating wildfire behavior (Cansler et al., 2022; Collins et al., 2013; Evans et al., 2011, Sanna et al. 2025). Increasingly, secondary benefits are achieved such as reduced competition to improve individual-level tree growth, which reduces the rate of drought and insect induced mortality (Bradford and Bell 2017, Bradford et al. 2021, 2022, Young et al. 2023, McCauley et al. 2024) and understory restoration (Demarest et al. 2023). Treatments can also alter fire behavior outside of the treated area itself – described as a landscape-level treatment effect. Given the threat of large, high severity wildfires, a pressing question is **how much area needs to be treated within a large landscape to avoid large patches of high-severity fire?** A robust answer to this question requires additional research, particularly because landscape-level treatment effects depend on many factors, including scale, longevity, landscape condition, and optimization of treatment location.

Factors affecting efficacy of landscape-scale treatments

Spatial Scale

An important factor in assessing fuel treatment efficacy is the measurement scale, i.e., the extent of the assessed area. Lydersen and colleagues (2017) examined how treatment effectiveness varies with spatial extent, and they found at small scales (e.g., 200 ha) nearly 75% of the landscape needed to be treated to reduce fire behavior (e.g., flame length or rate of spread) significantly, whereas at larger scales (e.g., 2,000 ha), fire behavior was mediated with as little as 20% treatment (Lydersen et al. 2017). Jones and colleagues (2025) observed similar patterns following the 2022 Black Fire in a fire-restored forest in New Mexico. At larger spatial scales (4,000 ha) reductions in high-severity fire began to occur at 25% of the landscape treated and sharply declined after 50%. Areas treated with previously managed wildfires and thinning had a reduction of 51% high-severity fire compared to those that did not experience treatment (Jones et al. 2025). However, wildfires are randomly located and not optimized (see below), tending to burn larger areas at a mixed severity given fuel, weather, and topography.

Treatment Longevity

Treatment longevity is a key question – how long do fuel reduction treatments last? Fuel accumulation from tree regeneration, needle cast, leaf litter, and dead and down debris occurs naturally over time at rates that may be slower in dry, cool environments and faster in warm and wet environments. In the dry forests of the Rocky Mountains and the southwest, oak resprouting following treatments is a common issue – similar to aspen resprouting at higher elevations. This reduces the lifetime of treatments considerably, creating flammable ladder fuels beneath conifer canopies. Thus, even in dry environments where productivity is assumed slow, species composition and abundance can also serve as an indicator of treatment lifetime.

Tinkham et al. (2016) found that treatment longevity was associated with site productivity and the number of seedlings per hectare, with reduced treatment longevity in more productive and heavily stocked stands. Fuel build-up also varies among species (e.g., conifers versus hardwoods) and among trees with different canopy structures. For example, in the Shasta-Trinity Alps of northern California, treatments less than five years old reduced fire behavior, but not those 10 years or greater (Benkmann et al. 2025). In the northern Rockies of Montana, Hood and colleagues (2024) describe low amounts of fuel accumulation up to 24 years post-treatment. Pinyon-juniper mastication longevity has been documented to last at least 10 years (Wozniak et al. 2020). Stephens and colleagues (2011) demonstrated reduced efficacy in highly productive Sierran mixed-conifer forests after seven years, but staggering the implementation of treatments could lengthen such positive impacts to 20 years.

In practice, most studies examine treatment effectiveness as a binary, before and after 10 years, and tend to find that treatments younger than 10 years are more effective than treatments older than 10 years (e.g., Davis et al. 2024). This creates a common 'rule of thumb' in fuel reduction treatment planning – treatment cycles recurring approximately every 10 years or less are likely to confer resilience to future fire. Of course, a 15-year-old treated area is likely to burn less severely than a dog-hair thicket which never experienced treatment, especially in a slow growing system. The variation across different ecosystems indicates that treatment longevity is a continuum, rather than a binary, and should be interpreted within the context of the ecology, trajectory, and stewardship goals.

Landscape factors

Topography is an essential driver of fire behavior. As fire burns uphill, it burns with greater intensity, particularly on steeper slopes, because vegetation is heated by the flaming front. Existing vegetation also impacts fire behavior because of changes in flammability. For example, aspen groves can impede wildfire spread because of their higher moisture content and reduced flammability (Harris et al 2025). Meadows, ponds, streams, valleys, ridges and other features can also reduce wildfire spread (Fairfax and Whittle 2020, Moravek et al. 2025). Yocom-Kent and colleagues (2019) found both roads and past wildfires consistently intersected with wildfire perimeters, indicating their broad utility for suppression and management operations. Previous wildfire occurrence alters fuel structures, which reduce the severity, occurrence, and spread of subsequent wildfires by creating patchwork mosaics of fuel breaks (Hessburg et al. 2020, Jones et al. 2025, Parks et al. 2015 and 2016, Stevens-Rumman et al. 2016, Young and Ager 2024, Young et al. 2022), which can be especially effective when tied into existing networks of treatment. Because topography commonly funnels and guides fire on the landscape, placing treatments or fire-resistant features in these areas could act as a leverage point to maximize fuel treatment efficacy.

Treatment Optimization

Early work by Finney (1998, 2001) compared randomized and strategically located treatments across varying proportions of the landscape through simulations of fire spread. By altering the size, arrangement, and placement of treatments, Finney identified rate of reduction in fire behavior (a relative burn rate) with increasing area treated. Optimized treatment patterns covering ~20% of the landscape resulted in a ~75% reduction in fire behavior (Finney 2001). Treating a greater percentage of the landscape leads to a continued reduction in fire behavior, but at a much slower rate (Finney 2001, Figure 8). In a similar study conducted by Finney and others (2007), they found a strong decline in the effectiveness of further treatments beyond 30 to 40% of the total landscape area, approximately the point at which fire can no longer percolate through a landscape. The steepest increase in effectiveness occurs around 10 to 30% (Finney et al. 2007, Fig.4), thus many have used a 20% number as another common heuristic to plan outcomes for landscape-scale restoration projects (See US Forest Service, 2022). While treating 20% of an area is a useful rule of thumb, treating as little as 5 to 10% of the landscape can significantly affect fire behavior (Cochrane et al. 2012). Careful review of the existing scientific literature highlights the difficulty of generalizing across studies (McKinney et al. 2022). Of the 2,240 papers McKinney and colleagues reviewed only 12 demonstrated treatments affected fire severity, progression, and extent outside of the treatment boundaries. A similar systematic review of 86 modeling studies found that while damaging wildfire decreased because of treatments in most cases, extent, placement, size, prescription, and timing of treatments influenced outcomes (Ott et al 2023).

Fuel breaks are one approach to optimizing treatment location and have been shown to be effective particularly when they facilitate access for firefighting (Syphard et al., 2011). Modeling shows that strategic location of fuel breaks in a wildland-urban interface required treating almost 50% more area than protecting structures independently (Bar Massada et al. 2011). Optimization of treatment locations is possible with constraints such as avoiding sensitive wildlife areas; in fact, these constraints may improve fuel treatment effectiveness by great aggregation of treatments

(Dow et al 2016). A shift to hotter and drier conditions may limit treatment effectiveness and spur large, high-severity wildfires, for example, a modeling study in the Southwest indicated that even a fuel treatment rotation of 9% annually on an 11-year rotation was not enough to forestall ecological change (Loehman et al 2018).

Stewardship Implications

From this review of fuel treatments and their impact on wildfire behavior, a few key points emerge that help answer the question: **how much forest needs to be treated to restore resilience to dry conifer ecosystems?**

A. When fuel treatments that combine thinning and prescribed fire cover from 10 to 40% of the landscape, fire behavior is significantly reduced. Research continues to support the 'rule of thumb' that an appropriate landscape goal is 20% in fuel treatments.
B. There is a positive and non-linear relationship (with diminishing returns beyond 30-40% of a total landscape) between fuel treatment effectiveness and the area treated, the size of individual treatments, and the spatial scale examined.
C. Treatment longevity varies but lasts about 10-20 years in southwestern dry conifer forests.
D. Landscape factors like vegetation and disturbance history strongly limit fire spread and should be incorporated in the treatment optimization.

Acknowledging the caveat that each landscape and ecosystem is different, a rule of thumb provides a starting point: Stewards should aim for treatment rates averaging 2% of a landscape annually over 10 years. This assumes maintenance of previous treatments at least 10 years after initial treatment at a similar annual rate. A warming and drying climate may necessitate an initial increase in investment of the area treated annually to forestall future changes. Conversely, aridity may limit fuel regrowth and accumulation, lengthening the interval required between maintenance treatments. This requires an approach that is flexible, responsive to sudden changes, and accepting of some risk. Stewardship of future forest function, cover, and resilience requires an all-hands all-lands approach to meet ambitious goals. Managed wildfire is an effective and likely necessary addition to mechanical thinning and prescribed fire to attain treatment goals of 20% per decade. While any single project may be limited by parcel boundaries or ownership, wildland fire is not, thus an effective system of risk reduction relies on collaborative, cross boundary, and landscape-scale efforts. Implementing initial and maintenance treatments on an average of 2% of the landscape annually will contribute to the maintenance of forest function, canopy cover, and ecosystem resilience into the future.

Table 1: Highlighted studies of fuel treatment effectiveness

Lead Author (year)	% landscape treated	Reduction in fire behavior metric
Finney (2001)	0 - 40%	Non-linear decrease in relative rate of spread
Finney (2007)	0 - 50%	Non-linear decrease in area burned
Ager (2007)	0 – 50 %	Reduction in forest loss as low as 10%
Wei (2008)	12.5%	50% reduction in forest loss from future fire with 12.5% treatment
Schmidt (2008)	0 - 27%	Max 70% reduction in fire severity
Ager (2010)	10%	70% reduction in WUI structures lost
Cochrane (2012)	5 - 57%	2-63% reduction in wildfire area burned
Tubbesing (2019)	18%	Reduction in percent stand replacing area, stand replacing patch size, and core patch area
Lydersen (2017)	45%	Lowest Severity in thinned and burned
Jones (2025)	-	4% of gigafire burned at high severity, greatest decrease with >50% landscape treated
Beckmann (2025)	23%	Reduced fire severity for approximately 5 years
McKinney (2022)*	22% (avg.)	Tables 1 and 3 summarize 26 studies on landscape level treatment effectiveness
Ott (2023)*	-	See Fig. 6, standardized values of wildfire response metrics against % treated
Bar Massada (2011)	-	Treating 56% of landscape resulted in greater benefits than individual structure protection
Collins (2013)	19%	Half fold reduction in conditional burn probability (i.e., flame lengths > 2m)
Schroder (2016)	17%	Modeled treatment across 17% of the area reduced habitat loss 75%

*Literature review or meta-analysis

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