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# Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring

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Stand-level spatial pattern influences key aspects of resilience and ecosystem function such as disturbance behavior, regeneration, snow retention, and habitat quality in frequent-fire pine and mixed-conifer forests. Reference sites, from both pre-settlement era reconstructions and contemporary forests with active fire regimes, indicate that frequent-fire forests are complex mosaics of individual trees, tree clumps, and openings. There is a broad scientific consensus that restoration treatments should seek to restore this mosaic pattern in order to restore resilience and maintain ecosystem function. Yet, methods to explicitly incorporate spatial reference information into restoration treatments are not widely used. In addition, targets from reference conditions must be critically evaluated in light of climate change. We used a spatial clump identification algorithm to quantify reference patterns based on a specified inter-tree distance that defines when trees form clumps. We used climatic water balance parameters, downscaled climate projections, and plant associations to assess our historical reference sites in the context of projected future climate and identify climate analog reference conditions. Spatial reference information was incorporated into a novel approach to prescription development, tree marking, and monitoring based on viewing stand structure and pattern in terms of individuals, clumps, and openings (ICO) in a mixed-conifer forest restoration case study. We compared the results from the ICO approach with simulations of traditional basal area and spacing-based thinning prescriptions in terms of agreement with reference conditions and functional aspects of resilience. The ICO method resulted in a distribution of tree clumps and openings within the range of reference patterns, while the basal area and spacing approaches resulted in uniform patterns inconsistent with known reference conditions. Susceptibility to insect mortality was lower in basal area and spacing prescriptions, but openings and corresponding opportunities for regeneration and *in situ* climate adaptation were fewer. Operationally, the method struck a balance between providing clear targets for spatial pattern directly linked to reference conditions, sufficient flexibility to achieve other restoration objectives, and implementation efficiency. The need to track pattern targets during implementation and provide immediate feedback to marking crews was a key lesson. The ICO method, especially when used in combination with climate analog reference targets, offers a practical approach to restoring spatial patterns that are likely to enhance resilience and climate adaptation.



## 1. Introduction

Increasing ecological resilience has become a central objective in management of public forestlands due to the combined effects of past management and projected climate change (Baron et al., 2009; Joyce et al., 2009). Ecological resilience (hereafter, resilience) includes the capacity to persist through and re-organize after disturbance, adapt to shifting environmental conditions, and maintain basic ecosystem structure and function over time (Walker et al., 2004). There is increasing evidence that spatial heterogeneity at multiple scales, in addition to forest structure and composition, is a critical component of ecosystem resilience (Levin, 1998; Moritz et al., 2011; North et al., 2009; Stephens et al., 2008). General

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frameworks that incorporate ecologically-based guidelines for spatial pattern have been developed for some forest ecosystems (Carey, 2003; Franklin and Johnson, 2012; Hessburg et al., 2004, 1999; Franklin et al., 2007; Mitchell et al., 2006). A major remaining task is the identification of spatial pattern targets for specific ecosystems that are empirically linked to resilience, climate adaptation, and desired ecological functions (Puettmann et al., 2009). A related challenge is translating such targets into operationally-efficient prescriptions and monitoring protocols (North and Sherlock, 2012; O'Hara et al., 2012).

In frequent-fire pine and mixed-conifer forests in western North America (hereafter, *dry forests*), pre-settlement era forests are commonly used as reference systems to inform treatment targets (Larson and Churchill, 2012). Contemporary dry forests with minimally altered or restored fire regimes are increasingly being used as reference sites as well (Lydersen and North, 2012; Stephens et al., 2008; Taylor, 2010). At the stand level, tree patterns in these forests are commonly characterized by an uneven-aged mosaic of individual trees, clumps ranging from 2 to more than 20 trees, and openings (Kaufmann et al., 2007; Larson and Churchill, 2012). Such mosaics persisted for centuries in a dynamic system of fine-scale, gap-phase replacement driven primarily by frequent fire and insect mortality (Agee, 1993; Cooper, 1960). Patch size and within-patch heterogeneity varied temporally at individual sites, and across different biophysical environments (Kaufmann et al., 2007). Infrequent moderate to high-severity disturbances did occasionally reset these stand-level patterns as well (Arno et al., 1995; Hessburg et al., 2007). Here, we refer to stands as patches embedded in a hierarchy of landscape organization; smaller than sub-watersheds and larger than the largest tree clumps and openings (Urban et al., 1987). Historical patch size distributions of stands in dry forests ranged from 1 to $10^4$ ha (Perry et al., 2011), different from the traditional view of stands as 10–50 ha management units.

The fine-scale mosaic pattern is thought to be a key factor underpinning the resilience of dry forest ecosystems (Allen et al., 2002; Binkley et al., 2007; Stephens et al., 2010). Irregular tree patterns, large openings, and resulting variation in surface fuels inhibit the spread of crown fire and perpetuate variable post-fire patterns (Beaty and Taylor, 2007; Pimont et al., 2011; Stephens et al., 2008), analogous to strategic placement of fuel treatments at larger spatial scales (Finney et al., 2007). Heterogeneous stand structures impede the buildup of epidemic insect outbreaks by disrupting pheromone plumes and breaking up the continuity of susceptible species, as well as age and size classes (Fettig et al., 2007).

Similarly, openings create barriers to the spread of dwarf mistletoes and fungal pathogens (Goheen and Hansen, 1993; Hawksworth et al., 1996; Shaw et al., 2005). Likewise, openings and frequent disturbances facilitate periodic tree regeneration in dry forests (Boyden et al., 2005; Sánchez Meador et al., 2009), which is thought to be partly responsible for high levels of local genetic diversity of trees (Linhart et al., 1981; Hamrick et al., 1989). Snow retention is highest where canopy openings are large enough reduce canopy interception, but small enough to be shaded and protected from wind (Varhola et al., 2010). In addition, the contrasting light, moisture, and soil nutrient environments in heterogeneous stands increase understory plant abundance and diversity (Dodson et al., 2008; Moore et al., 2006).

There is a growing scientific consensus that to increase resilience, mechanical and prescribed-fire treatments should seek to restore the range of mosaic patterns found in reference stands (Allen et al., 2002; Franklin et al., 2008; Hessburg et al., 2005; Moore et al., 1999; North et al., 2009; Perry et al., 2011), in addition to retaining large and old fire-tolerant trees and following other resilience principles (Table 1). Widespread adoption of prescription approaches based on spatial reference information has been slow, however, despite numerous operational-level research studies (e.g. Graham et al., 2007; Knapp et al., 2012; Lynch et al., 2000; USFS, 2008; Waltz et al., 2003).

The fundamental challenge facing managers is the mismatch between the grain and variation of pattern found in dry forests and the tools commonly used to quantify and manage them. Most silvicultural methods are based on stand-average density metrics originally designed to create homogenous stands (Puettmann et al., 2009). Modifying these approaches to manage for within-stand spatial variability requires re-conceptualizing "stands" as mosaics of variably sized canopy patches (Puettmann et al., 2009). This shift—and the associated changes in mensuration tools, operational methods, and contractual mechanisms—can be initially complex and time consuming (Knapp et al., 2012; North and Sherlock, 2012). Thus, many managers continue to employ stand-average basal area or spacing-based approaches (e.g. Powell, 2010). There is concern that these approaches create evenly spaced stands inconsistent with ecologically important fine-scale processes, and may have unintended negative effects to wildlife and disturbance behavior. The tradeoffs between the effort of transitioning to new approaches and gains in ecological functionality and resilience are unknown, however.

Projected changes in climate and related shifts in disturbance behavior present an additional challenge to the use of historical

**Table 1**
Comparison of three stand-level treatment approaches in dry-mixed conifer forests: fuels treatments and hazard reduction, restoration of pre-settlement or current reference conditions, and climate adaptation/resilience management. Treatment targets for different strategies may vary considerably between the three different approaches.

| Recommended strategies | Fuels treatments[a] | Restoration[b] | Resilience/ adaptation[c] |
|---|---|---|---|
| 1. Reduce surface and ladder fuels; increase crown base height | x | x | x |
| 2. Reduce and maintain lower tree densities; decrease crown bulk density. | x | x | x |
| 3. Increase relative composition of fire and drought tolerant species | x | x | x |
| 4. Increase mean tree diameter and individual tree vigor by generally retaining larger trees with healthy crowns | x | x | x |
| 5. Conserve existing species and genetic diversity, including pre-settlement trees | | x | x |
| 6. Restore horizontal spatial heterogeneity of forest structure, including openings where early-seral species can establish | | x | x |
| 7. Re-introduce fire to reduce fuel loads, stimulate understory species, and maintain desired fuel beds | x | x | x |
| 8. Reduce and/or maintain appropriate levels of pathogens, insects, and other disturbances in order to create decadence, mortality, and interactions with fire that lead to regeneration of new tree cohorts and diverse understories | | x | x |
| 9. Replant desired native species, especially after high severity disturbances | | | x |
| 10. Plant new genotypes and/or species | | | x |
| 11. Monitor key processes such as mortality, regeneration, growth, fuel accumulation, and new species colonization to inform future management | x | x | x |

[a] Agee and Skinner (2005), Graham et al. (2004), and Peterson et al. (2005).
[b] Allen et al. (2002), Covington et al. (1997) and Franklin and Johnson (2012).
[c] Chmura et al. (2011), Peterson et al. (2011), Spies et al. (2010) and Stephens et al. (2010). These include resistance, resilience, response, and realignment options.