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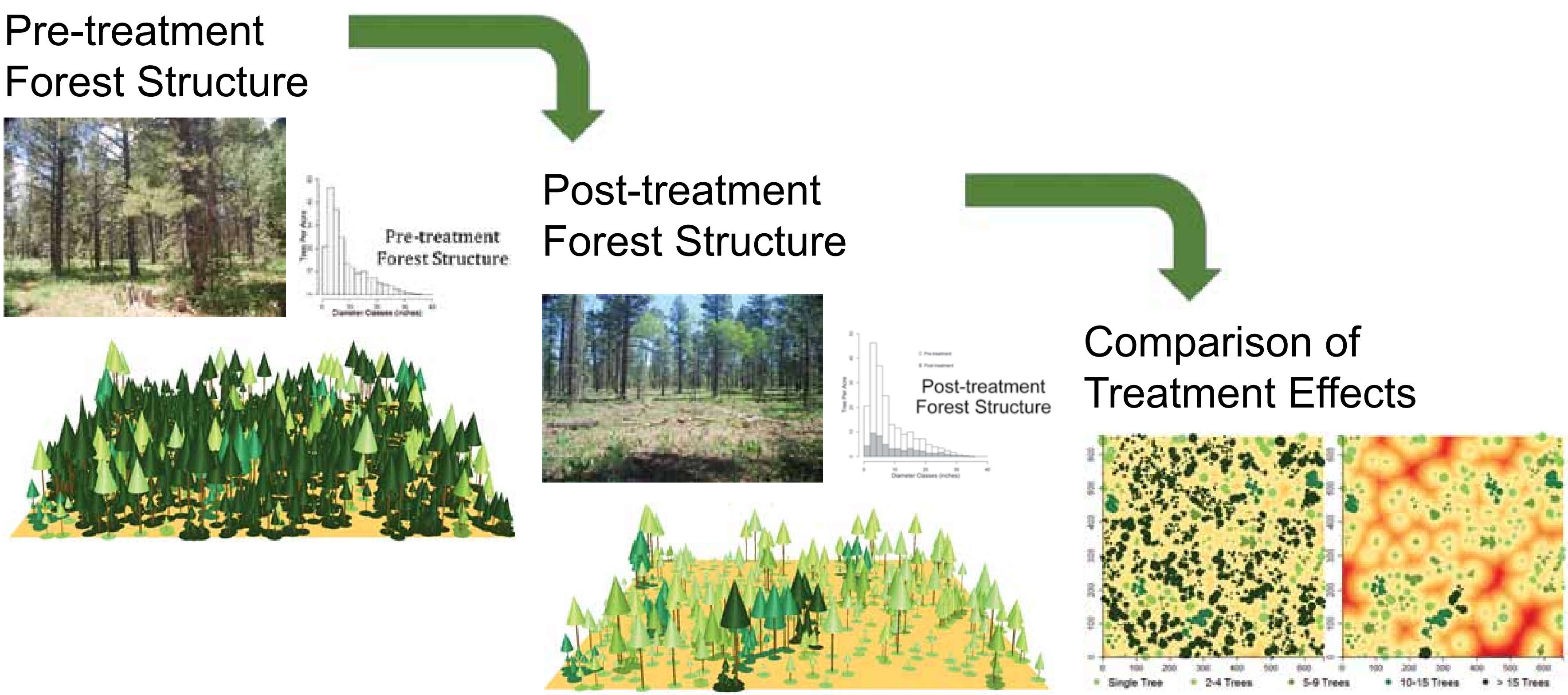
Visualization of Heterogeneous Forest Structures Following Treatment in the Southern Rocky Mountains

Wade T. Tinkham, Yvette Dickinson, Chad M. Hoffman, Mike A. Battaglia, Seth Ex, and Jeffrey Underhill



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Abstract

Manipulation of forest spatial patterns has become a common objective in restoration prescriptions throughout the central and southern Rocky Mountain dry-mixed conifer forest systems. Pre-Euro-American settlement forest reconstructions indicate that frequent-fire regimes developed forests with complex mosaics of individual trees, tree clumps of varying size, and openings. While it is broadly agreed upon that restoration to these forest conditions will improve ecosystem function, development of treatment prescriptions that can achieve desired spatial patterns on the landscape have been met with different levels of success. The central purpose of this tool is to link quantitative and visual descriptions of immediate post-treatment spatial forest structure to help communicate desired spatial structures at the stand level in dry forest types of the Rocky Mountains. This tool was developed by simulating four different treatments across four stands with varying productivity that had been identified as candidates for ecological restoration. The simulated treatments included a thin from below, random tree selection, moderate clumping, and high clumping prescriptions. Following the simulated treatments, we produced a visual representation of the spatial pattern of the residual trees and openings; calculated traditional stand-scale metrics; and described the fine-scale forest structure including individual trees, clumps of trees, and openings. This tool is intended to help communicate the outcomes of complex silvicultural treatments to resource managers, contractors, specialists, and others when attempting to meet spatially explicit treatment objectives.

Keywords: spatial heterogeneity, forest restoration, spatial statistics, spatial structure, point pattern analysis, structural complexity, variable retention harvesting

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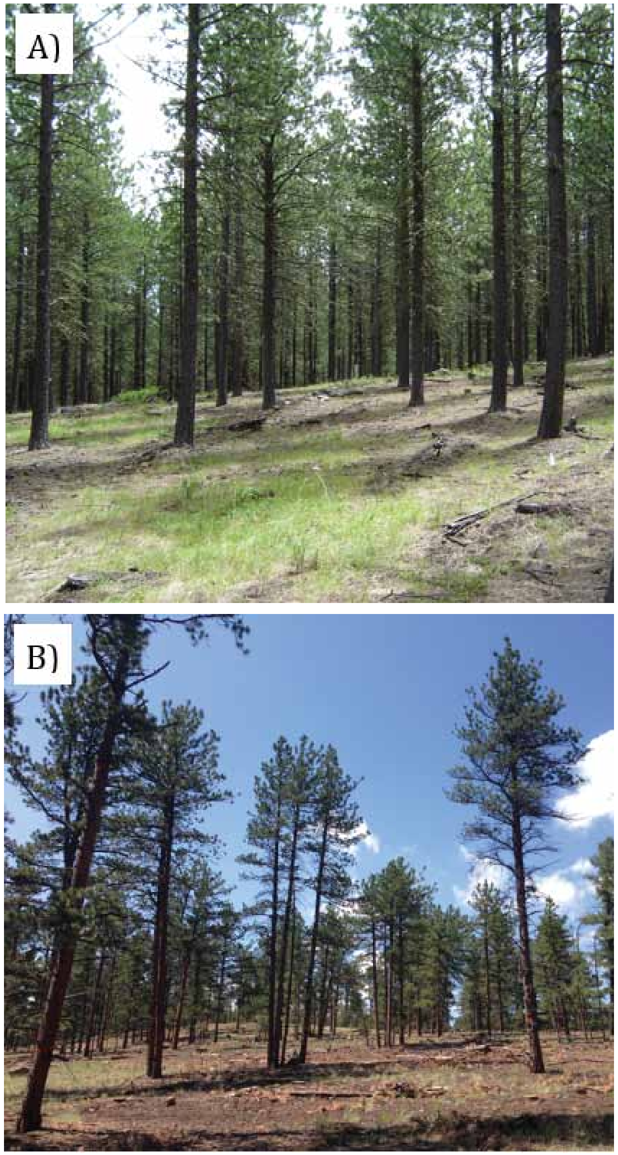

Figure 1—Examples of post-treatment stands after (a) spacing-based and (b) spatially explicit prescriptions (photos: Mike Battaglia, U.S. Forest Service).

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Introduction

Increased wildfire hazard has prompted a targeted effort to reduce fuels in dry-mixed conifer forests of the western United States. To meet fuel hazard reduction objectives, treatments have traditionally emphasized the removal of smaller trees (i.e., thin from below) within a fixed spacing interval (Schwilk et al. 2009). Such treatments have been shown to meet objectives targeting reduced fuel loading and stand density and controlling inter-tree competition (Graham et al. 1999; Larson and Churchill 2012). However, a side effect of these treatments is that resulting forest structure rarely mimics the historical spatial heterogeneity of dry conifer forests of the western United States. Dry conifer forests are characterized as a complex matrix of tree clumps interspersed with gaps and isolated individuals that are thought to promote resilience to disturbance (Allen et al. 2002; Fulé 2008; Gunderson 2000; Holling 1973; Larson and Churchill 2012). More recently, management efforts have emphasized variable retention harvesting (VRH) prescriptions to promote spatial heterogeneity while meeting ecological and fuel hazard reduction objectives (fig. 1; Churchill et al. 2013a; Fulé et al. 2001; Graham and Jain 2005; Keith 2003; Noss et al. 2006; Reynolds et al. 2013; Youtz et al. 2008). Variable retention harvesting treatments differ from traditional fuel hazard reduction treatments by explicitly incorporating spatial objectives that promote spatial heterogeneity rather than creating simple forest structures consisting of evenly spaced trees (Evans et al. 2011; Gustafsson et al. 2012; Johnson et al. 2007). This document provides visual and quantitative data to assist in communicating the outcomes of both VRH and traditional treatments on spatial and non-spatial forest metrics to resource managers, contractors, specialists, and others.

Variable retention harvesting treatments may take the role of a regeneration treatment within a multi-aged silvicultural system, or an intermediate tending treatment in an even-aged silvicultural system depending on the forest management objectives, site conditions, and level of growing space released for new regenerating trees following harvest (Mitchell and Beese 2002). Several VRH treatment implementation strategies have been developed, including the individuals, clumps, and openings (ICO) method (Churchill et al. 2013b), the ecosystem resiliency framework presented by Reynolds et al. (2013), the goshawk habitat management implementation strategy described by Youtz et al. (2008), or the free selection approach described by Graham et al. (2007). Despite a number of VRH implementation strategies, the widespread use of these treatments remains limited due to a legacy of past timber management and the use of non-spatial fuels planning and management tools (Graham and Jain 2005). In addition, the objectives commonly associated with spatially explicit treatments have met resistance because they are counter to many traditional forest management objectives such as timber production and maximizing growth and yield. These less production-focused objectives run contrary to current contract design approaches like designation by diameter, which has slowed their incorporation. Despite these challenges, VRH treatments provide considerable flexibility in meeting both spatial and non-spatial forest objectives and are likely to increase in use in the coming decades.

This document is intended to provide a visual tool that can assist managers in communicating the effects of various treatments on spatial and non-spatial stand structure in dry forest types of the Rocky Mountains. This tool is meant for use after stand management objectives have been defined to discuss and communicate how different treatments can be used to achieve fine-scale spatial objectives. To assist in visualizing the effect of treatments on stand spatial structure, we simulated four treatments representing two space or size-based and two VRH implementation strategies across four sites that are characteristic of dry conifer forests of the southern Rocky Mountains (fig. 2). These sites were selected because they had been identified as being in need of ecological restoration. The simulated treatments were identified as the most commonly used silvicultural practices within the southern Rocky Mountains (Underhill et al. 2014). The sites cover a range of productivity and complexity in ponderosa pine (*Pinus ponderosa*) forests and woodlands at site indexes of 35, 55, 65, and 90 ft at base age 100 (low-moderate density single story, moderate density multi-storied, moderate-high density multi-storied stand, and high density multi-storied stand in order of site index). Within each site, ponderosa pine is the dominant overstory species, with Douglas-fir (*Pseudotsuga menziesii*) and quaking aspen (*Populus tremuloides*) representing minor components of stand structure. A summary of each stand's structure is presented using common forest metrics (e.g., basal area, trees per acre, and so on), clump size distributions, opening area, and spatial statistics (Plotkin et al. 2002; Sánchez-Meador et al. 2011; Schneider et al. 2015). In addition, visualizations are provided to assist users in seeing what these spatial and non-spatial metrics look like.

How to Use This Tool

The central purpose of this tool is to link quantitative and visual descriptions of immediate post-treatment spatial forest structure following space/diameter-based and VRH treatments. The visual and quantitative data in this tool can be utilized to (1) fine-tune silvicultural targets related to spatial forest structure, (2) provide insight on the effect that different silvicultural treatments may have on spatial forest structure, and (3) facilitate communication among land managers, stakeholders, and contractors in regard to desired spatial structures at the stand level.

The first step in developing any silvicultural treatment for a site is to develop site-specific management objectives. Once management objectives are well defined, this tool might be used to assist with interpreting how the spatial patterns created by different treatments could achieve management objectives. This could include promoting fuel discontinuity that might be better evaluated by the size of clumps and openings rather than through traditional canopy fuel estimates. To fully understand the differences

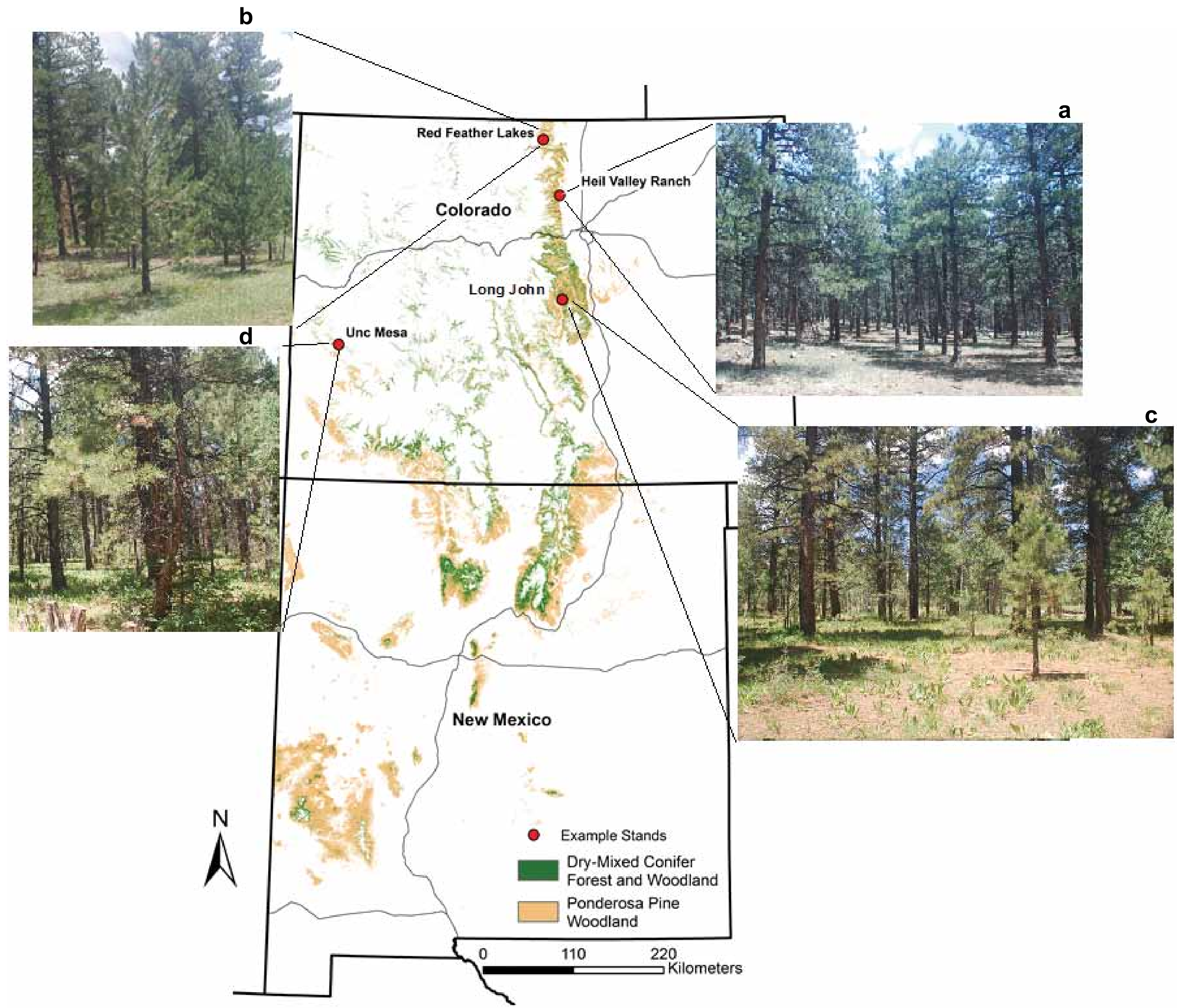


Figure 2—Distribution of 11.8 million acres of ponderosa pine woodlands and dry-mixed conifer forest and woodlands within the Rocky Mountains of Colorado and New Mexico, USA. Inset photos depict pre-treatment forest structure of example stands, in order of structural complexity: (a) Heil Valley Ranch, (b) Red Feather Lakes, (c) Long John, and (d) Unc Mesa. In the visualization, these stands are referred to as Low-Moderate Density Single-Story Stand, Moderate Density Multi-Storied Stand, Moderate-High Density Multi-Storied Stand, and High Density Multi-Storied Stand, respectively (photos: Emma Vakili, USDA Forest Service).

in treatment outcomes, it will be necessary to look at the range of forest structures produced by treatments.

Although this tool focuses on describing stands through the fine-scale structures they are composed of, these structures exist across a range of spatial scales that influence forest composition, structure, function, and processes in spatially and temporally dynamic ways. Some of these specific structures provide vital functions for habitat and other management concerns (Youtz et al. 2008). At the fine scale (0.25 acres or 0.1 ha), the key compositional and structural elements of interest typically include the distribution, size, and characteristics of openings, isolated trees, and clumps of trees (see box 1; Larson and Churchill 2012). Stands are the next scale of interest and are commonly considered to be smaller than subwatersheds and larger than the largest tree clumps and openings desired for the system (Urban et al. 1987). Stands can be described as the aggregate of fine-scale units (clumps of trees, individual trees, and openings). Descriptions at the stand scale can include both averaged values across the stand (i.e., trees per acre and basal area per acre) as well as the variability among the finer scale patches, openings, and individual trees that are present within the stand (i.e., percentage of isolated trees or mean opening size). Finally, the largest scale of interest is referred to as a landscape (2,500 and 250,000 acres), where the variability is defined by the stands that are encompassed by any given landscape (see box 2).

Box 1: Fine-Scale Forest Structures

Fine-scale forest structure describes patterns of individual trees at a grain size of approximately 0.25 acres (0.1 ha), which is slightly larger than typical forest inventory plots. These features are the fundamental building blocks used within this guide to describe stand scale forest patterns. Larson and Churchill (2012) provide five common features that can be used to describe fine-scale structural patterns: openings, isolated trees, regeneration patches, clumps of overstory trees, and clumps of mixed-sized trees (figs. 3 and 4). Understanding the defining features of fine-scale structures, and specifically clumps, is important for successfully marking any spatially explicit treatment. Long-term upkeep of these features is likely to require repeated disturbances through fire, insects, or silvicultural intervention; otherwise, ingrowth will slowly increase the density and basal area of these stands.

Following the protocols described by Churchill et al. (2013a,b), openings include any space within the stand that is greater than 19.7 ft (6 m) from a tree (fig. 4a). Openings include small interstitial spaces among trees, as well as larger spaces within the stand that receive direct sunlight throughout the day. Throughout this tool, we characterize clumps of trees as those that have a neighbor within 19.7 ft (6 m), but they can be further described using a variety of metrics. In many cases the size and shape of clumps is described by the area, number of trees per clump, or the edge to perimeter ratio. However,

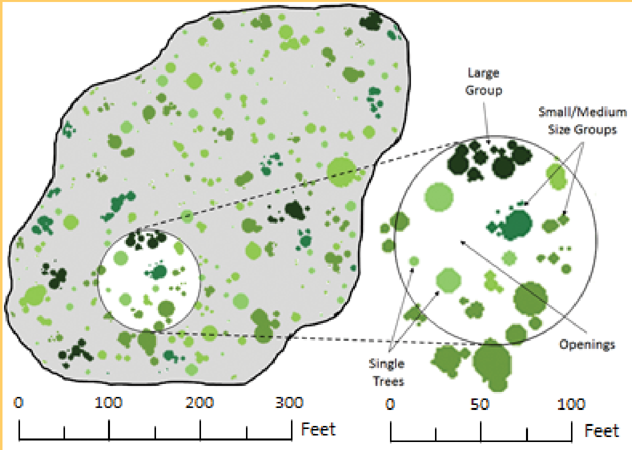


Figure 3—Depiction of stand-scale forest pattern, with inset of fine-scale structures in a restored ponderosa pine forest.

as suggested by Larson and Churchill (2012), the vertical structure of a clump of trees can be broadly classified as patches of regeneration or smaller trees, patches of overstory trees, or patches of mixed sized trees (figs. 4c-e respectively). In addition, each of the three types of tree clumps (regeneration patch, overstory trees, and mixed-sized) could be just a single species (pure) or a mixture of species. Altering the combination of fine-scale structures can serve to achieve a variety of different management objectives ranging from promoting understory biodiversity or improving wildlife habitat, to restoring ecological process like frequent-fire regimes. By varying the apportionment of different clump sizes and types in different stands, these fine-scale features can contribute to creating landscape scale heterogeneity.

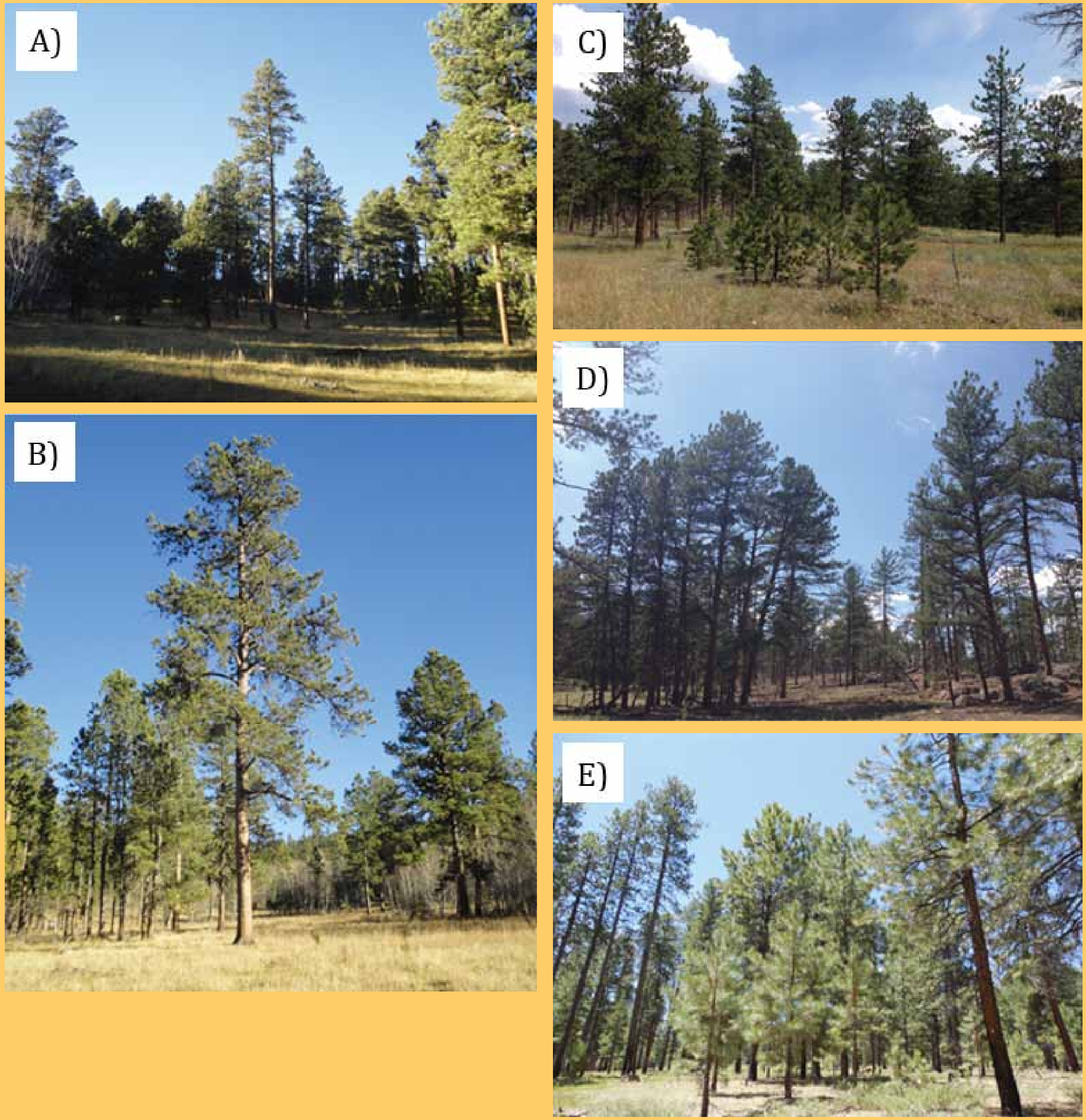


Figure 4—Examples of fine scale stand structure progressing (a-e) through (a) openings, (b) isolated trees, (c) regeneration clumps, (d) mature clumps, and (e) mixed clumps (photos: Mike Battaglia, U.S. Forest Service).

Although restoration or fuel hazard reduction treatments often consider changes in forest structure across all of these scales, this tool focuses on describing stand-scale distributions of individual trees, tree clumps, and openings along with common forest metrics. Tree clumps are described across each of the simulated stands based on the density of trees in each clump, while openings are described in terms of their size as measured by the distance to the nearest individual tree. While other metrics can be used to describe fine-scale structures within clumps (i.e., multiage vs. single age clumps) and openings (i.e., shape or edge to area ratios), they are not included in this tool but could be important considerations depending on specific management objectives.

Some of the difficulties among forest managers in communicating desired heterogeneous structures stem from issues with grasping and describing structures across these scales. Although spatial patterns exist at local tree-to-tree scales, within stands, across landscapes, and regionally, it is important to remember that heterogeneity at one scale does not necessarily result in heterogeneity at larger scales (Hessberg et al. 2015). The ecological impact of forest structure is likely to vary across these scales, with the influence of heterogeneity at fine scales differing from those at coarse scales. Therefore, it might be important for forest managers to carefully consider the context of their forest, including management objectives, forest type,

Box 2: Landscape-Scale Heterogeneity

While forest managers apply silvicultural treatments at stand scales, it is important to consider the impact of treatments on large landscape-scale phenomena. Heterogeneity at landscape-scales—defined here as areas between 2,500 and 250,000 acres—describes the spatial patterns of the stands within the landscape. Landscape scale heterogeneity is influenced by a number of factors, including: variation in stand types, topography, site conditions, soil, and hydrology. Following Bettinger et al. (2009), we suggest defining stand types based on a combination of metrics, such as forest successional pathways and stages, species composition, or site index. From a forest planning perspective, these factors, along with others such as property ownership boundaries and pre-existing roads, and infrastructure will constrain the ability for treatments to affect landscape-scale heterogeneity. Some common factors to consider when assessing landscape scale heterogeneity include the arrangement, distribution, and variability of stand types, sizes, and shapes along with the relative spatial relationship of different stands structures to each other. Understanding the diversity of stand types and their relationship to one another across a landscape will dictate the range of management alternatives and how they may be placed into the landscape. In landscapes with many similar stands in proximity, it may be necessary to think about staggering the timing of their treatment to prevent creating large blocks of homogeneous stand types.

At the coarsest level of consideration, we suggest landscapes that only contain a few forest conditions (fig. 5a and c) might have a narrower range of possible future conditions than a landscape starting from a more diverse position (fig. 5b and d). For example, in a landscape with only a couple of starting forest conditions, the timing of treatments within adjacent stands of similar forest conditions will be an important component in future landscape heterogeneity. The next level of consideration when planning treatment placement within a broader landscape includes looking at the size and distribution of stand sizes across the landscape. Stands can be very uniform in their size across a landscape (fig. 5a and b) or could vary from large homogeneous blocks to small patches of unique structures (fig. 5c and d). The way in which stand diversity and sizes vary and intermix must be considered when planning the sequence or timing of multiple treatments in order to keep from producing homogeneity at landscape scales when implementing multiple treatments in adjacent stands. Similarly, patch size has consequences for fragmentation if we attempt to over segment a landscape in the hope of creating diversity. Patch sizes should be considered in the context of reference landscape conditions or desired functions (Hessburg et al. 2015). It is important to note that landscape planning is a complex science and it is not our intention to provide a comprehensive framework to guide the landscape planning process, nor an exhaustive list of the facets that inform landscape-scale planning.

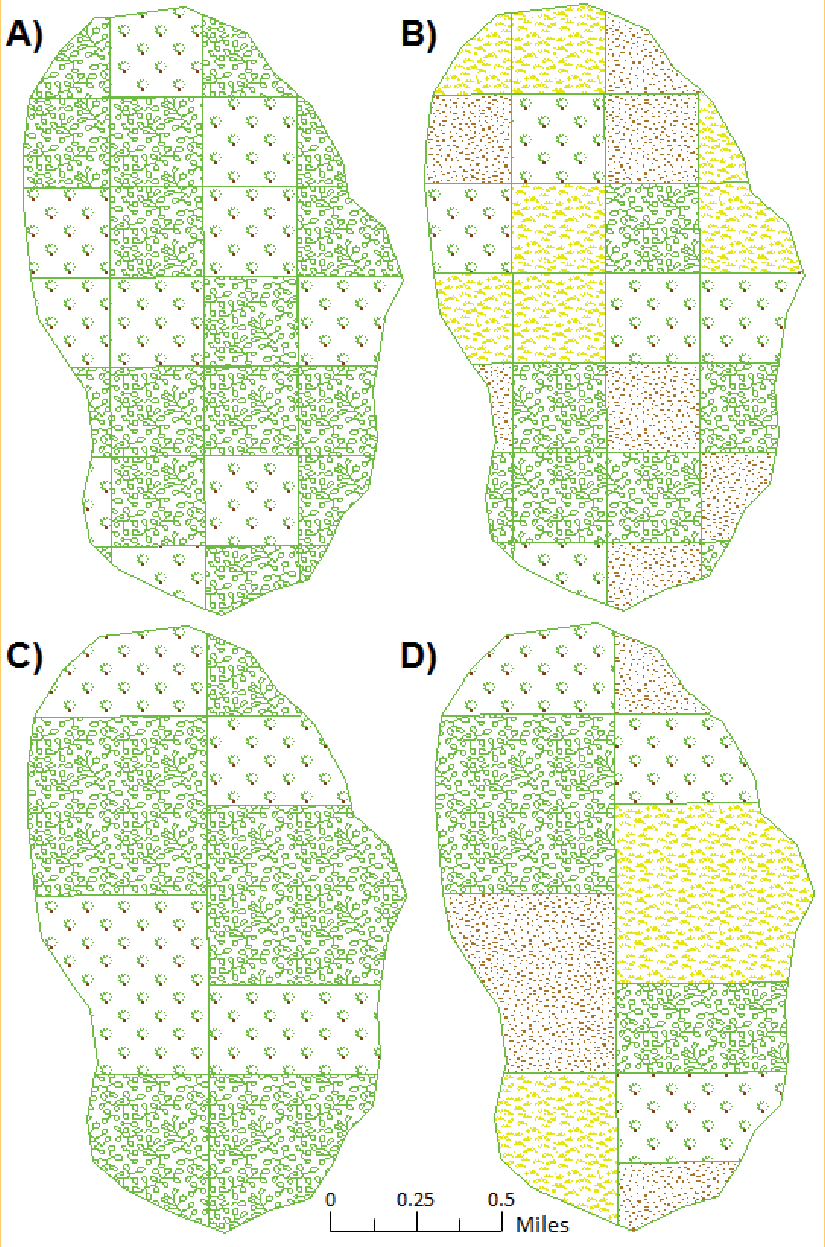


Figure 5—Comparison of how stand type diversity (a and c are Low, and b and d are High) and stand size variability (a and b are Low, and c and d are High) influence the intermixing and number of forest types and successional stages on a landscape. Stand diversity is often controlled by abiotic environmental factors (e.g., climate gradients) and stand size is usually an artifact of past management decisions and disturbance patterns.

historical disturbance regime, topography, climate, and adjacent structures at each scale, before deciding on a desired forest structure for their stand.

Once desired fine- and stand-scale structures for a project have been identified, the stands visualized in this tool could be compared with specific project pre-treatment forest structures to determine which stands have the greatest similarities. As this tool is designed to examine spatial structure, it is important when comparing the example visualization to consider how the mean and distribution of tree sizes and densities, as well as current spatial pattern of the trees, compare to project specific structures.

After example stand(s) have been identified, this tool can be used to compare how treatment alternatives might affect the distributions of clump sizes and openings. It is unlikely that a single simulated post-treatment structure perfectly fits any given project's specific objectives, making it likely that a composite of example treatments might be necessary. Furthermore, the visualizations within this tool might be a useful reference in management planning documents and/or help with communication if provided to prescription marking teams or contractors.

It is important to remember that the possible stand and landscape structures that can be created using silvicultural treatments are constrained by the forest structure currently present. Often it is necessary to implement a range of silvicultural treatments over a number of years to encourage both the regeneration of small trees and the growth of larger diameter trees within a stand. This consideration will be of particular importance when reentering a stand that had previously been treated in the past to create stands of evenly spaced or sized trees.

Additionally, in order to modify landscape-scale forest structure, a number of treatments will probably be needed. This visual tool is a simple aid to help communicate desired (or undesired) forest structures and evaluate treatment alternatives. The consideration of project-specific context is always important when designing silvicultural treatments. Furthermore, this tool does not consider many of the commonly important considerations within the prescription marking process such as regional practices, like preferentially removing Douglas-fir and true fir species in favor of aspen, which are often implemented to modify species composition and diversity. The simulated treatments do not consider common tree selection criteria like species preference, crown position, crown ratio, tree health, or legacy trees, all of which will influence the ability of a stand to include the full range of fine-scale forest structures. To that end, the example simulations represent an idealized post-treatment stand that was thinned without regard for common considerations like pathogens or crown ratio. In the face of real world prescription marking constraints, achieving the fine-scale structures seen in the examples may require multiple stand entries to increase the range of fine-scale structures possible over many decades. Finally, our simulated treatments only consider the immediate impacts on forest structure. During the selection of alternative treatments, it can be important to consider any potential long-term impacts of modifying forest structure on ecosystem processes, the ability to maintain these desired structures through additional treatment or prescribed burning, and any possible ecological or financial trade-offs.

Treatment Simulations

To derive the initial conditions in the visualization tool, we used stem-mapped data from Ziegler et al. (2017). Within each stand, the location, diameter at breast height (d.b.h.), height, and canopy base height was recorded for each tree (fig. 6). This inventory approach allowed for the simulation and evaluation of spatial silvicultural treatments on both spatial and non-spatial forest metrics.

The stands each received four simulated treatments resulting in a residual basal area of 40 ft^2 $acre^{-1}$ including a thinning from below, random tree selection, and two spatially VRH protocols at a high and moderate clumping intensity (Churchill et al. 2013b). These treatments were chosen because they are the most commonly utilized silvicultural practices within the southern Rocky Mountains (Underhill et al. 2014). Simulations do not consider common individual tree marking/tree selection criteria, which may

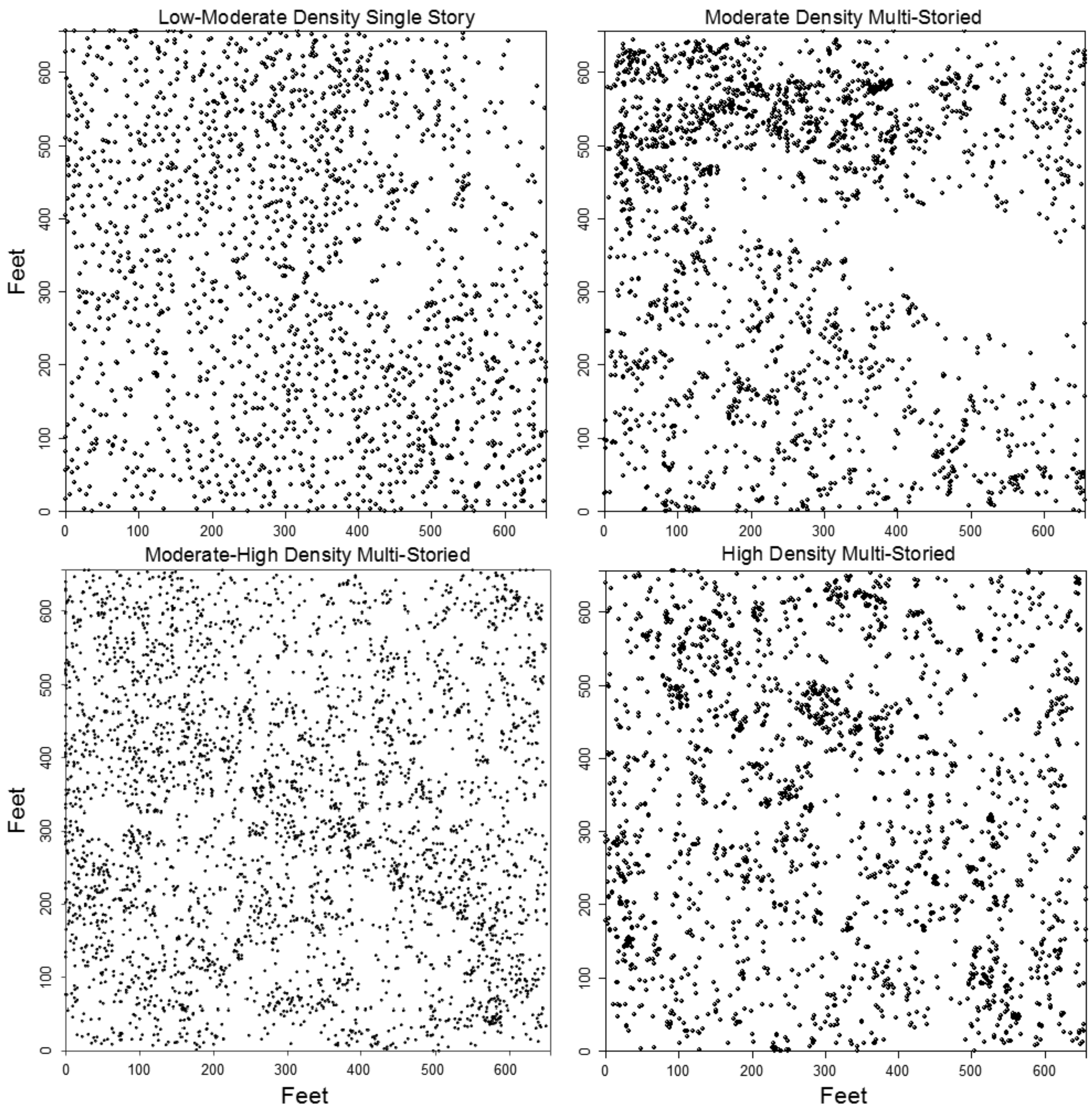


Figure 6—Pre-treatment tree stem map of 9.9 acre example sites, where each dot represents a tree location.

make it difficult to hit the exact structural category targets presented.

The thin from below implementation was performed by ranking the trees in order of individual basal area and removing the smallest trees until the target basal area was achieved. Random tree selection was simulated by randomly assigning a number to each tree and removing trees with the smallest assigned number until the target residual basal area was achieved.

To implement the VRH simulations on our stands, a Python script was created to run on each stand's stem map shapefile in ArcMap 10.0 (ESRI 2011). The script was written to mimic the actions that an experienced tree marker or forester might use in marking which trees to keep during a harvest. The process allocates different percentages of the trees in a stand into the different fine-scale forest structures, depending on the desired output (table 1). The simulations were implemented to represent clumping levels seen in a range of forest historical reconstructions, but site-specific values should be considered if available when considering this distribution of clump sizes. Additionally, the process of locating clumps and openings in a stand should generally be informed by existing gradients of density and productivity (Churchill et al., in press). This process operates without regard for common secondary marking criteria like crown ratio or diameter, instead purely selecting trees to keep based on their spatial proximity to other trees. The script followed these steps:

Table 1—Specific numbers of trees are proportionally allocated into different fine-scale stand structures for the VRH treatment simulations. These structural categories are only examples and structure classes should be locally developed to meet management objectives and forest conditions.

Structure	Moderate clumping (percent)	High clumping (percent)
Single trees	35	10
2–4 Tree clump	30	30
5–9 Tree clump	20	35
10–15 Tree clump	10	15
>15 Tree clump	5	10

1. Using the mean tree size within a stand, the approximate number of trees that should be left after treatment to achieve the target basal area is calculated.
2. This target number of trees is proportionally allocated to the group sizes (table 1) to calculate the target number of trees in each group size.
3. The script then starts locating structures starting with the largest group size (i.e., groups >15 trees first, then 10–15 trees, 5–9 trees, 2–4 trees, and finally Single trees last).
    a. The script finds groups of trees of the appropriate size that already exist and keeps those groups first (regardless of tree size).
    b. If more trees are needed in the target group size, the script then finds all trees that are in groups larger than the size needed. It randomly selects one tree in these groups and selects the first *x* trees around that focal tree to create a group.
    c. As the script selects groups of trees to keep, it removes the trees within a buffer zone surrounding those groups.
    d. Once the target number of trees for that group size has been reached or it is no longer possible to make more groups, the script moves onto the next smallest group size. Step 3 is repeated for each group size until all structures have been identified.
4. Once the targets have been reached or all trees have been assigned (as trees to keep or remove), the script outputs the post-treatment stand tree list.

It should be noted that for the VRH simulations it was not always possible to achieve both the target residual basal area and the exact group size distribution (i.e., some runs with higher residual basal area targets left no trees greater than 19.7 ft (6 m) from a neighboring tree to create Single trees). The post-treatment structure will always be constrained by what exists pre-treatment, it is difficult to create some forest structures immediately post-treatment, and it may take time or repeated entries to achieve objectives.

Summary and Visualization

In order to characterize the pre- and post-treatment stand conditions, the mean, minimum, maximum, and coefficient of variation of traditional forest inventory metrics were calculated by dividing each site into sixty-four 82 x 82 ft square plots. Using the 64 plots, we calculated the mean and variability in trees acre^{-1}, basal area per acre (BA acre^{-1}), and canopy base height (CBH). In addition, we estimated the total available canopy fuel load and stand quadratic mean diameter (QMD), height, and stand density index for each site using the Fire and Fuel Extension of the Forest Vegetation Simulator (Dixon 2002; Reinhardt and Crookston 2003) and generated histograms of 2-inch tree diameter class distributions for each site. Finally, each stand was placed into ArcMap, where the trees were buffered and merged according to their field measured crown radius to estimate the percentage of canopy cover pre- and post-treatment.

To assess the spatial variability and allocation of fine-scale forest structures, we used ArcMap (ESRI 2011) to apply a 19.7 ft buffer to each tree that was merged with any neighbors it overlapped with in order to assess how many trees it was clumped with. The clumping criteria of 19.7 ft was reached based on the average overstory tree crown radius of 9.85 ft for the trees inventoried across the plot, similar to methods applied by Abella and Denton (2009). Once trees were linked with the neighbors they shared a clump with, the distribution of clump sizes and areas and apportionment of trees per acre and basal area per acre within each clump size was calculated. Each stand also underwent point pattern analysis using the spatstats package (Baddeley et al. 2015) in the R statistics program (R Core Team 2016), where methods for the empty space function *F* (Ripley 1981) were used to generate a map showing the distance from any point in the stand to the nearest tree.

Within this, all distances greater than 19.7 ft from a tree were assumed to be within openings and provide an estimate of the openness of the stands. Further, stand opening size distribution are reported by identifying areas within each stand that meet a minimum width of 29.5 ft (9 m). This threshold of 29.5 ft should be considered in the context of the desired openings function, where openings of different sizes may serve different purposes ranging from understory plant stimulation to disrupting fire behavior. The location of each tree was appended to the map, scaled to represent its crown radius, and colored according to the clump size it belonged to.

Additionally, the empty space function was summarized by plotting a histogram showing the shift in opening sizes following treatment (fig. 7). Finally, 3-D representations of each simulation were created using the Smokeview package of the Fire Dynamics Simulator (Forney 2015). Each stand was visualized according to its trees' inventoried d.b.h., height, CBH, crown and radius, and trees were colored according to the clump size they belonged to (fig. 8). Similar 3-D visualizations can also be accomplished by using the Stand Visualization System of stem-mapped trees as presented by Graham et al. (2007). However, caution should be taken in trying to project future stand conditions because the Forest Vegetation Simulator is an aspatial growth model and may prove inadequate for projecting heterogeneous stand structures.

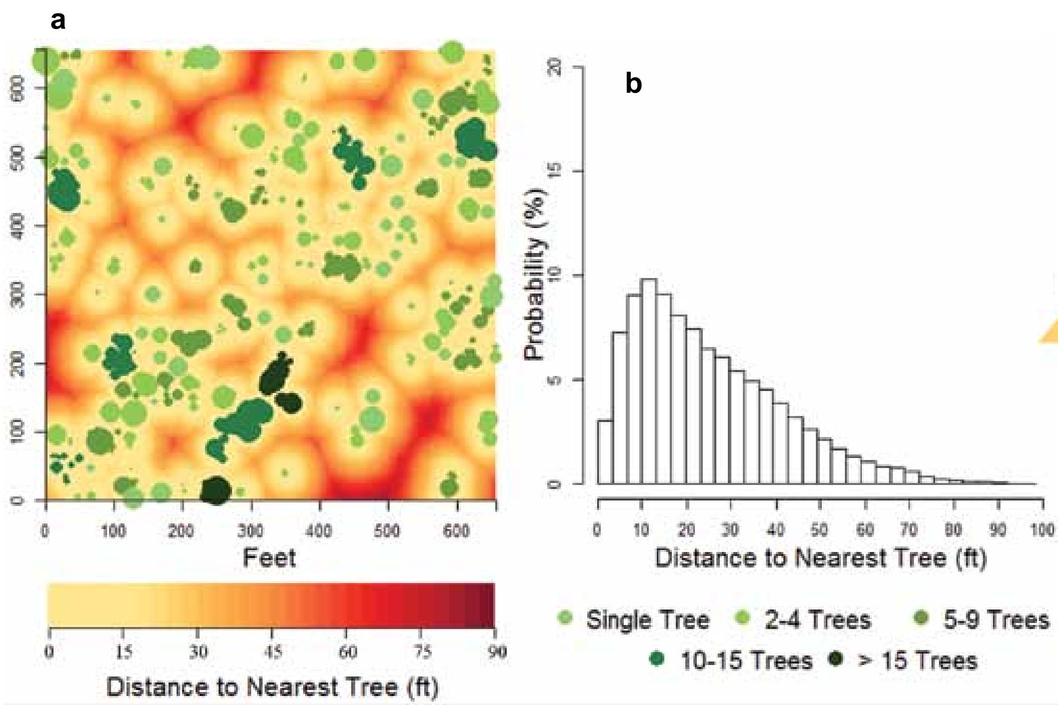


Figure 7—Example (a) stem map and (b) histogram of empty space function, showing the distribution of distances from the nearest tree into openings.

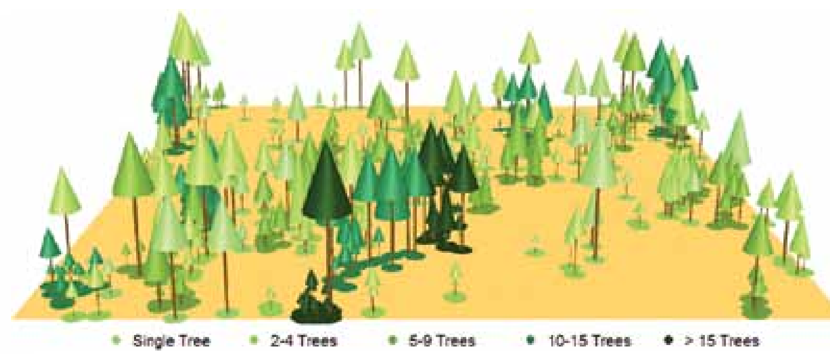


Figure 8—Example of Fire Dynamics Simulator visualization, with trees scaled to field inventoried values and colored according to the size of clump they belong to. Circles at the base of each tree are 19.7 ft in radius to help identify individual clumps.

Stand Visualizations

Pre-treatment: Low-Moderate Density Single Story Stand

This stand was comprised of 98 percent ponderosa pine, with small portions of the stand occupied by Douglas-fir and quaking aspen. The site is typical of many xeric low elevation (~7,000 ft above sea level) ponderosa pine stands with a site index of 35 ft at a base age of 100 (fig. 9). Prior to treatment, the stand was dominated by trees between 6 and 10 inches d.b.h. and had a QMD of 9.6 inches with a canopy base height of 12 ft (fig. 10; table 2). This stand was at a moderately high density of 169 trees per acre but with regions of higher density (>275 trees per acre) and horizontal continuity, with a single clump containing more than 1,200 trees (table 3; figs. 11 and 12). Only 4 percent of the stand was classified as openings having a radius greater than 20 ft. The stand underwent the 4 simulated thinnings to a residual basal area of 40 ft^2 $acre^{-1}$ (9.2 m^2 ha^{-1}).

Figure 9—Pre-treatment forest structure of a low-moderate density single story stand (photo: Emma Vakili, U.S. Forest Service).

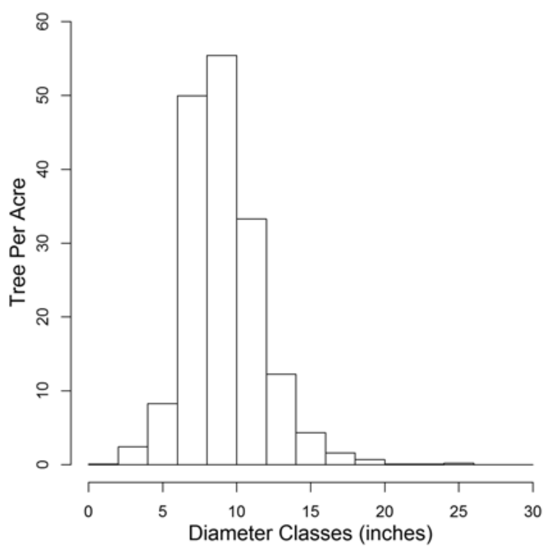


Figure 10—Pre-treatment distribution of trees per acre by 2-inch size classes for the low-moderate density single story stand.

Table 2—Pre-treatment stand characteristics for the low-moderate density single story stand. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment
Trees per acre	169 (26–291; 34%)
BA	83 ft^2 (11–131; 32%)
QMD	9.6 in (7.5–12.4; 23%)
Tree height	26 ft (21–32; 10%)
Canopy base height	12 ft (8–15; 13%)
Crown biomass	8.26 tons $acre^{-1}$

Table 3—Pre-treatment clump size distribution for the low-moderate density single story stand.

Cluster size	#/Acre	% TPA	% BA
Single tree	2.9	1.7	2.6
2–4 Trees	2.8	4.3	4.7
5–9 Trees	0.5	1.9	2.2
10–15 Trees	0.3	2.2	1.7
>15 Trees	0.9	89.9	88.8

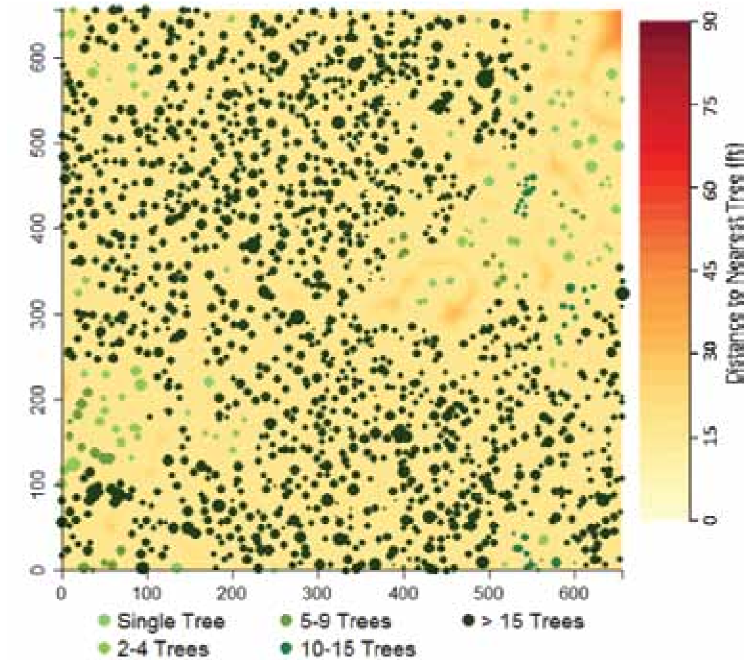


Figure 11—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters. Clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

Figure 12—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, CBH, and crown widths and are colored following the clustering scheme above (fig. 11), **b)** profile view of stand structure before treatment.

Thin From Below to 40 ft^2 ac^{-1} of Basal Area

Thin from below approaches tend to homogeneous stand structure and in this case resulted in all trees less than 10 inches d.b.h. being removed (fig. 13) and an increase in stand level QMD from 9.6 to 12.5 inches while reducing the local variability of QMD (table 4). Following completion of the thinning, the stand's canopy cover shifted from 86 to 57 percent and there was a substantial increase in the variability of local basal area and trees per acre. While local horizontal variability increased, there was no change to vertical structure. The horizontal continuity of the stand was greatly reduced as a result of the thinning.

Single tree and 2–4 Tree clumps went from being represented by 6.0 to 69.1 percent of the trees in the stand, with the largest clump containing 22 trees (table 5).

The thinning also resulted in an increase in the number of and mean size of stand openings, with openings now reaching 49 ft in radius as can be seen by the darker colors within the empty space function (figs. 14 and 15).

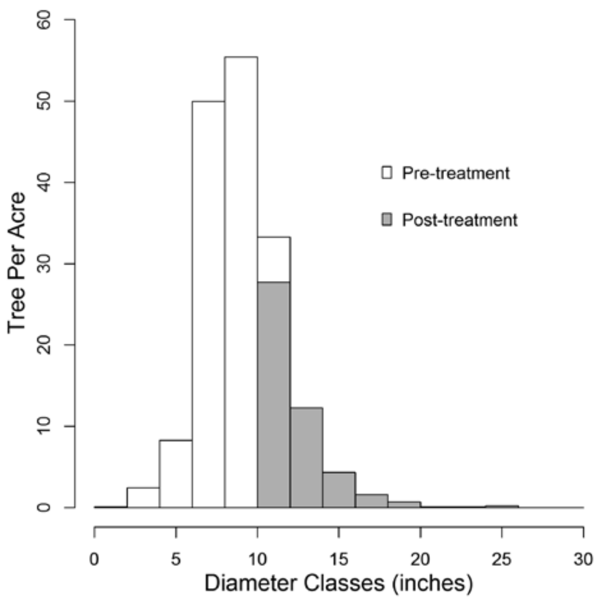


Figure 13—Comparison of trees per acre distribution within 2-inch size classes for the thin from below treatment.

Table 4—Changes in stand characteristics for the low-moderate density single story stand after a thin from below treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	169 (26–291; 34%)	47 (7–104; 53%)
BA per acre	83 ft^2 (11–131; 32%)	40 ft^2 (4–96; 54%)
QMD	9.6 in (7.5–12.4; 23%)	12.5 in (10.7–17.1; 21%)
Total height	26 ft (21–32; 10%)	29 ft (17–35; 11%)
CBH	12 ft (8–15; 13%)	13 ft (9–17; 14%)
Crown biomass	8.26 tons $acre^{-1}$	4.26 tons $acre^{-1}$

Table 5—Changes in clump size distribution for the low-moderate density single story stand after the thin from below treatment.

	Pre			Post		
Cluster size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	2.9	1.7	2.6	15.3	32.3	34.0
2–4 Trees	2.8	4.3	4.7	6.8	36.8	35.5
5–9 Trees	0.5	1.9	2.2	1.4	19.5	19.3
10–15 Trees	0.3	2.2	1.7	0.3	6.6	6.6
>15 Trees	0.9	89.9	88.8	0.1	4.7	4.6

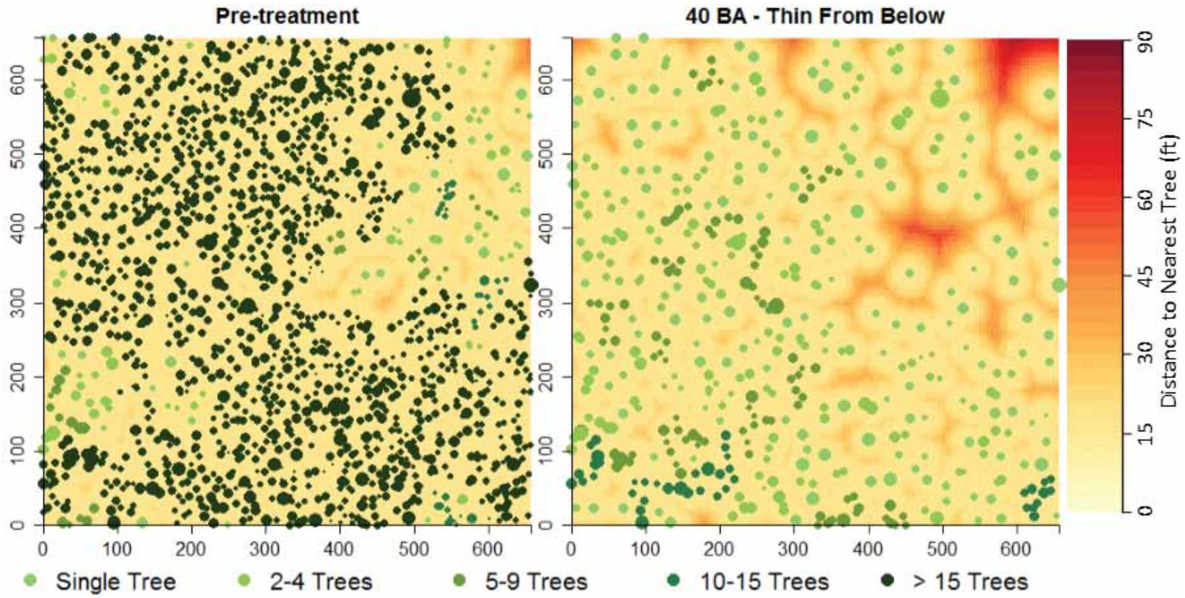


Figure 14—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters. Clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

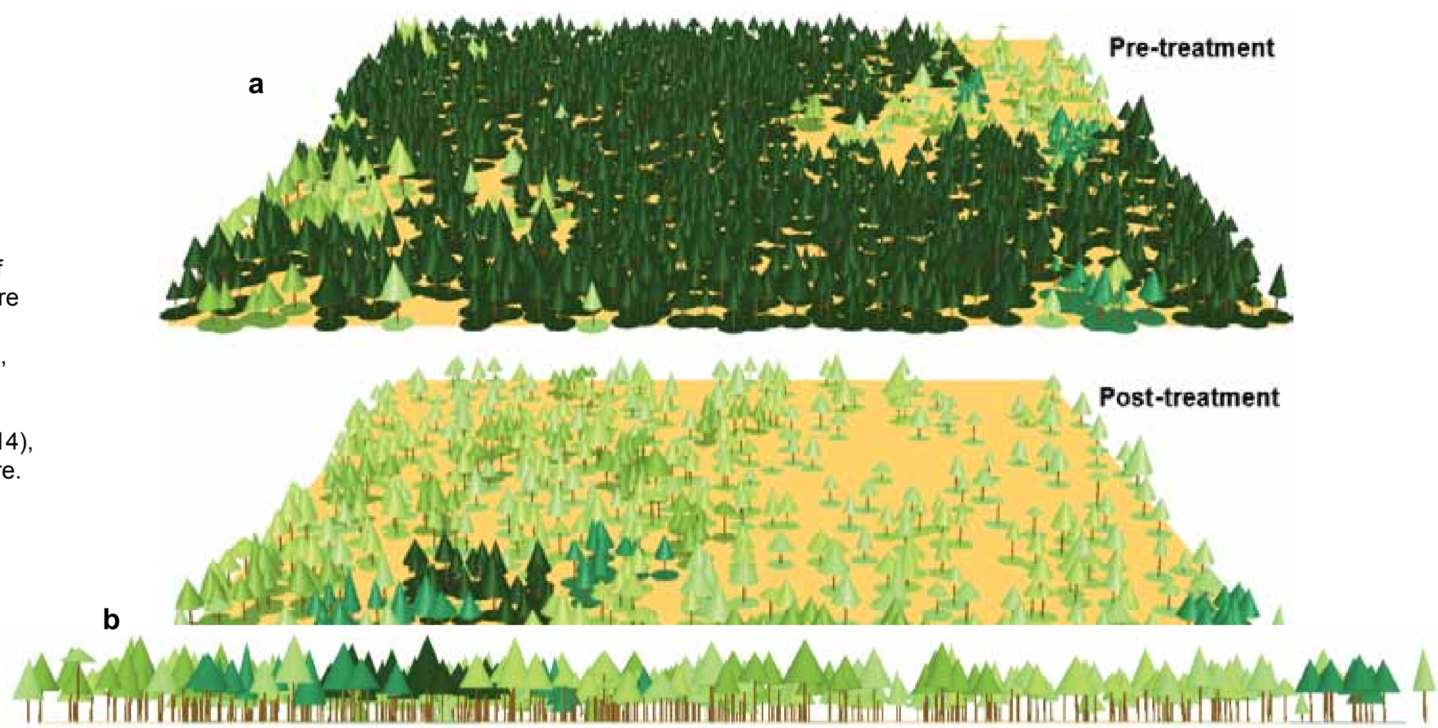


Figure 15—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 14), **b)** profile view of stand structure.

Random Thinning to 40 ft^2 ac^{-1} of Basal Area

Proportional thinning throughout the diameter range or random thinning techniques tend to preserve the pre-existing stand structure and in this case removed about 50 percent of trees from each diameter class (fig. 16), with the stand level QMD holding at 9.6 inches and increasing the range of QMDs seen throughout the stand (table 6). While the range of trees and basal area per acre was lowered, the local variability in horizontal forest structure increased. Following completion of the thinning, the stand's canopy cover shifted from 86 to 60 percent and there were small increases in the local variation in vertical forest structure.

The stand went from being dominated by a single large clump (>1,200 trees) to having a nearly uniform distribution of trees in structures from Single trees to 15–20 tree clumps (table 7).

The thinning increased the number of openings and produced a greater range of opening sizes with radii ranging from 15–49 ft (figs. 17 and 18).

Table 6—Changes in stand characteristics for the low-moderate density single story stand after a random thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	169 (26–291; 34%)	81 (7–136; 38%)
BA per acre	83 ft^2 (11–131; 32%)	40 ft^2 (3–74; 37%)
QMD	9.6 in (7.5–12.4; 23%)	9.6 in (7.8–17.0; 35%)
Total height	26 ft (21–32; 10%)	26 ft (20–26; 12%)
CBH	12 ft (8–15; 13%)	12 ft (7–16; 16%)
Crown biomass	8.26 tons $acre^{-1}$	4.00 tons $acre^{-1}$

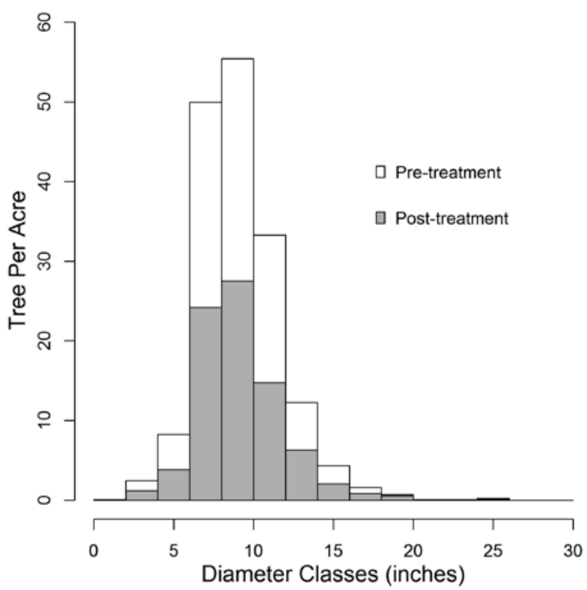


Figure 16—Comparison of trees per acre distribution within 2-inch size classes for the random thinning treatment.

Table 7—Changes in clump size distribution for the low-moderate density single story stand after the random thinning treatment.

	Pre			Post		
Cluster size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	2.9	1.7	2.6	10.4	12.7	16.1
2–4 Trees	2.8	4.3	4.7	6.6	21.7	22.7
5–9 Trees	0.5	1.9	2.2	2.9	23.1	22.9
10–15 Trees	0.3	2.2	1.7	1.1	16.6	14.5
>15 Trees	0.9	89.9	88.8	0.8	25.9	23.8

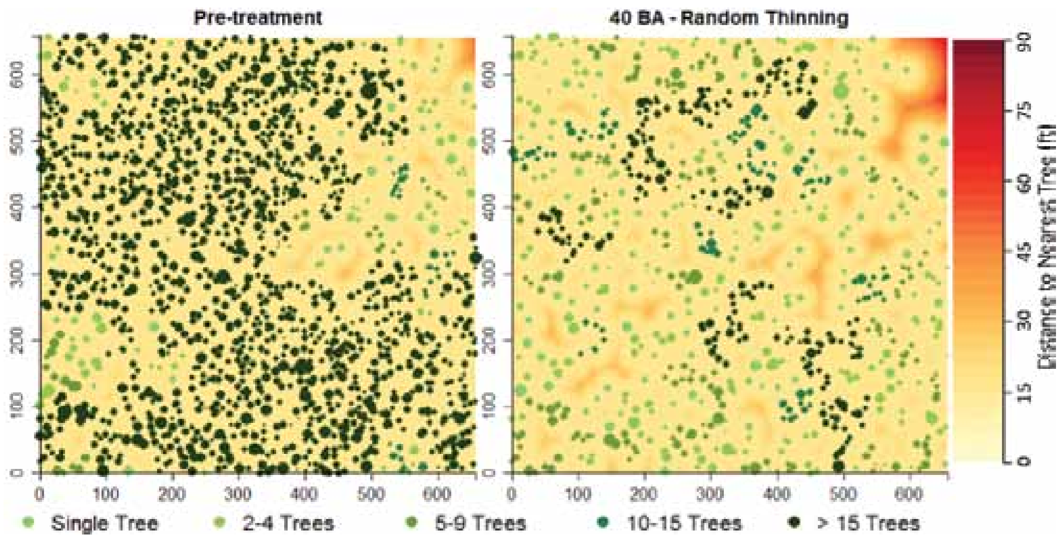


Figure 17—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters. Clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

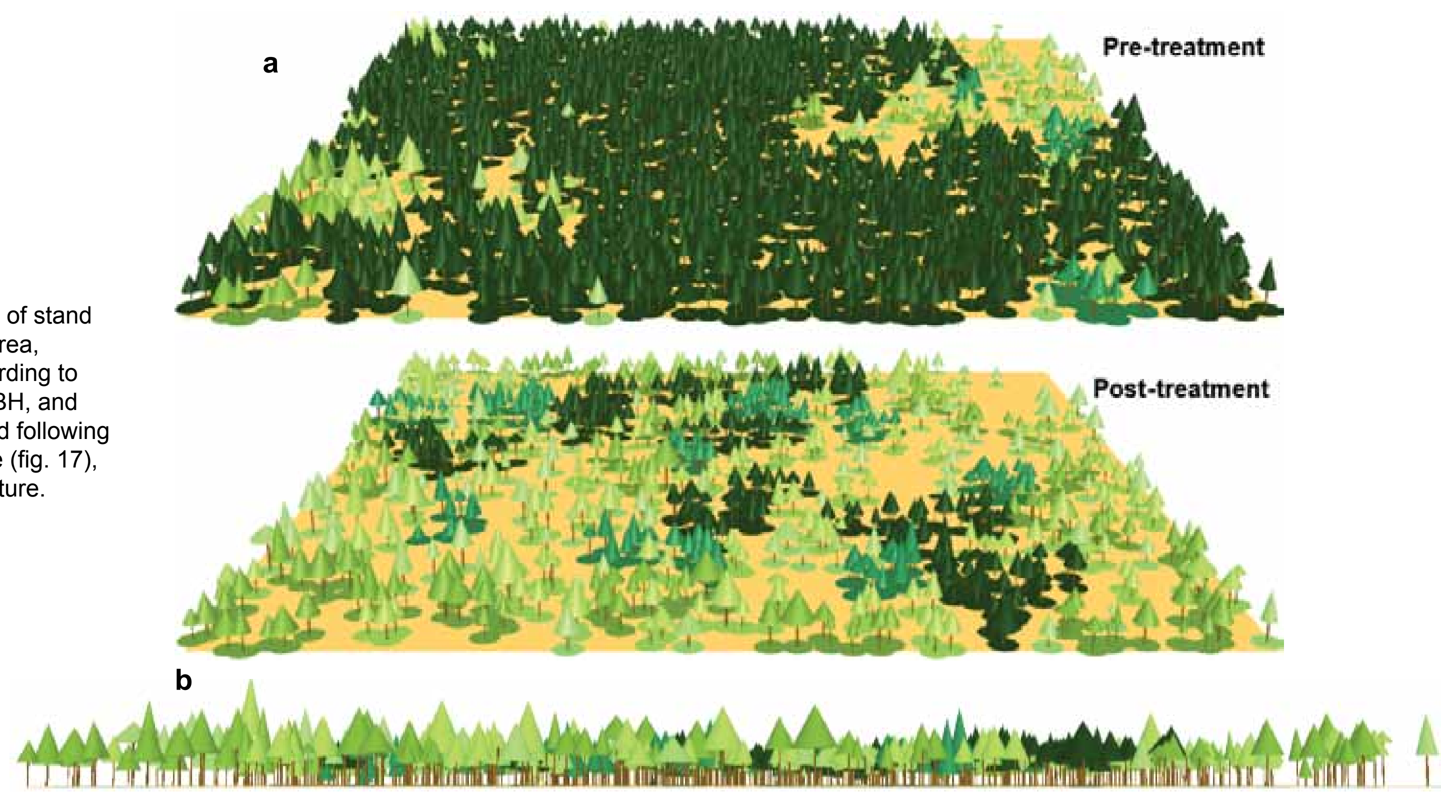


Figure 18—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 17), **b)** profile view of stand structure.

Moderately Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

A moderate clumping scenario following individual, clump, and opening thinning approach attempts to increase the number of small clumps, and in this case it resulted in a proportional removal of trees throughout the range of diameters (fig. 19) and only a minimal increase to stand level QMD from 9.6 to 9.7 inches (table 8). Following completion of the thinning, the stand's canopy cover shifted from 86 to 64 percent. There were also decreases in the range of horizontal structures and nearly no shift in local variability of vertical and horizontal structures, generally failing to meet the goals of spatially explicit prescriptions.

The stand went from being dominated by large clumps to having Single tree and clumps from 2–4 trees representing the majority of the stand (table 9).

The thinning increased the number and mean size of stand openings, ranging from 15–39 ft. However, it failed to create large openings (>1/4 acre) within the stand (figs. 20 and 21).

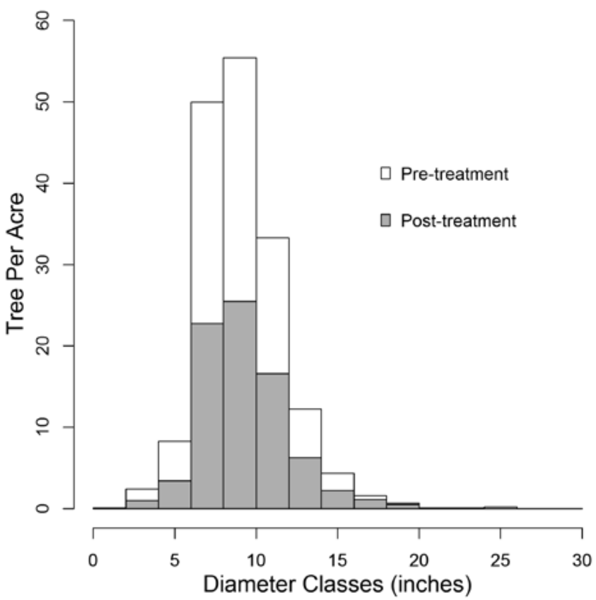


Figure 19—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the moderately clumped thinning treatment.

Table 8—Changes in stand characteristics for the low-moderate density single story stand after a moderately clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	169 (26–291; 34%)	83 (13–188; 32%)
BA per acre	83 ft^2 (11–131; 32%)	42 ft^2 (5–93; 38%)
QMD	9.6 in (7.5–12.4; 23%)	9.7 in (7.3–12.2; 24%)
Total height	26 ft (21–32; 10%)	26 ft (21–32; 11%)
CBH	12 ft (8–15; 13%)	12 ft (8–15; 14%)
Crown biomass	8.26 tons $acre^{-1}$	4.28 tons $acre^{-1}$

Table 9—Changes in clump size distribution for the low-moderate density single story stand after the random thinning treatment.

	Pre			Post		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	2.9	1.7	2.6	24.9	31.3	33.0
2–4 Trees	2.8	4.3	4.7	8.8	31.1	32.4
5–9 Trees	0.5	1.9	2.2	2.7	22.0	21.0
10–15 Trees	0.3	2.2	1.7	0.6	9.1	6.9
>15 Trees	0.9	89.9	88.8	0.3	6.5	6.7

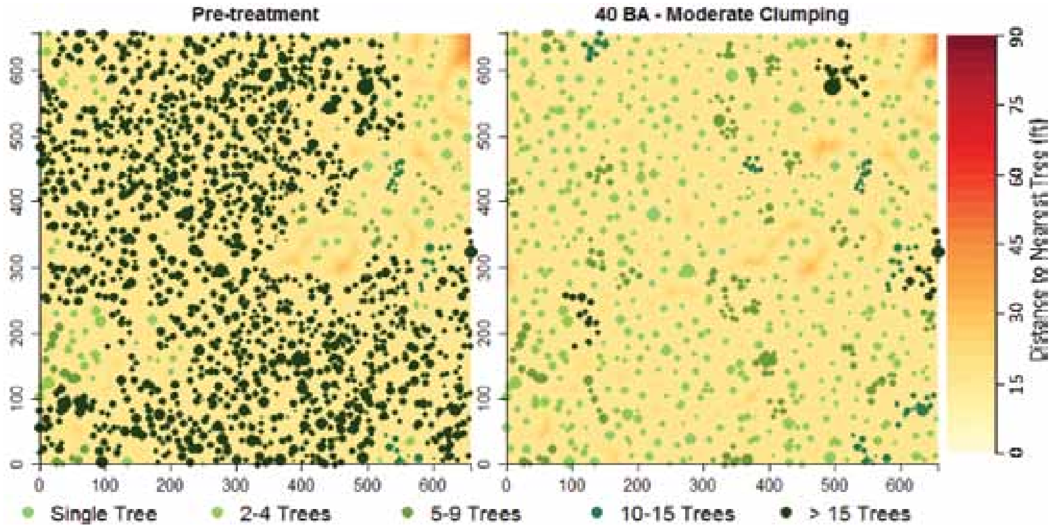


Figure 20—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

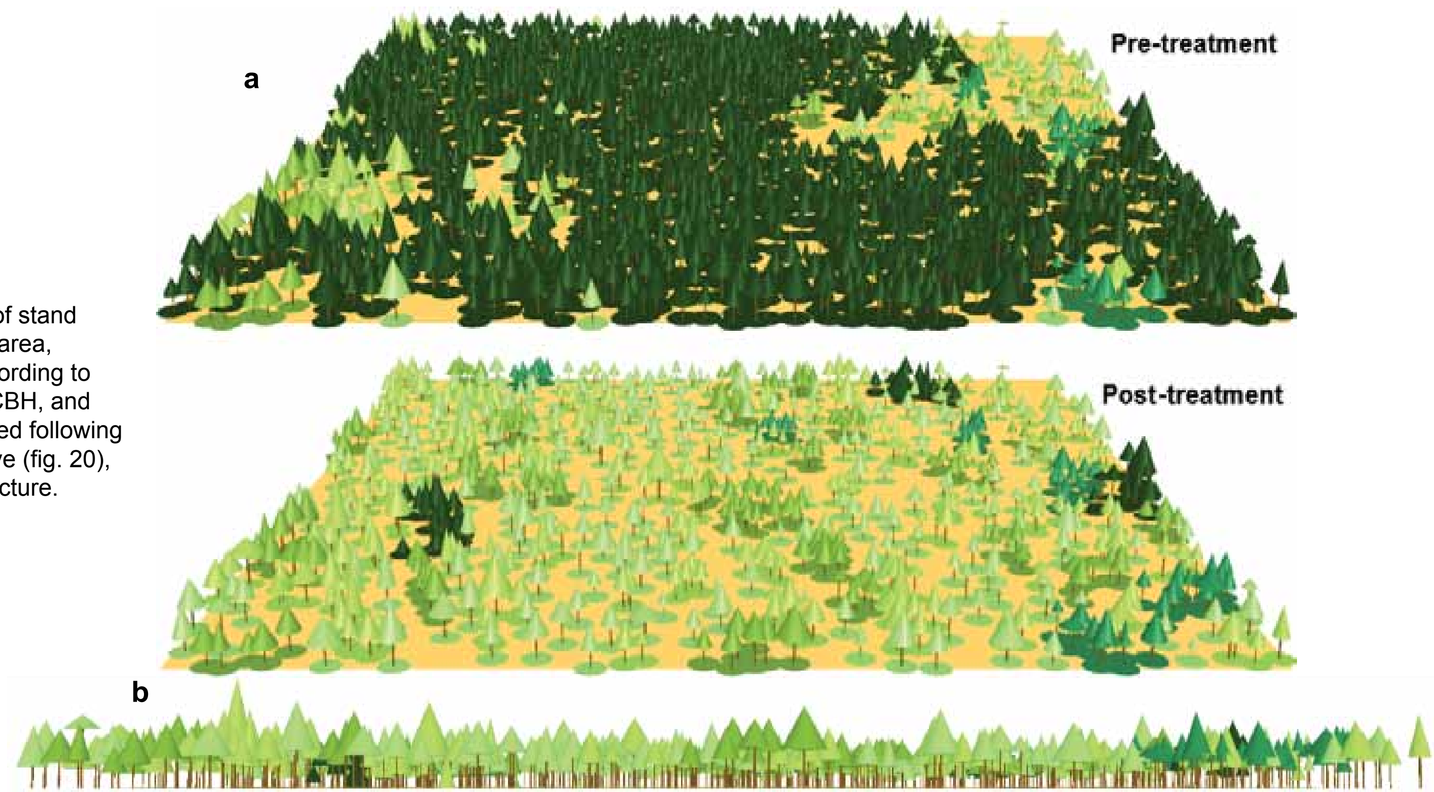


Figure 21—Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 20), **b)** profile view of stand structure.

Highly Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

Under the high clumping scenario following individual, clump, and opening thinning, the goal was to distribute the stands throughout the range of clump sizes. In this case, it resulted in a proportional removal of trees through the range of diameters (fig. 22), with the stand level QMD holding at 9.6 inches and a slight increase to the range of local QMDs (table 10). Following completion of the thinning, the stand's canopy cover shifted from 86 to 58 percent. This treatment provided the greatest increase in local variability in trees and basal area per acre, in line with the goals of spatially explicit prescriptions.

- The stand went from being dominated by large clumps to having a balanced distribution of clump sizes (table 11).
- The thinning also resulted in a significant increase in the number and mean size of stand openings, with several openings now reaching minimum radii of 49 ft, represented in openings of approximately 1/6 to 1/3 acre (figs. 23 and 24).

Table 10—Changes in stand characteristics for the low-moderate density single story stand after a highly clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	**Post**
Trees per acre	169 (26–291; 34%)	80 (26–149; 42%)
BA per acre	83 ft^2 (11–131; 32%)	41 ft^2 (11–83; 46%)
QMD	9.6 in (7.5–12.4; 23%)	9.6 in (7.1–12.4; 25%)
Total height	26 ft (21–32; 10%)	26 ft (20–32; 11%)
CBH	12 ft (8–15; 13%)	12 ft (8–19; 15%)
Crown biomass	8.26 tons $acre^{-1}$	4.18 tons $acre^{-1}$

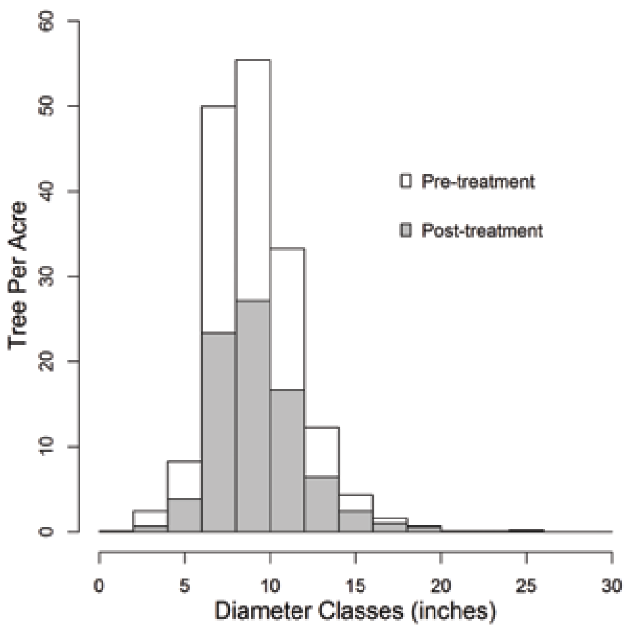


Figure 22—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the highly clumped thinning treatment.

Table 11—Changes in clump size distribution for the low-moderate density single story stand after the highly clumped thinning treatment.

	Pre			**Post**		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	2.9	1.7	2.6	8.2	9.9	12.0
2–4 Trees	2.8	4.3	4.7	8.7	29.7	31.0
5–9 Trees	0.5	1.9	2.2	4.4	36.2	34.3
10–15 Trees	0.3	2.2	1.7	0.9	13.8	12.4
>15 Trees	0.9	89.9	88.8	0.5	10.4	10.4

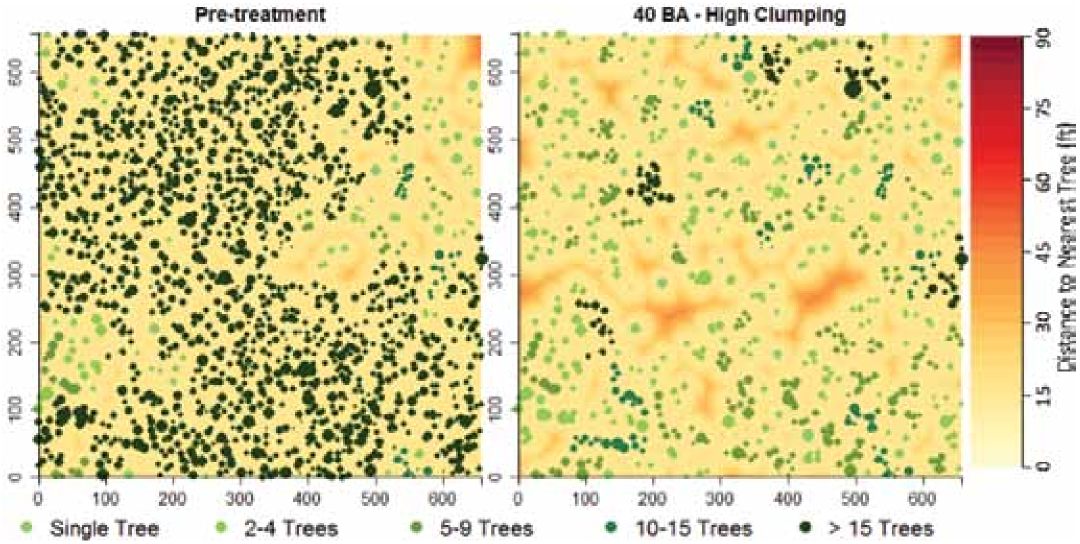
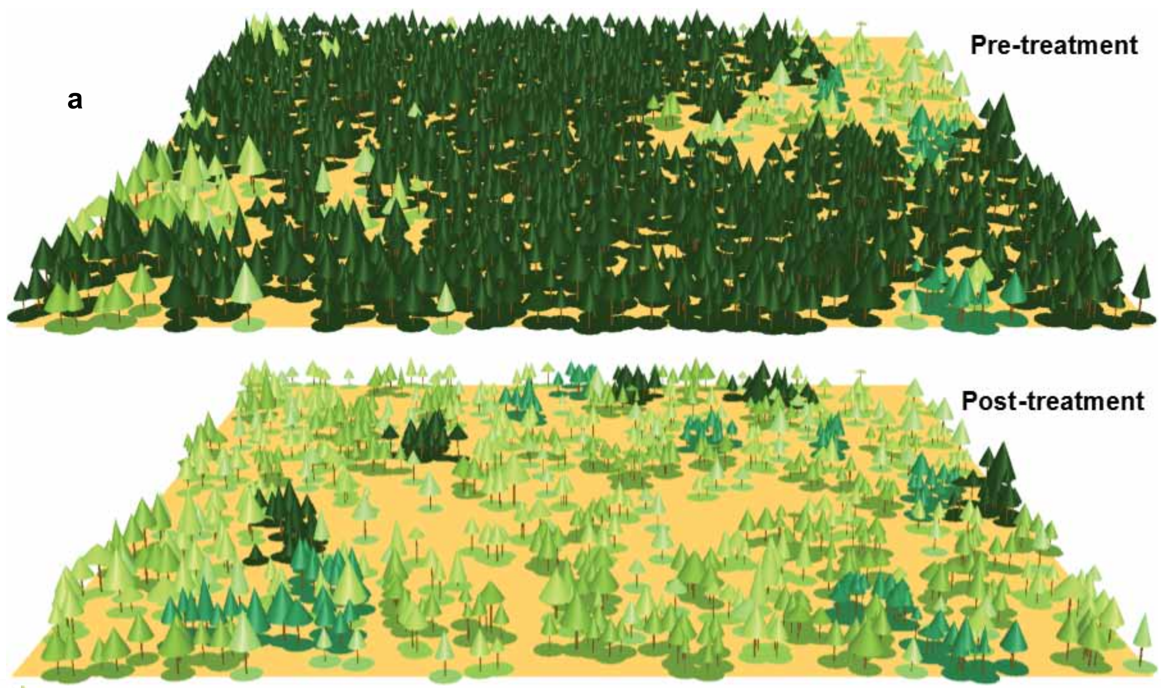


Figure 23—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

a



b

Figure 24—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clumping scheme above (fig. 23) **b)** profile view of stand structure.

Summary: Low-Moderate Density Single Story Stand

Prior to treatment, this stand had regions of significant density (>600 trees per acre) and horizontal continuity, with a single clump containing more than 1,200 trees. The stand was dominated by trees 6 to 12 inches at d.b.h. (85 percent of trees) and had a QMD of 9.6 inches. There was also a moderate level of vertical complexity throughout the stand (fig. 25, table 12).

- Following the simulated treatments, mean stand density was greatly reduced while increasing the relative variability of tree density in all but the thin from below simulations. This increase in variability is an important indicator of meeting horizontal heterogeneity treatment objectives.
- The relative level of variability in vertical structure also increased under all simulated treatments, with the spatially explicit simulations providing the greatest increase in complexity.

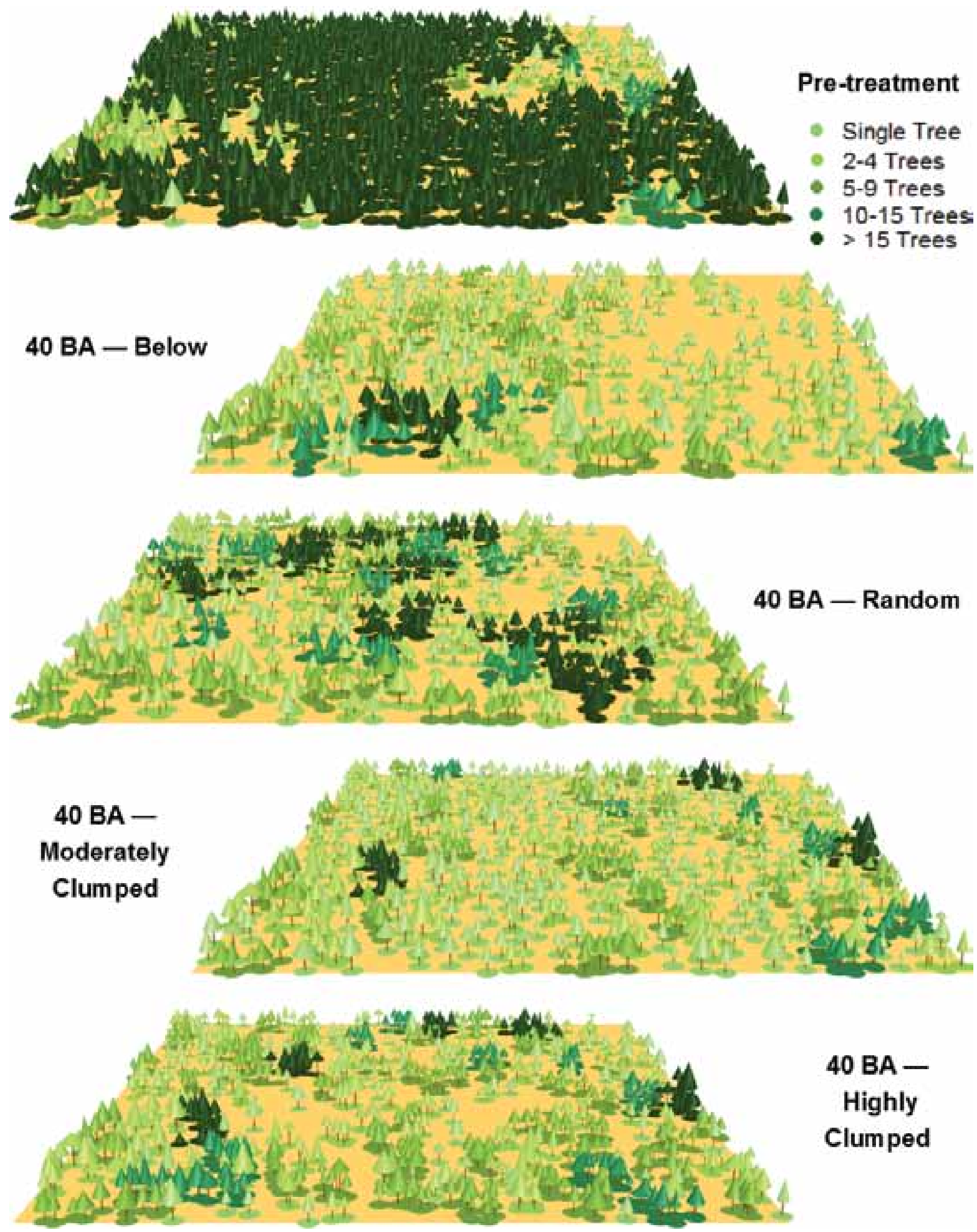


Figure 25—Virtual rendering of stand structure over the 9.9 acre area for each of the various thinning treatments according to inventoried height, d.b.h., CBH, and crown widths.

Table 12—Changes in stand characteristics for the low-moderate density single story stand after various thinning treatments. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment	Thin from below	Random thinning	Moderately clumped	Highly clumped
Trees per acre	169 (26–291)	47 (7–104)	81 (7–136)	83 (13–188)	80 (26–149)
BA per acre	83 ft^2 (11–131)	40 ft^2 (4–96)	40 ft^2 (3–74)	42 ft^2 (5–93)	41 ft^2 (11–83)
QMD	9.6 in (7.5–12.4)	12.5 in (10.7–17.1)	9.6 in (7.8–17.0)	9.7 in (7.3–12.2)	9.6 in (7.1–12.4)
Mean tree height	26 ft (21–32)	29 ft (17–35)	26 ft (20–26)	26 ft (21–32)	26 ft (20–32)
Canopy base height	12 ft (8–15)	13 ft (9–17)	12 ft (7–16)	12 ft (8–15)	12 ft (8–19)
Crown biomass	8.26 tons $acre^{-1}$	4.26 tons $acre^{-1}$	4.00 tons $acre^{-1}$	4.28 tons $acre^{-1}$	4.18 tons $acre^{-1}$

The pre-treatment stand condition placed most of the trees into a single very large and continuous clump of trees, containing more than 85 percent of the stands trees and basal area (table 13).

- Both the thin from below and moderate clumping simulations shifted most of the stand into Single tree or small clumps, while the random thinning evenly distributed the stand into the different structures.
- The high clumping simulation placed a third of the stand in 5–9 tree clumps and then evenly distributed the remaining trees to all of the other structures. This simulation resulted in the greatest diversity in forest structures and opening sizes.

Table 13—Changes in clump size distribution for each of the thinning treatments for the low-moderate density single story stand.

	Pre-treatment			Thin from below			Random thinning			Moderately clumped			Highly clumped		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**%BA**	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	2.9	1.7	2.6	15.3	32.3	34.0	10.4	12.7	16.1	24.9	31.3	33.0	8.2	9.9	12.0
2–4 Trees	2.8	4.3	4.7	6.8	36.8	35.5	6.6	21.7	22.7	8.8	31.1	32.4	8.7	29.7	31.0
5–9 Trees	0.5	1.9	2.2	1.4	19.5	19.3	2.9	23.1	22.9	2.7	22.0	21.0	4.4	36.2	34.3
10–15 Trees	0.3	2.2	1.7	0.3	6.6	6.6	1.1	16.6	14.5	0.6	9.1	6.9	0.9	13.8	12.4
>15 Trees	0.9	89.9	88.8	0.1	4.7	4.6	0.8	25.9	23.8	0.3	6.5	6.7	0.5	10.4	10.4

Prior to treatment, only 7 percent of the stand was within openings (>6 m from a tree) with the largest opening being less than 1/10 acre (figs. 26 and 27; table 14).

- Following treatment, all of the treatments experienced a shift toward more and larger openings.
- The thin from below created the largest shift in mean and max opening size, putting 29 percent of the stand into openings, but openings were dominated by a single large opening.
- While both the random thinning and moderate clumping simulations shifted the stand so that approximately 17 percent of the stands were within openings, the number of openings and range of opening sizes was very different.
- The high clumping simulation resulted in the most openings and greatest median opening size, while putting 29 percent of the stand into openings. This created a balance between creating forest structures and establishing openings.

Table 14—Changes in clump and opening area for each of the thinning treatments for the low-moderate density single story stand.

	Clump area (acres)				
	Mean		Median	Min	Max
Pre-treatment	0.147		0.018	0.008	4.878
Below	0.022		0.016	0.008	0.131
Random	0.032		0.020	0.009	0.170
Moderate	0.022		0.017	0.008	0.090
High	0.024		0.020	0.007	0.090
	Opening area (acres)				
	n	**Mean**	**Median**	**Min**	**Max**
Pre-treatment	6	0.047	0.042	0.019	0.078
Below	18	0.198	0.049	0.019	2.258
Random	18	0.092	0.057	0.019	0.432
Moderate	9	0.051	0.047	0.019	0.082
High	20	0.116	0.058	0.019	0.529

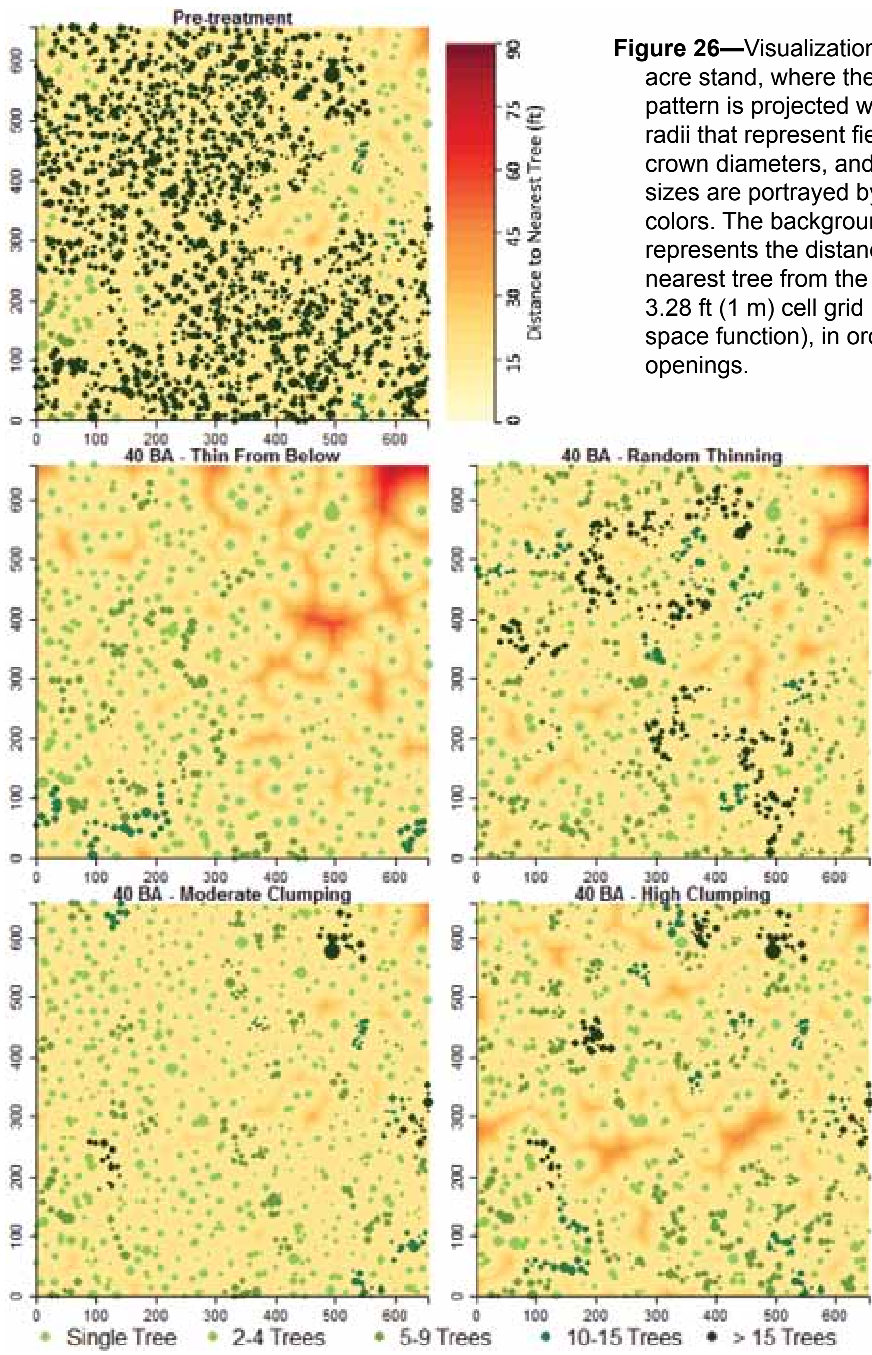


Figure 26—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function), in order to portray openings.

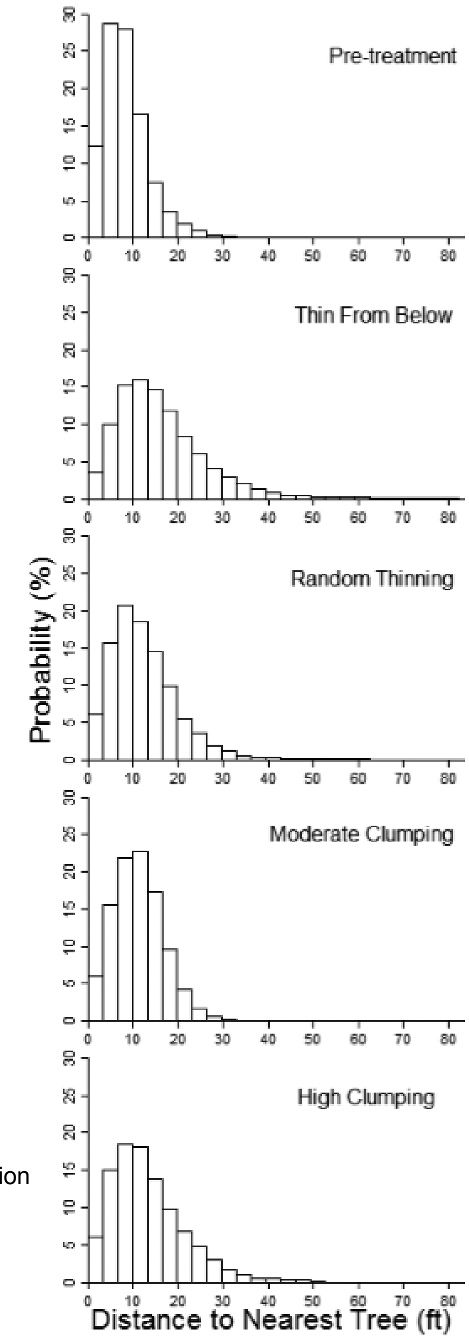


Figure 27—Treatment effects on the distribution of the distance to the nearest tree.

Pre-treatment: Moderate Density Multi-Storied Stand

This stand was composed of 95 percent ponderosa pine, with small portions of the stand occupied by Douglas-fir and quaking aspen. The site represents many mid-elevation (about 8,400 ft above sea level) ponderosa pine stands with a site index of 65 ft at a base age of 100 (fig. 28). Prior to treatment, the stand was dominated by trees less than 10 inches d.b.h. (fig. 29) and had the highest starting local variability in horizontal and vertical forest structure (table 15) of any of the simulated stands. This stand had regions of significant density (>600 trees per acre) and horizontal continuity, with a single clump containing more than 1,100 trees (table 16; figs. 30 and 31). Outside of the large pre-existing opening, more than 90 percent of the stand was within 20 ft of a tree. The stand underwent 4 simulated thinnings to a residual basal area of 40 ft^2 ac^{-1} (9.2 m^2 ha^{-1}).

Figure 28—Pre-treatment forest structure of a moderate density multi-storied stand (photo: Emma Vakili, U.S. Forest Service).

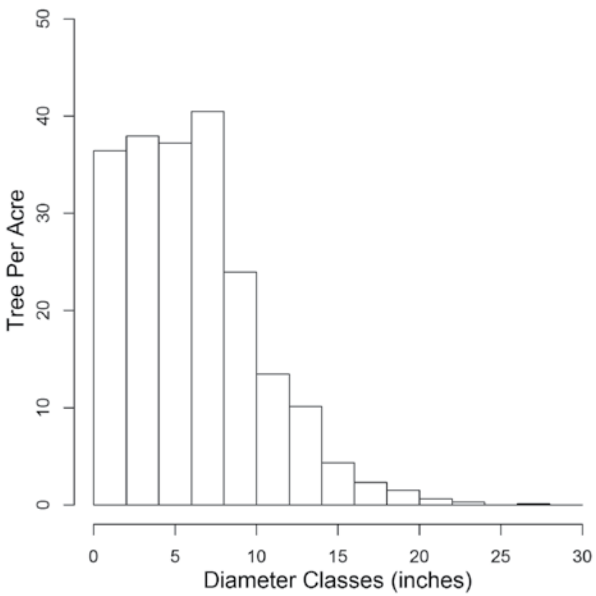


Figure 29—Pre-treatment distribution of trees per acre by 2-inch d.b.h. size classes of the moderate density multi-storied stand.

Table 15—Pre-treatment stand characteristics for the moderate density multi-storied stand. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment
Trees per acre	209 (0–667; 70%)
BA	62 ft^2 (0–132; 52%)
QMD	7.6 in (0–12.9; 49%)
Tree height	25 ft (13–52; 26%)
Canopy base height	10 ft (4–36; 41%)
Crown biomass	7.15 tons $acre^{-1}$

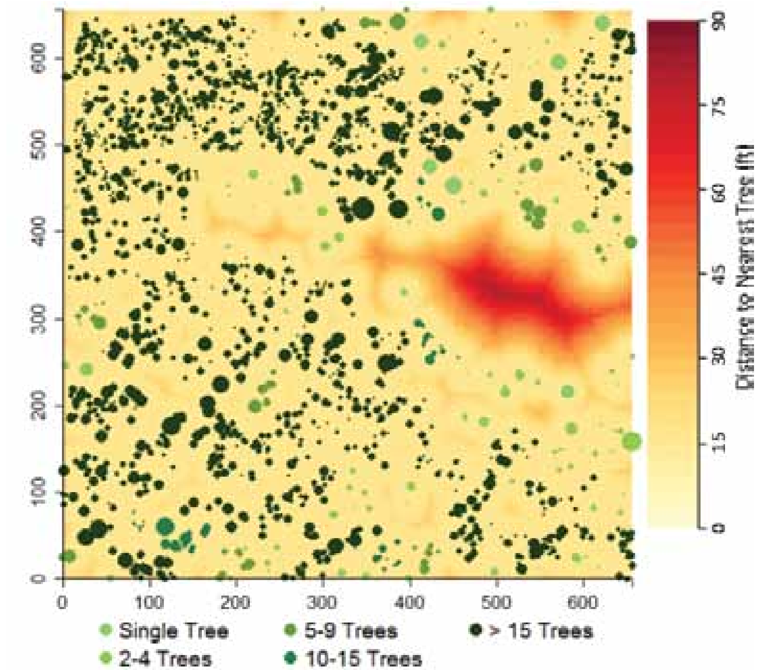


Figure 30—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

Table 16—Pre-treatment clump size distribution for the moderate density multi-storied stand.

Clump size	#/Acre	% TPA	% BA
Single tree	3.9	1.9	4.1
2–4 Trees	1.1	3.2	3.6
5–9 Trees	2.5	3.7	10.1
10–15 Trees	0.5	2.7	5.5
>15 Trees	1.1	88.5	76.6

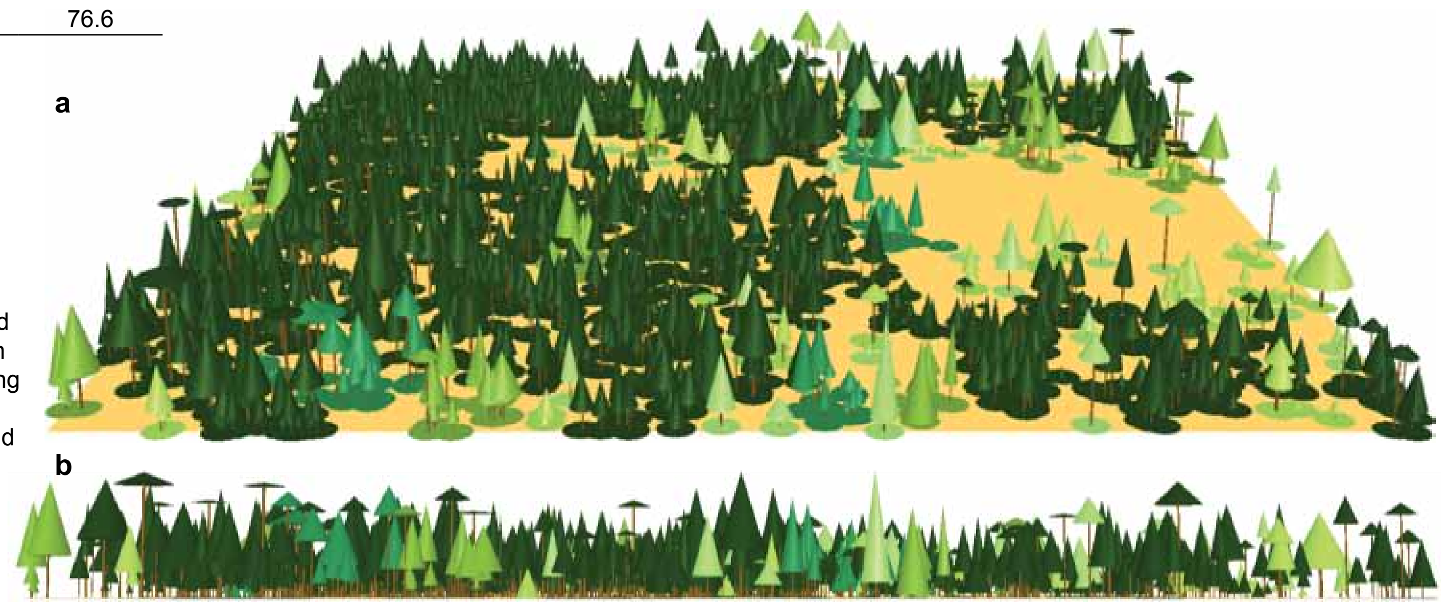


Figure 31—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 30), **b)** profile view of stand structure.

Thin from Below to 40 ft^2 ac^{-1} of Basal Area

Thinning from below tends to homogenize stand structure and in this case resulted in all trees less than 8 inches d.b.h. being removed (fig. 32) and an increase in stand-level QMD from 7.6 to 12.2 inches (table 17). Following completion of the thinning, the stand's canopy cover shifted from 67 to 52 percent. The local variability of horizontal and vertical forest structure was greatly reduced in every category except basal area per acre that saw a slight increase.

- Single tree and 2–4 Tree clumps went from representing 5.6 to 52.6 percent of the trees in the stand (table 18).
- The thinning also resulted in an increase to the number of and the mean size of stand opening, with many openings now reaching more than 60 ft in radius or openings greater than 1/4 acre (figs. 33 and 34).

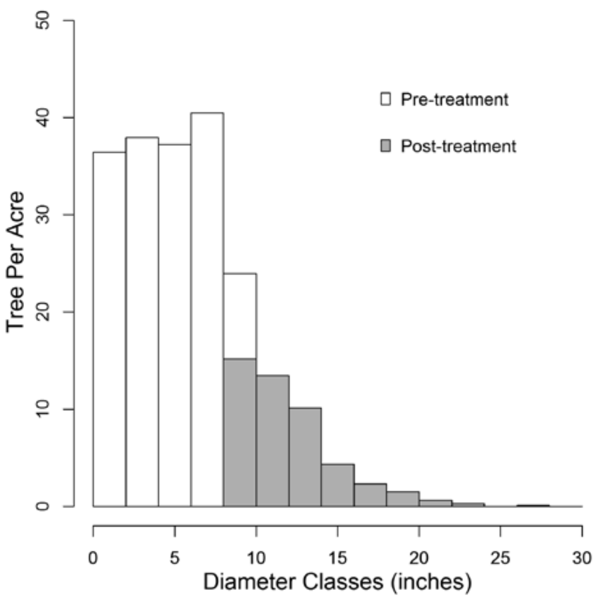


Figure 32—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the thin from below treatment.

Table 17—Changes in stand characteristics for the moderate density multi-storied stand after a thin from below treatment. Stand-level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	209 (0–667; 70%)	48 (0–117; 56%)
BA per acre	62 ft^2 (0–132; 52%)	40 ft^2 (0–106; 60%)
QMD	7.6 in (0–12.9; 49%)	12.2 in (0–23.5; 46%)
Total height	25 ft (13–52; 26%)	41 ft (31–57; 13%)
CBH	10 ft (4–36; 41%)	17 ft (9–36; 27%)
Crown biomass	7.15 tons acre^{-1}	4.60 tons acre^{-1}

Table 18—Changes in clump size distribution for the moderate density multi-storied stand after the thin from below treatment.

	Pre			Post		
Clump size	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA
Single tree	4	1.9	4.1	8.1	16.9	17.7
2–4 Trees	1.1	3.7	3.6	17.1	35.7	35.5
5–9 Trees	2.5	3.2	10.1	13.2	27.6	27.3
10–15 Trees	0.5	2.7	5.5	5.8	12.0	11.8
>15 Trees	1.1	88.5	76.6	3.7	7.8	7.9

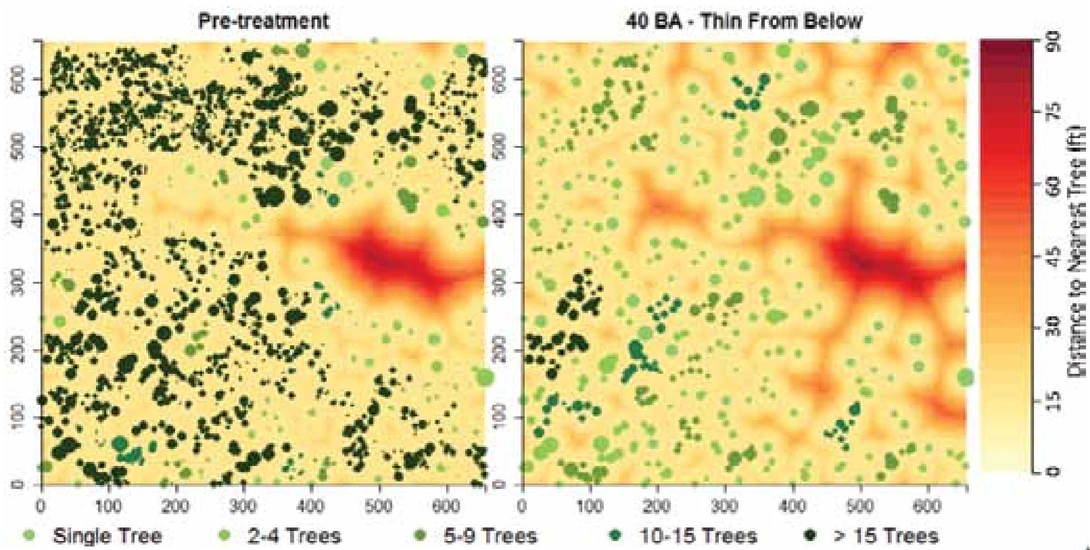


Figure 33—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

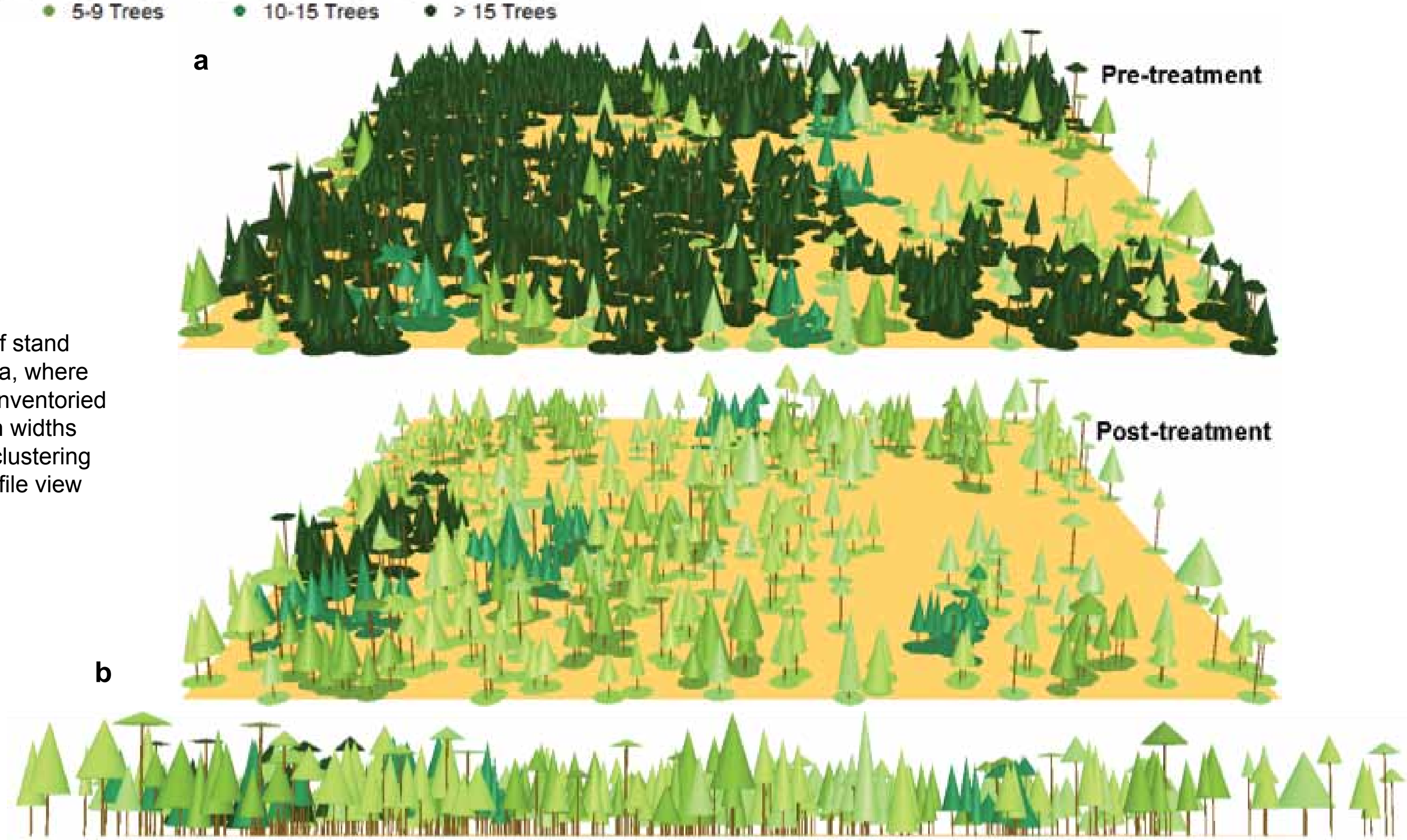


Figure 34—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 33), **b)** profile view of stand structure.

Random Thinning to 40 ft^2 ac^{-1} of Basal Area

Proportional thinning throughout the diameter range or random thinning approaches tend to preserve the pre-existing stand structure and in this case removed about 35 percent of trees from each diameter class (fig. 35), causing only a small shift in stand level QMD from 7.6 to 7.3 inches and a slight lowering in local QMD variability (table 19). Following completion of the thinning, the stand's canopy cover shifted from 67 to 53 percent, with very little change in the variability of horizontal and vertical forest structures.

- The stand shifted slightly from its pre-treatment condition with many clumps of 200+ trees to having a greater number of clumps containing 25–50 trees, but still with a clump of 500+ trees and more than 15 tree clumps dominating forest structure (table 20).
- The thinning extended the pre-existing opening and created several small gaps with radii reaching 30 ft (figs. 36 and 37).

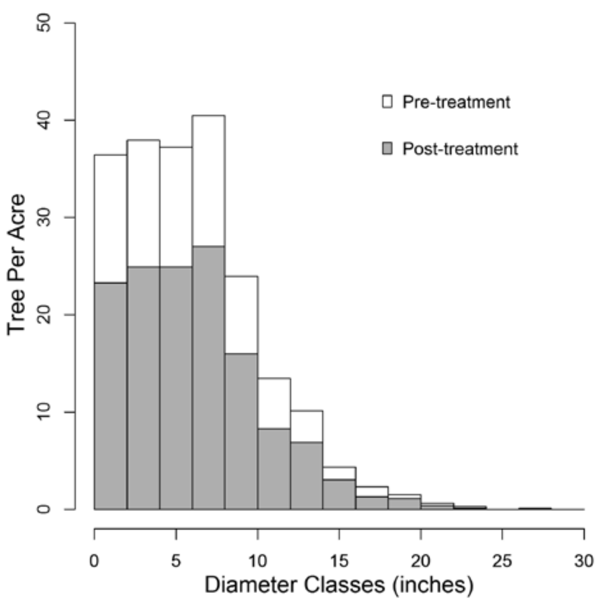


Figure 35—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the random thinning.

Table 19—Changes in stand characteristics for the moderate density multi-storied stand after a random thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	**Post**
Trees per acre	209 (0–667; 70%)	137 (0–395; 68%)
BA per acre	62 ft^2 (0–132; 52%)	40 ft^2 (0–107; 54%)
QMD	7.6 in (0–12.9; 49%)	7.3 in (0–12.3; 53%)
Total height	25 ft (13–52; 26%)	25 ft (7–52; 26%)
CBH	10 ft (4–36; 41%)	10 ft (1–36; 43%)
Crown biomass	7.15 tons $acre^{-1}$	4.61 tons $acre^{-1}$

Table 20—Changes in clump size distribution for the moderate density multi-storied stand after the random thinning treatment.

	Pre			**Post**		
Clump size	**#/Acre**	**%TPA**	**%BA**	**#/Acre**	**%TPA**	**%BA**
Single tree	4	1.9	4.1	5.7	4.1	6.7
2–4 Trees	1.1	3.7	3.6	4.0	8.3	13.6
5–9 Trees	2.5	3.2	10.1	1.7	8.2	10.6
10–15 Trees	0.5	2.7	5.5	0.6	5.2	7.9
>15 Trees	1.1	88.5	76.6	1.4	74.3	61.3

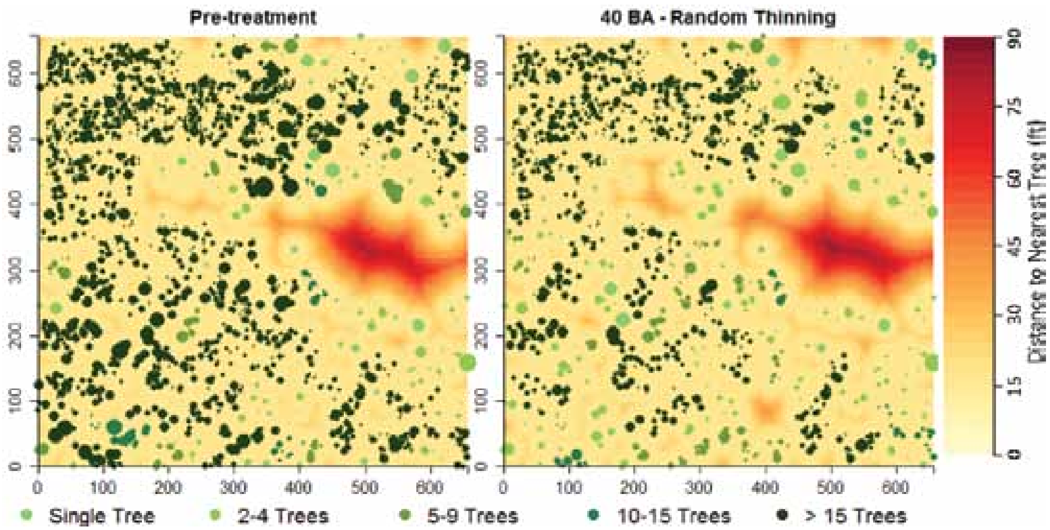


Figure 36—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

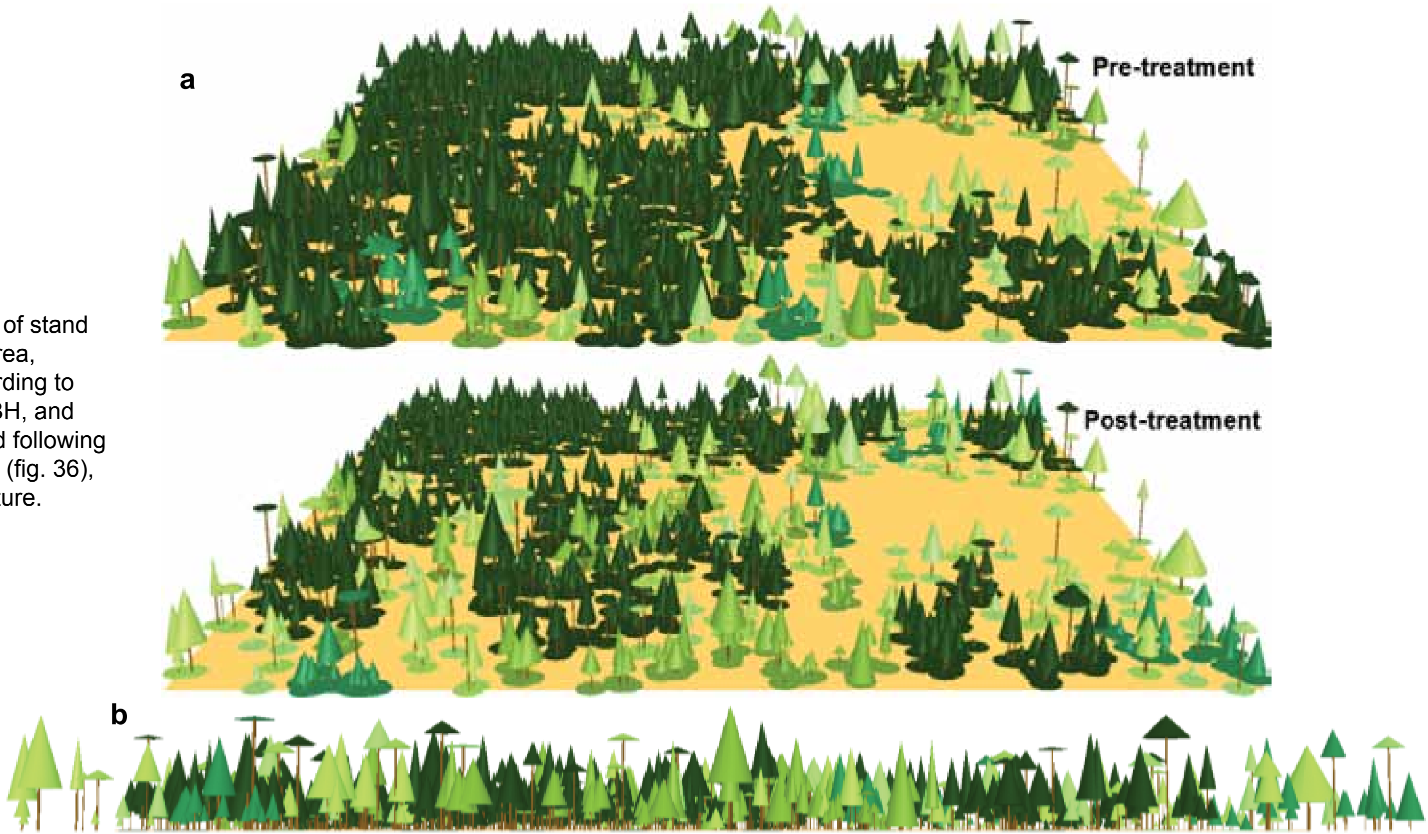


Figure 37—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 36), **b)** profile view of stand structure.

Moderately Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

A moderate clumping scenario following individual, clump, and opening thinning approach attempts to increase the number of small clumps, and in this case it resulted in a removal of trees throughout the diameter trees (fig. 38) and no change in stand level QMD (table 21). Following completion of the thinning, the stand's canopy cover shifted from 67 to 53 percent, with no changes in local horizontal and vertical structure variability except for the decrease in trees per acre.

- The stand went from being dominated by large clumps to having a balanced distribution of clump sizes (table 22).
- Due to the existing pockets of very high density, the thinning struggled to achieve its intended goal of placing a higher proportion of trees into Single tree and 2-4 tree clumps (table 22; figs. 39 and 40).

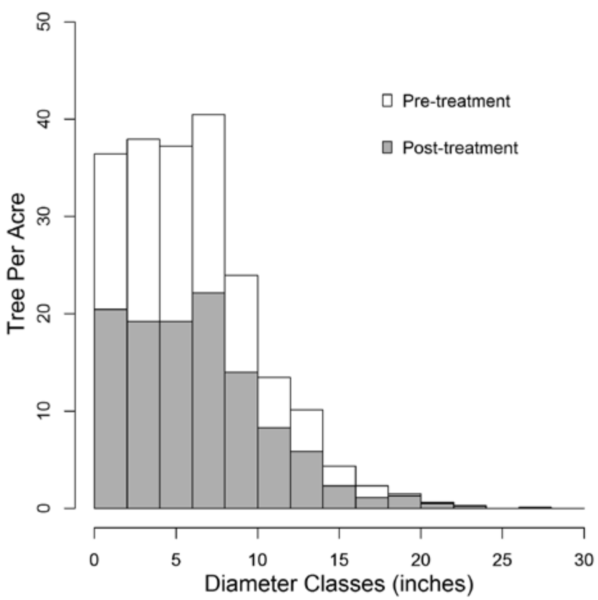


Figure 38—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the moderately clumped thinning treatment.

Table 21—Changes in stand characteristics for the moderate density multi-storied stand after a moderately clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	209 (0–667; 70%)	115 (0–227; 44%)
BA per acre	62 ft^2 (0–132; 52%)	36 ft^2 (0–96; 53%)
QMD	7.6 in (0–12.9; 49%)	7.6 in (0–12.9; 50%)
Total height	25 ft (13–52; 26%)	25 ft (13–52; 27%)
CBH	10 ft (4–36; 41%)	10 ft (3–36; 43%)
Crown biomass	7.15 tons $acre^{-1}$	4.27 tons $acre^{-1}$

Table 22—Changes in clump size distribution for the moderate density multi-storied stand after the moderately clumped thinning treatment.

	Pre			Post		
Clump size	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA
Single tree	4	1.9	4.1	7.0	6.1	10.7
2–4 Trees	1.1	3.7	3.6	7.0	17.7	20.8
5–9 Trees	2.5	3.2	10.1	7.5	45.7	45.5
10–15 Trees	0.5	2.7	5.5	1.8	19.0	15.4
>15 Trees	1.1	88.5	76.6	0.7	11.5	7.6

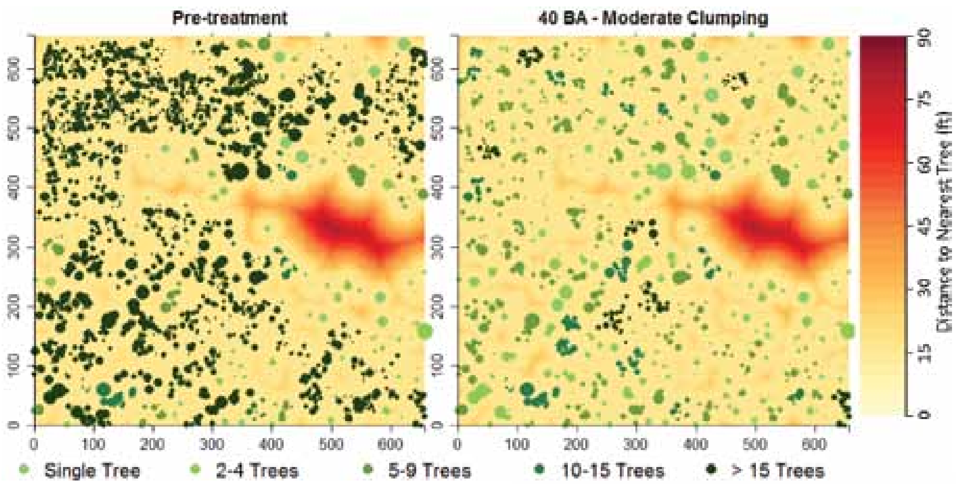


Figure 39—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

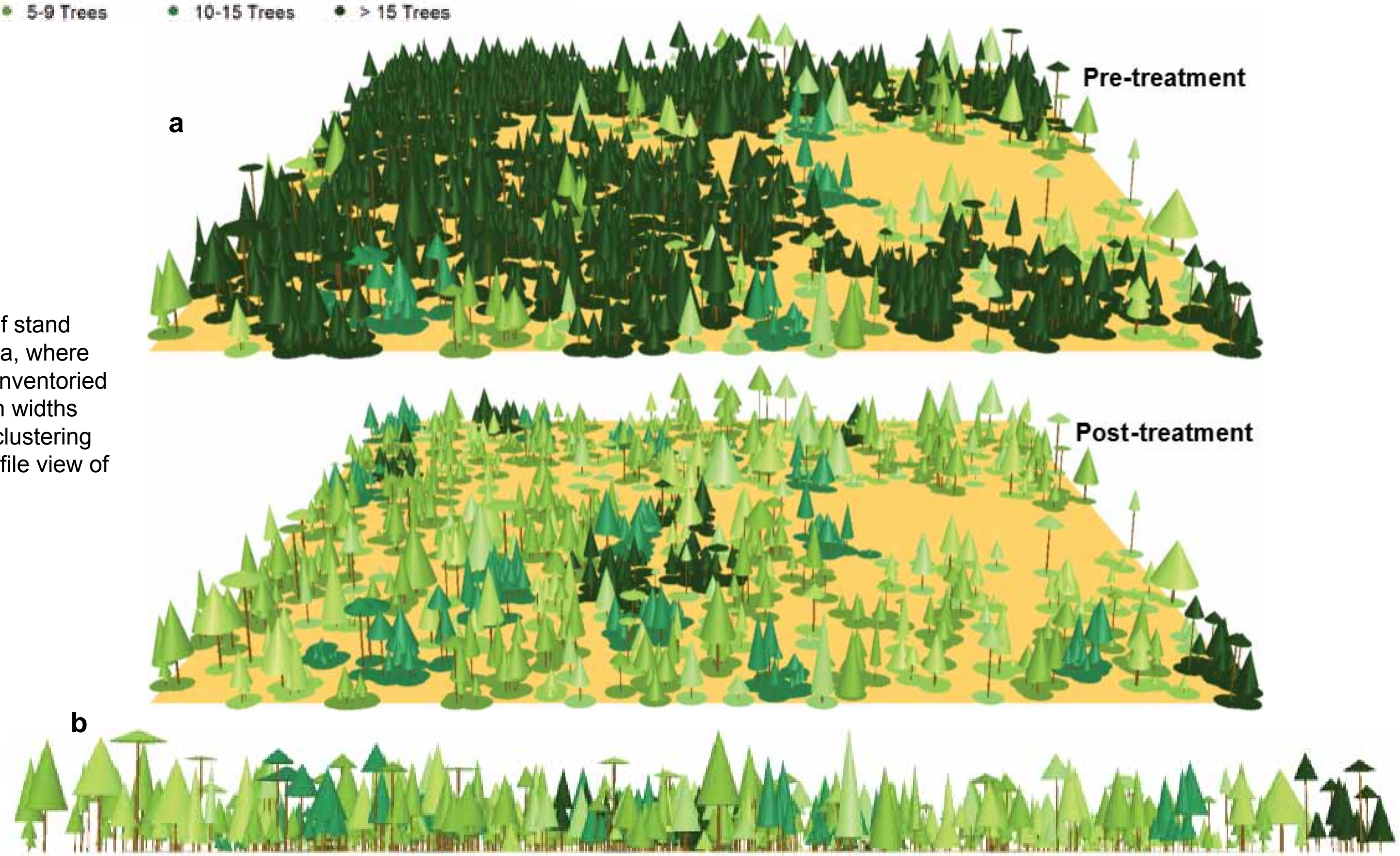


Figure 40—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 39), **b)** profile view of stand structure.

Highly Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

Under the high clumping scenario following individual, clump, and opening thinning, the goal was to distribute the stand's structure throughout the range of clump sizes, and in this case it resulted in a proportional removal of trees throughout the range of diameters (fig. 41) and a negligible increase in stand level QMD from 7.6 to 7.7 inches (table 23). Following completion of the thinning, the stand's canopy cover shifted from 67 to 54 percent, with no changes in local horizontal and vertical structure variability except for the decrease in trees per acre.

- The stand went from being dominated by large clumps to meeting its intended condition with a balanced distribution of clump sizes (table 24).
- The thinning also doubled the number of openings within the stand, while maintaining a wide range of opening sizes (figs. 42 and 43).

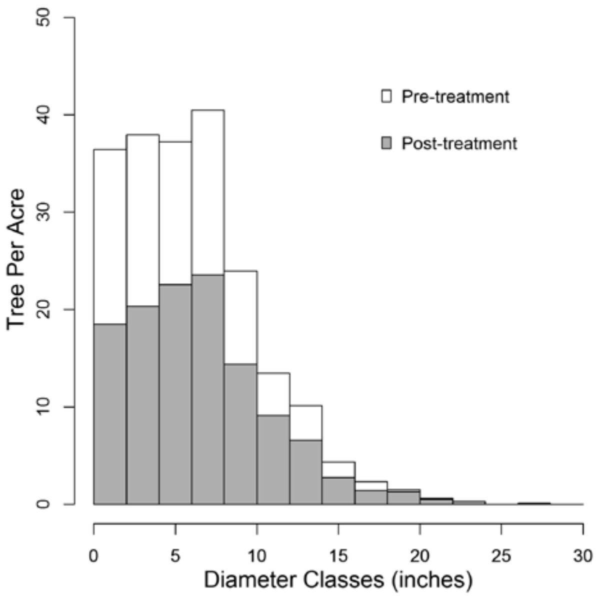


Figure 41—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the highly clumped thinning treatment.

Table 23—Changes in stand characteristics for the moderate density multi-storied stand after a highly clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	209 (0–667; 70%)	121 (0–278; 47%)
BA per acre	62 ft^2 (0–132; 52%)	39 ft^2 (0–89; 48%)
QMD	7.6 in (0–12.9; 49%)	7.7 in (0–12.9; 47%)
Total height	25 ft (13–52; 26%)	25 ft (13–52; 26%)
CBH	10 ft (4–36; 41%)	10 ft (4–36; 42%)
Crown biomass	7.15 tons $acre^{-1}$	4.53 tons $acre^{-1}$

Table 24—Changes in clump size distribution for the moderate density multi-storied stand after the highly clumped thinning treatment.

	Pre			Post		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	4	1.9	4.1	6.7	5.5	7.9
2–4 Trees	1.1	3.7	3.6	6.1	13.5	14.7
5–9 Trees	2.5	3.2	10.1	5.5	31.8	33.9
10–15 Trees	0.5	2.7	5.5	2.7	27.2	26.1
>15 Trees	1.1	88.5	76.6	1.4	22.0	17.3

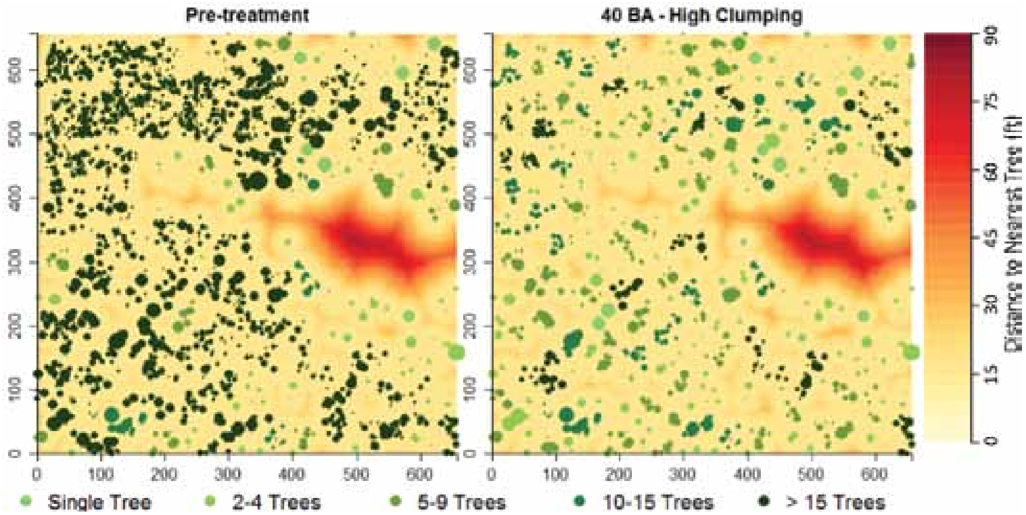
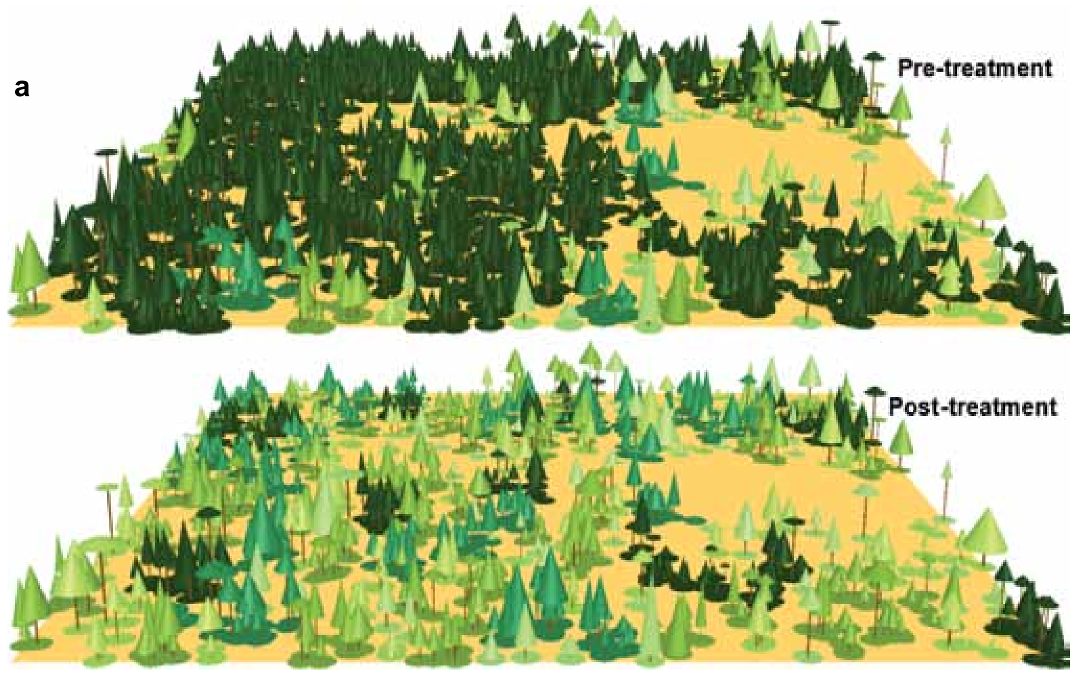


Figure 42—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

a



b

Figure 43—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clumping scheme above (fig. 42), **b)** profile view of stand structure..

Summary: Moderate Density Multi-Storied Stand

Prior to treatment, this stand had regions of significant density (>600 trees per acre) and horizontal continuity, with a single cluster containing more than 1,100 trees. The stand was dominated by trees less than 10 inches d.b.h. (85 percent of trees) and had a QMD of 7.6 inches with a canopy base height of only 10 ft (table 25). Outside of the large pre-existing opening, most canopy openings were less than 26 ft in radius (figs. 44–46).

- Following the simulated treatments, mean stand density was greatly reduced while increasing the relative variability of tree density in all but the thin from below simulations (table 25; figs. 44 and 45). This increase in variability is an important indicator of meeting horizontal heterogeneity treatment objectives.

The pre-treatment stand condition placed most of the trees into a single very large and continuous clump of trees, containing more than 80 percent of the stand's trees and basal area (table 26).

- The thin from below simulations shifted most of the stand into Single tree or small clumps, while the random thinning left a large portion of the stand (>60 percent) still in clumps of more than 15 trees.

Table 25—Changes in stand characteristics for the moderate density multi-storied stand after various thinning treatments. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment	Thin from below	Random thinning	Moderately clumped	Highly clumped
Trees per acre	209 (0–667)	48 (0–117)	137 (0–395)	115 (0–227)	121 (0–278)
BA per acre	62 ft^2 (0–132)	40 ft^2 (0–106)	40 ft^2 (0–107)	36 ft^2 (0–96)	39 ft^2 (0–89)
QMD	7.6 in (0–12.9)	12.2 in (0–23.5)	7.3 in (0–12.3)	7.6 in (0–12.9)	7.7 in (0–12.9)
Mean tree height	25 ft (13–52)	41 ft (31–57)	25 ft (7–52)	25 ft (13–52)	25 ft (13–52)
Canopy base height	10 ft (4–36)	17 ft (9–36)	10 ft (1–36)	10 ft (3–36)	10 ft (4–36)
Crown biomass	7.15 tons $acre^{-1}$	4.60 tons $acre^{-1}$	4.61 tons $acre^{-1}$	4.27 tons $acre^{-1}$	4.53 tons $acre^{-1}$

Table 26—Changes in clump size distribution for each of the thinning treatments for the moderate density multi-storied stand.

	Pre-treatment			Thin from below			Random thinning			Moderately clumped			Highly clumped		
Clump size	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA
Single tree	4	1.9	4.1	8.1	16.9	17.7	5.7	4.1	6.7	7.0	6.1	10.7	6.7	5.5	7.9
2–4 Trees	1.1	3.7	3.6	17.1	35.7	35.5	4.0	8.3	13.6	7.0	17.7	20.8	6.1	13.5	14.7
5–9 Trees	2.5	3.2	10.1	13.2	27.6	27.3	1.7	8.2	10.6	7.5	45.7	45.5	5.5	31.8	33.9
10–15 Trees	0.5	2.7	5.5	5.8	12.0	11.8	0.6	5.2	7.9	1.8	19.0	15.4	2.7	27.2	26.1
>15 Trees	1.1	88.5	76.6	3.7	7.8	7.9	1.4	74.3	61.3	0.7	11.5	7.6	1.4	22.0	17.3

- Following the simulated spatially explicit treatments (Moderately and Highly Clumped), the structures within the stand were reallocated throughout all of the tree clump sizes, providing a balance of these structures to help meet many restoration, wildlife, and fuels treatment objectives.

Prior to treatment, only 20 percent of the stand was within openings (>6 m from a tree) with a single 1.15 acre opening dominating this proportion (figs. 45 and 46; table 27).

- Following treatment, all of the stands approximately doubled the number of openings and experienced a shift in the percentage of the stand in openings.
- The thin from below simulation created the greatest shift in distribution, which is to be expected since the stand was thinned to 48 trees per acre. This resulted in the greatest mean and max opening size.
- The spatially explicit simulations enhanced the proportion of small and moderately sized stand openings. Now 29 percent of the stand was in openings with a slight decrease in the mean opening size. This indicates a shift toward more openings that were smaller in size

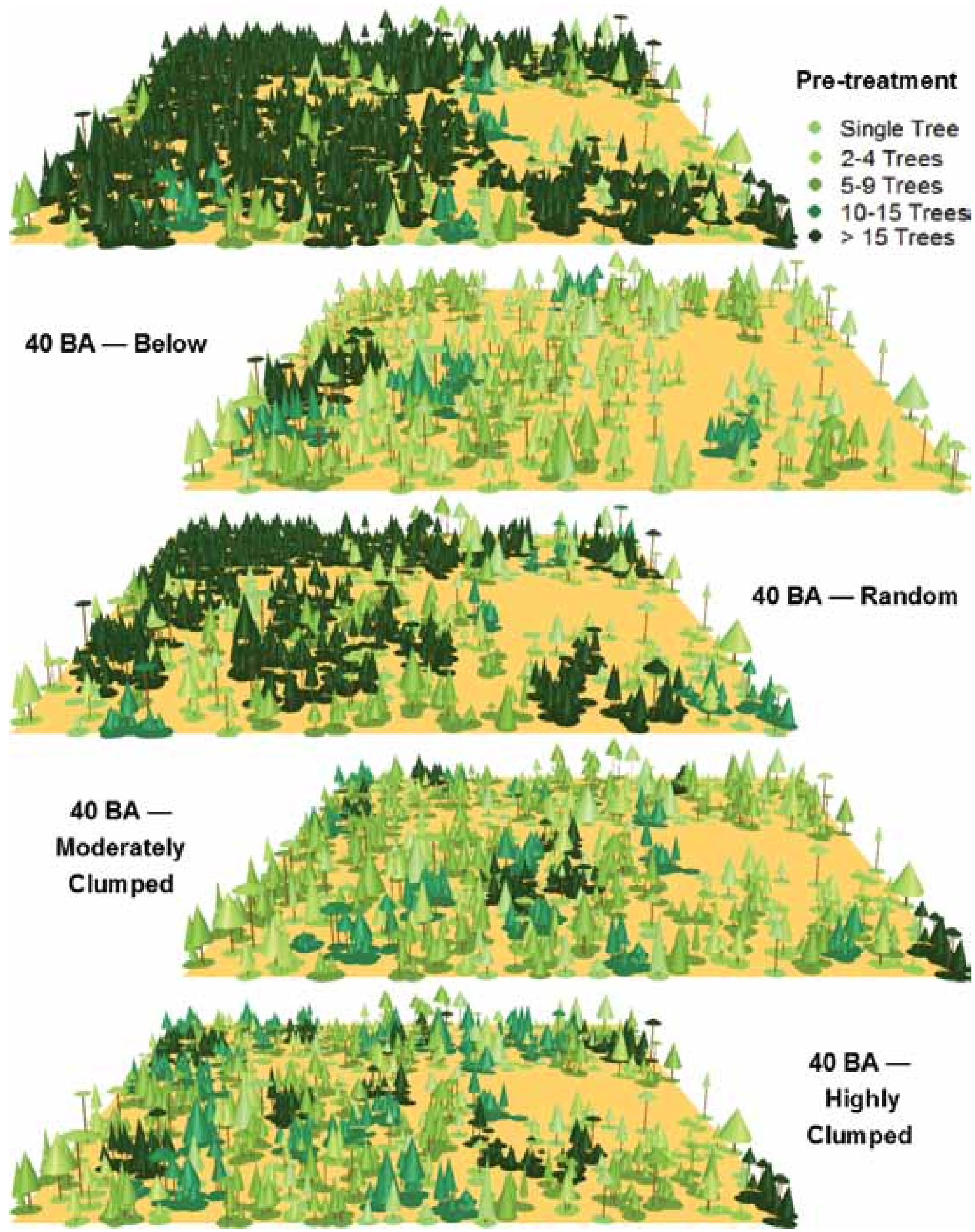


Figure 44—Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths.

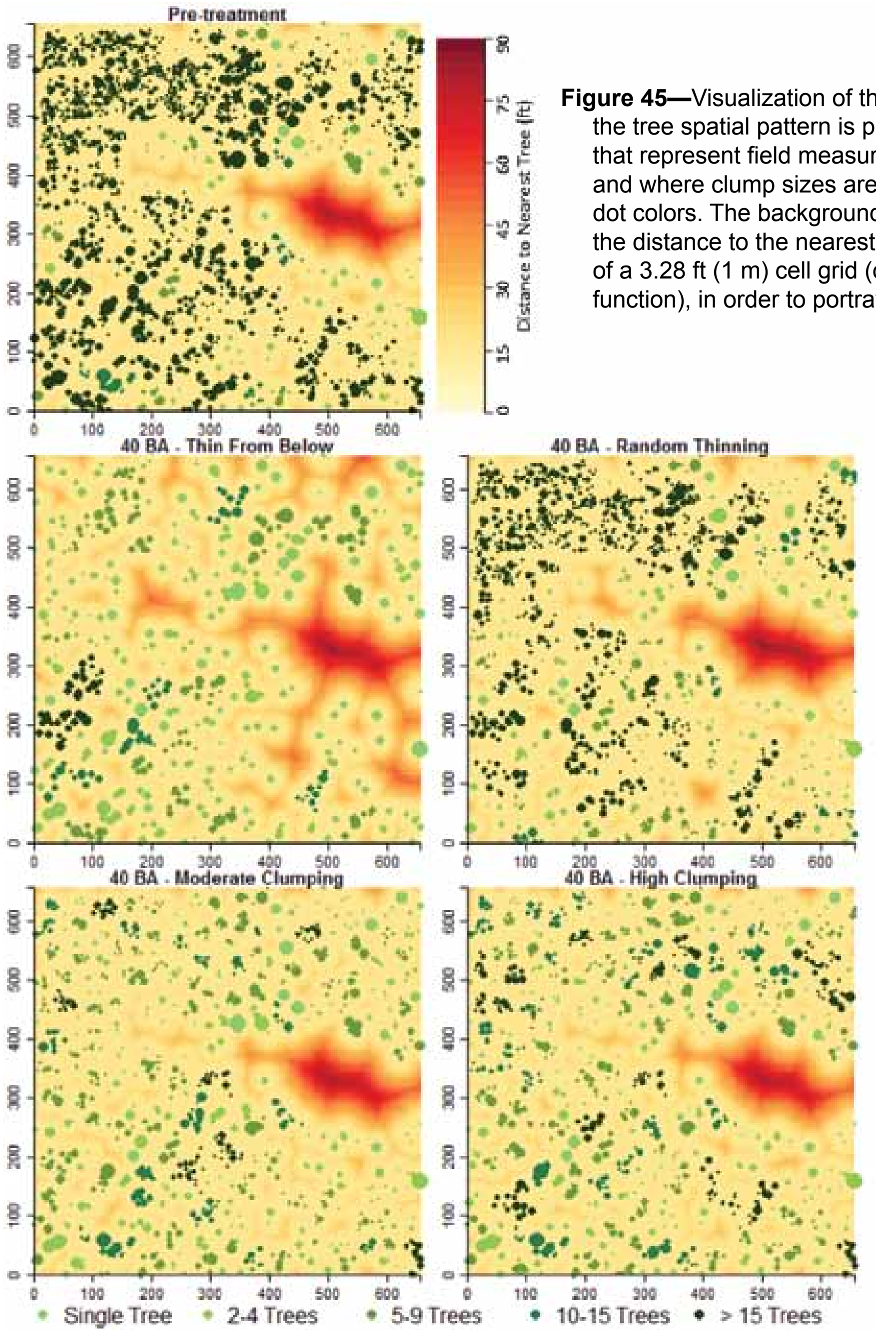


Figure 45—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function), in order to portray openings.

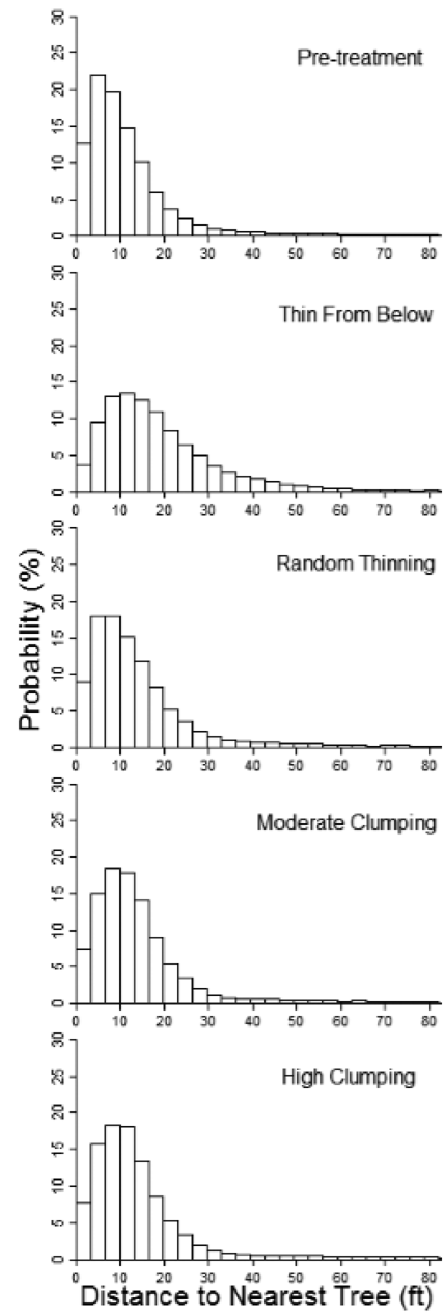


Figure 46—Treatment effects on the distribution of the distance to the nearest tree.

Table 27—Changes in clump and opening area for each of the thinning treatments for the moderate density multi-storied stand.

	Clump area (acres)				
	Mean		Median	Min	Max
Pre-treatment	0.101		0.022	0.008	2.185
Below	0.023		0.015	0.007	0.093
Random	0.054		0.021	0.007	1.527
Moderate	0.022		0.019	0.007	0.073
High	0.025		0.021	0.007	0.081
	Opening area (acres)				
	n	**Mean**	**Median**	**Min**	**Max**
Pre-treatment	11	0.147	0.034	0.013	1.150
Below	24	0.198	0.047	0.014	3.388
Random	19	0.119	0.035	0.013	1.230
Moderate	18	0.106	0.035	0.016	1.151
High	20	0.101	0.038	0.013	1.166

Pre-treatment: Moderate-High Density Multi-Storied Stand

This stand was composed of 82 percent ponderosa pine and 14 percent Douglas-fir, with small pockets of quaking aspen and Engelmann spruce. The site represents many mid-elevation (about 8,000 ft above sea level) ponderosa pine stands with a site index of 65 ft at a base age of 100 (fig. 47). Prior to treatment, the stand was largely occupied by trees between 2 and 8 inches d.b.h. (fig. 48), with a QMD of 8.6 inches and a canopy base height of 14 ft (table 28). This stand was high in density at 338 trees per acre but with regions of significant density (>600 trees per acre) and horizontal continuity, with a single clump containing more than 3,200 trees. More than 98 percent of the stand was classified within 20 ft of the nearest tree, meaning there were nearly no openings in the stand pre-treatment (table 29; figs. 49 and 50). The stand underwent 4 simulated thinnings to a residual basal area of 40 ft^2 $acre^{-1}$ (9.2 m^2 ha^{-1}).

Figure 47—Pre-treatment forest structure of a moderate-high density multi-storied stand (photo: Emma Vakili, U.S. Forest Service).

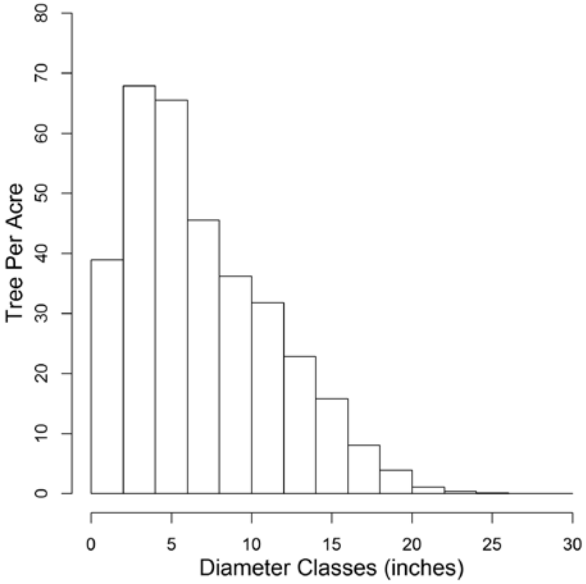


Figure 48—Pre-treatment distribution of trees per acre by 2-inch d.b.h. size classes for a moderate-high density multi-storied stand.

Table 28—Pre-treatment stand characteristics for the moderate-high density multi-storied stand. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment
Trees per acre	338 (123–602; 31%)
BA	130 ft^2 (76–326; 28%)
QMD	8.6 in (5.7–17.3; 20%)
Tree height	36 ft (24–54; 16%)
Canopy base height	14 ft (9–21; 18%)
Crown biomass	15.86 tons $acre^{-1}$

Table 29—Pre-treatment clump size distribution for the moderate-high density multi-storied stand.

Clump size	#/Acre	% TPA	% BA
Single tree	0.5	0.1	0.2
2–4 Trees	0.5	0.3	0.9
5–9 Trees	0.1	0.1	0.3
10–15 Trees	0.0	0.0	0.0
>15 Trees	0.2	99.4	98.6

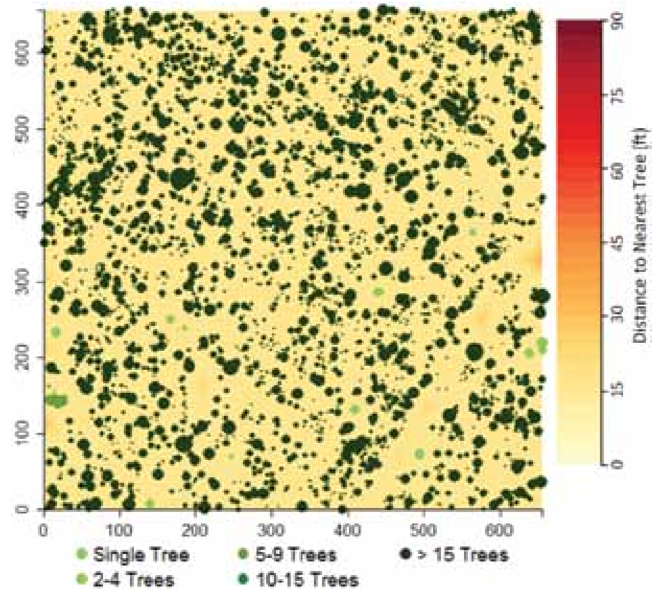


Figure 49—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

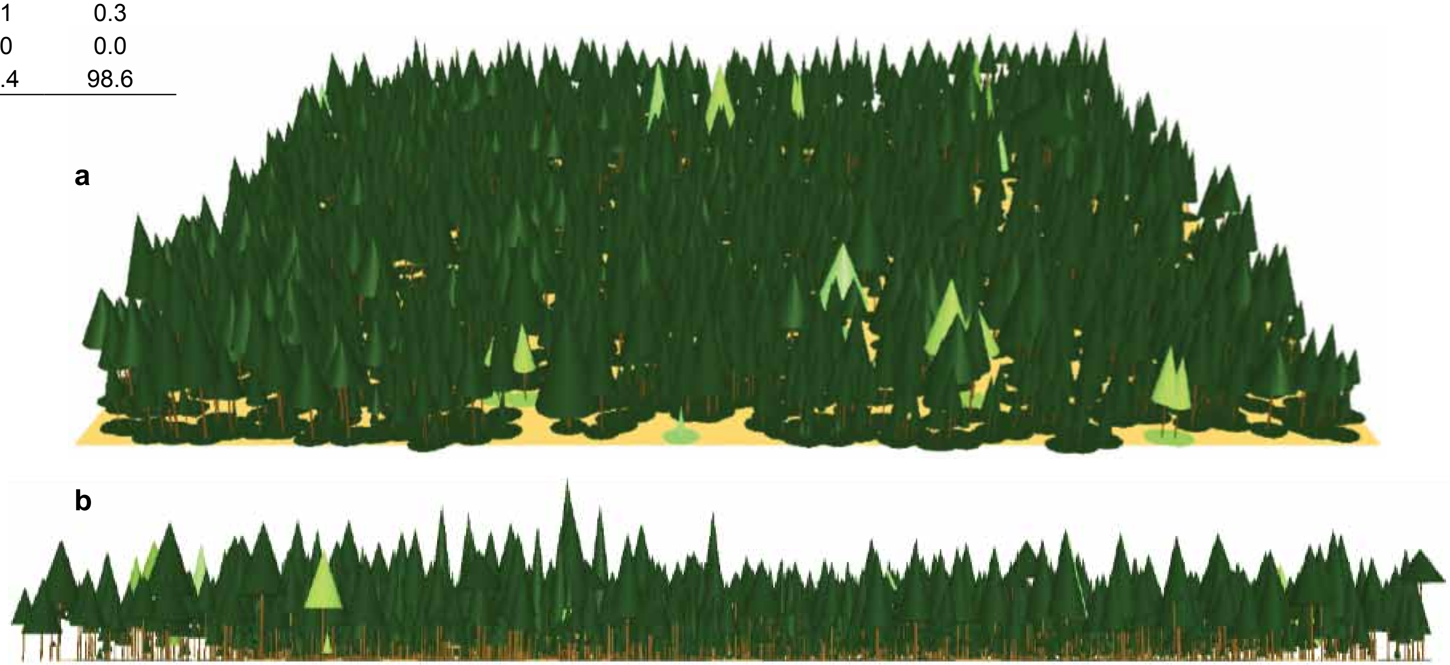


Figure 50—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 49), **b)** profile view of stand structure.

Thin From Below to 40 ft^2 ac^{-1} of Basal Area

Traditional thin from below approaches tend to homogenize stand structure and in this case resulted in all trees less than 14 inches d.b.h. being removed (fig. 51), leading to a substantial increase to stand level QMD from 8.6 to 16.8 inches, decreasing the relative variability of QMDs seen throughout the stand (table 30).

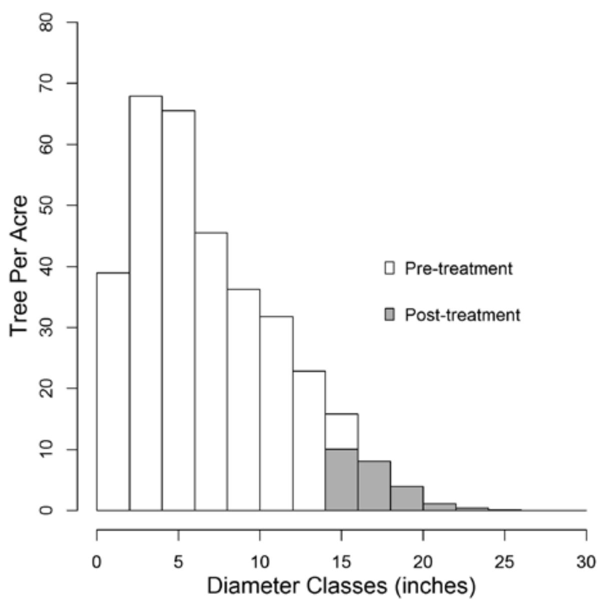


Figure 51—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the thin from below treatment.

Following completion of the thinning, the stand's canopy continuity was greatly reduced in terms of cover shifting from 94 to 52 percent. These reductions are consistent with the decreases seen in the means and ranges of the stand's tree density and basal area, where the mean and range of trees per acre were reduced to roughly one-twelfth of the pre-treatment condition (table 30).

Table 30—Changes in stand characteristics for the moderate-high density multi-storied stand after a thin from below treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	338 (123–602; 31%)	24 (0–52; 47%)
BA per acre	130 ft^2 (76–326; 52%)	40 ft^2 (0–259; 83%)
QMD	8.6 in (5.7–17.3; 49%)	16.8 in (0–32.4; 18%)
Total height	36 ft (24–54; 16%)	65 ft (48- 104; 9%)
CBH	14 ft (9–21; 18%)	24 ft (12–41; 25%)
SDI	236	55
Crown biomass	15.86 tons acre^{-1}	4.77 tons acre^{-1}

- Single tree and 2-4 Tree clumps went from being represented by 0.1 to 100 percent of the trees in the stand, with the largest clump only containing 25 trees (table 31).
- The thinning also resulted in an increase to the number of and mean size of stand opening, with openings now reaching 75 ft in radius (figs. 52 and 53).

Table 31—Changes in clump size distribution for the moderate-high density multi-storied stand after the thin from below treatment.

	Pre			Post		
Clump size	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA
Single tree	0.5	0.1	0.2	11.3	47.9	44.0
2–4 Trees	0.5	0.3	0.9	4.6	52.1	56.0
5–9 Trees	0.1	0.1	0.3	0.0	0.0	0.0
10–15 Trees	0.0	0.0	0.0	0.0	0.0	0.0
>15 Trees	0.2	99.4	98.6	0.0	0.0	0.0

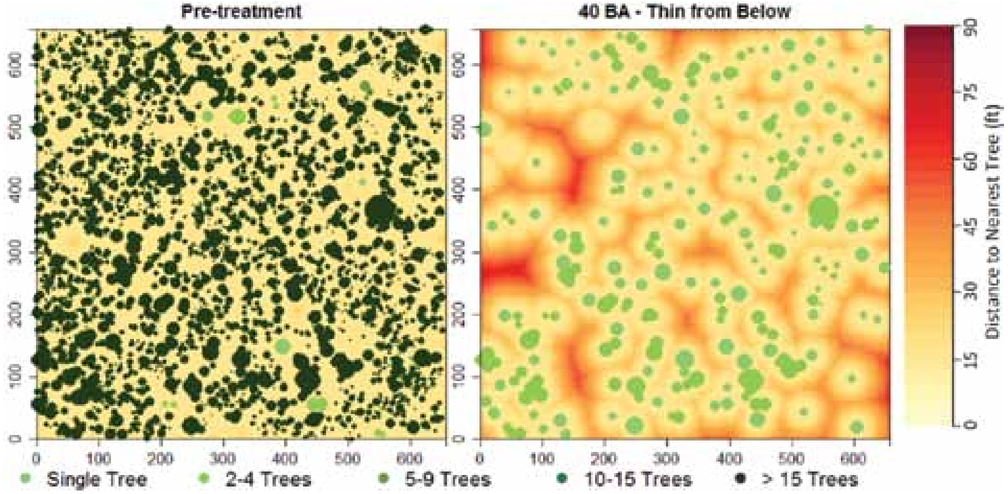
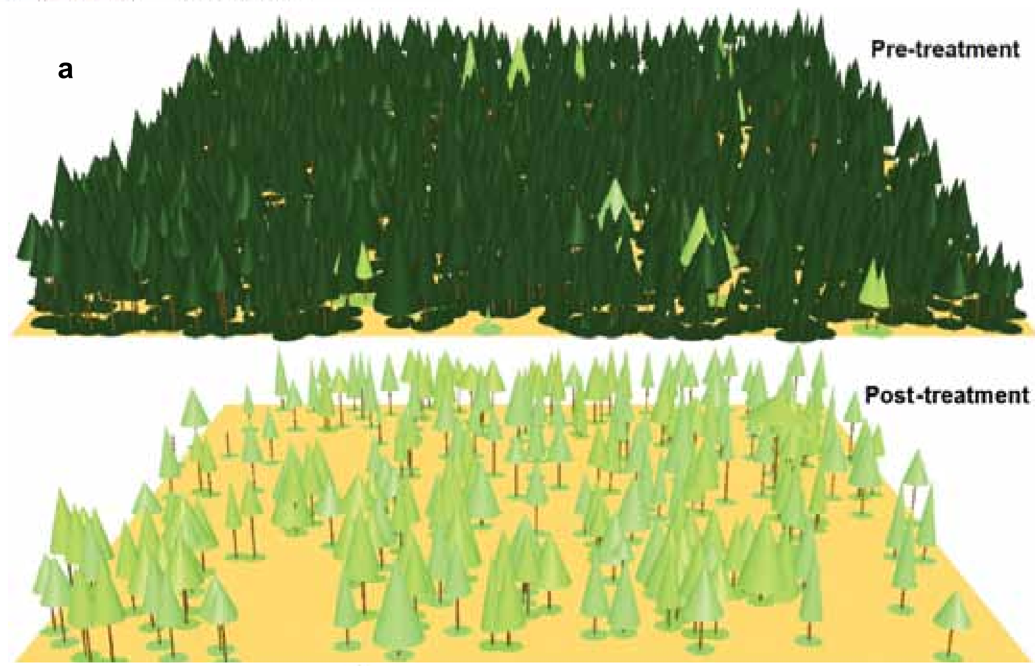


Figure 52—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).



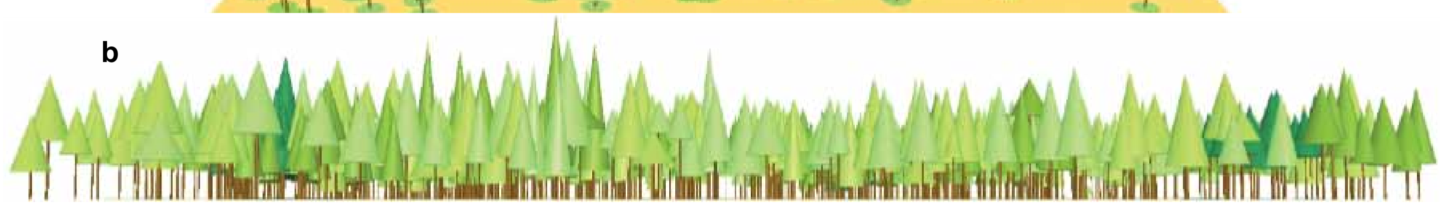


Figure 53—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 52), **b)** profile view of stand structure.

Random Thinning to 40 ft^2 ac^{-1} of Basal Area

Proportional thinning throughout the diameter range or random thinning approaches tend to preserve the pre-existing stand structure and in this case removed about 60 percent of trees from each diameter class (fig. 54), causing only a small shift in stand level QMD from 8.6 to 8.7 inches, but increasing the range of QMDs seen throughout the stand (table 32). Following completion of the thinning, the stand's canopy cover shifted from 94 to 60 percent and there was a substantial increase in the local vertical structure variability going from approximately 17 to 24 percent variation. The horizontal continuity of the stand was reduced as a result of the thinning, resembling the range of openings created by spatially explicit thinnings.

- The thinning reduced the proportion of trees located in more than 15 tree clumps from 99 to 52 percent, with strong increases in the proportion of trees in the smaller clump sizes (table 33).
- Following the thinning, about 15 percent of the stand would now be classified as being in openings, but the mean size of these openings was only about 0.04 acres in size (figs. 55 and 56).

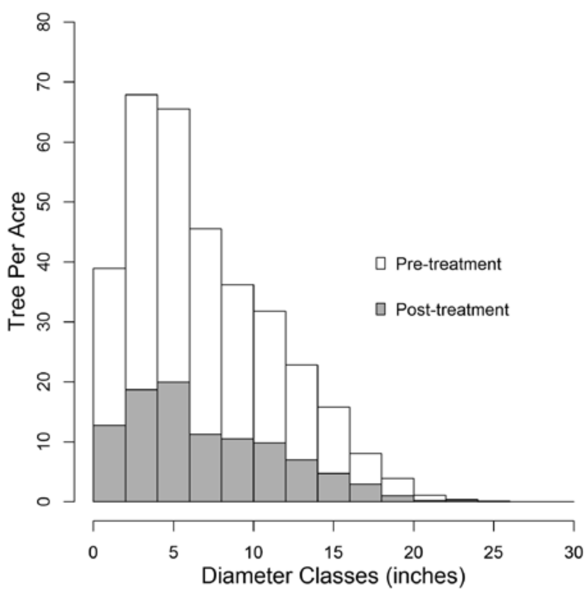


Figure 54—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the random thinning.

Table 32—Changes in stand characteristics for the moderate-high density multi-storied stand after a random thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	338 (123–602; 31%)	99 (26–188; 39%)
BA per acre	130 ft^2 (76–326; 52%)	40 ft^2 (9–149; 39%)
QMD	8.6 in (5.7–17.3; 49%)	8.7 in (4.7–21.7; 29%)
Total height	36 ft (24–54; 16%)	36 ft (22– 65; 23%)
CBH	14 ft (9–21; 18%)	14 ft (7–29; 25%)
SDI	236	71
Crown biomass	15.86 tons $acre^{-1}$	4.83 tons $acre^{-1}$

Table 33—Changes in clump size distribution for the moderate-high density multi-storied stand after the random thinning treatment.

	Pre			Post		
Clump size	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA
Single tree	0.5	0.1	0.2	7.2	7.2	11.0
2–4 Trees	0.5	0.3	0.9	6.3	17.5	20.8
5–9 Trees	0.1	0.1	0.3	2.7	17.5	19.4
10–15 Trees	0.0	0.0	0.0	0.5	5.6	5.8
>15 Trees	0.2	99.4	98.6	1.4	52.1	43.1

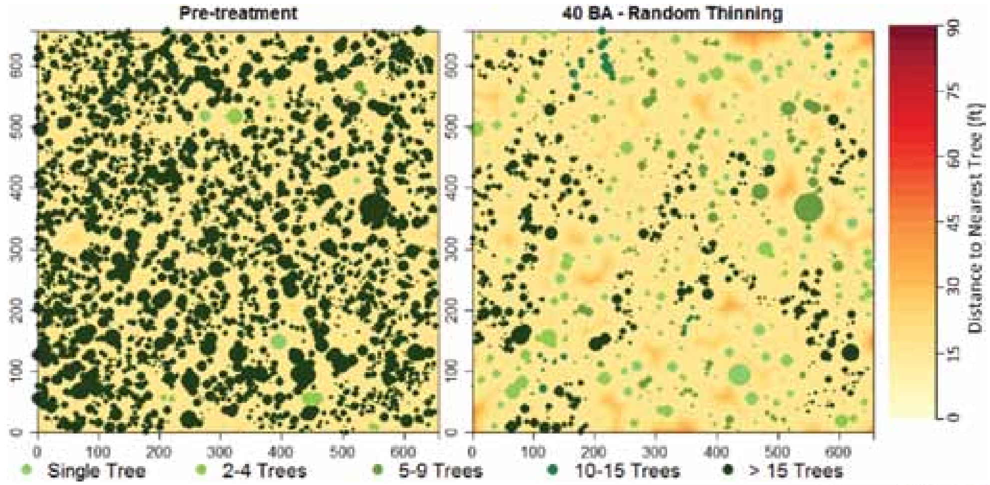


Figure 55—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

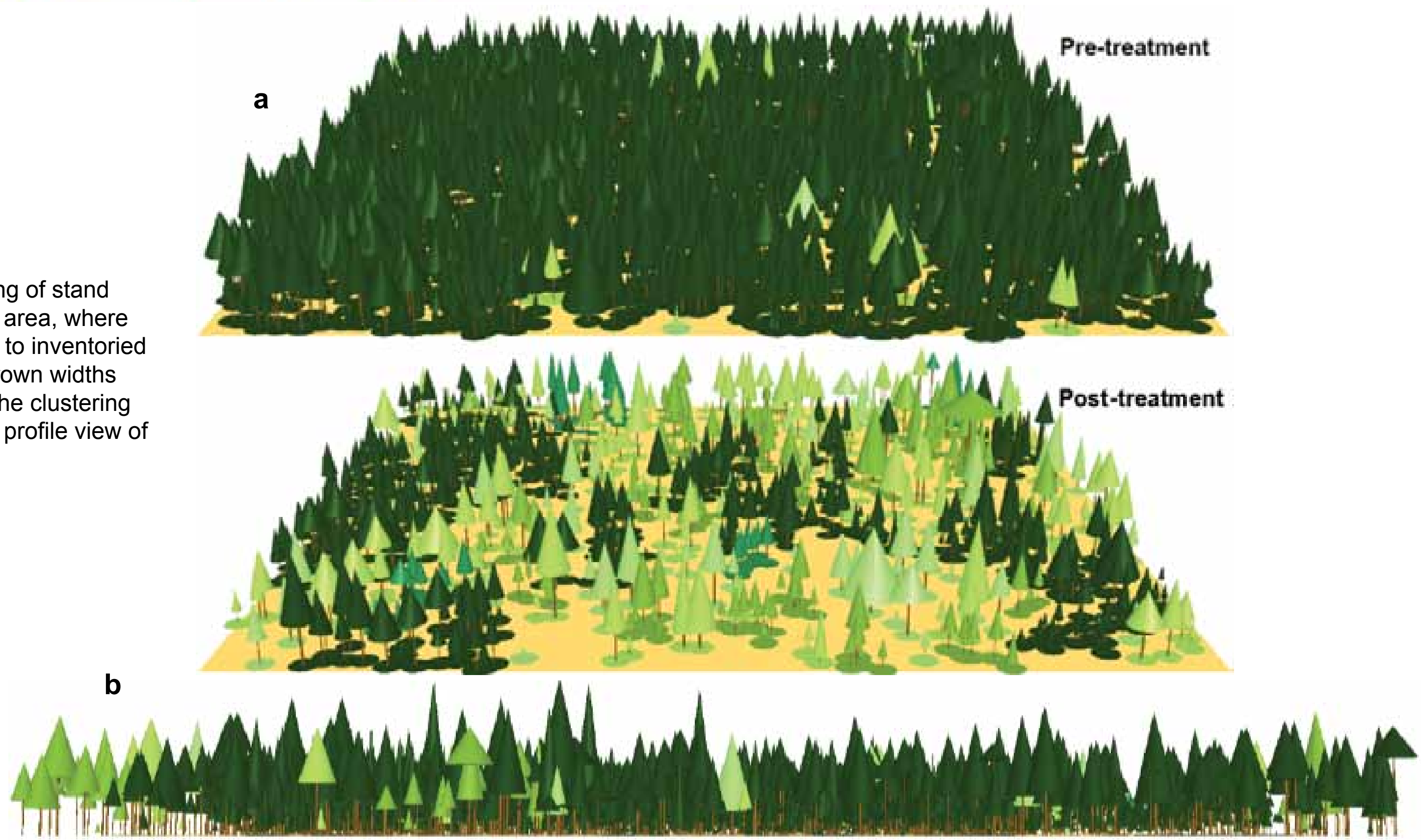


Figure 56—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 55), **b)** profile view of stand structure.

Moderately Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

A moderate clumping scenario following individual, clump, and opening thinning approach attempts to increase the number of small clumps, and in this case resulted in a proportional removal of trees throughout the range of diameters (fig. 57) and a small increase in stand level QMD from 8.6 to 8.9 inches (table 34).

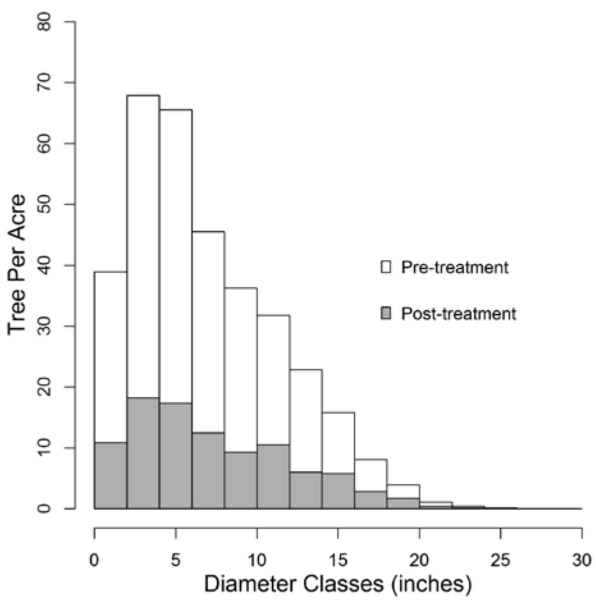


Figure 57—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the moderately clumped thinning treatment.

Following completion of the thinning, the stand's canopy cover shifted from 94 to 60 percent and the variability in local basal area nearly doubled from 28 to 47 percent. Local variability in both horizontal and vertical tree structures saw small increases, which is in line with the goals of spatially explicit prescriptions. The horizontal continuity of the stand was greatly reduced as a result of the thinning.

Table 34—Changes in stand characteristics for the moderate-high density multi-storied stand after a moderately clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	338 (123–602; 31%)	96 (39–188; 33%)
BA per acre	130 ft^2 (76–326; 52%)	41 ft^2 (10–139; 47%)
QMD	8.6 in (5.7–17.3; 49%)	8.9 in (5.9–18.1; 23%)
Total height	36 ft (24–54; 16%)	36 ft (24– 54; 19%)
CBH	14 ft (9–21; 18%)	14 ft (8–21; 22%)
SDI	236	72
Crown biomass	15.86 tons acre^{-1}	5.10 tons acre^{-1}

- The stand went from being dominated by a single large clump to having Single tree and clumps up to 9 trees occupy 83 percent of the trees in the stand (table 35).
- The thinning only resulted in a small shift in the proportion of the stand within openings, going from approximately 2 to 7 percent (figs. 58 and 59).

Table 35—Changes in clump size distribution for the moderate-high density multi-storied stand after the moderately clumped thinning treatment.

	Pre			Post		
Clump size	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA
Single tree	0.5	0.1	0.2	27.2	28.5	31.8
2–4 Trees	0.5	0.3	0.9	10.3	32.4	31.2
5–9 Trees	0.1	0.1	0.3	2.9	22.4	22.2
10–15 Trees	0.0	0.0	0.0	0.8	10.9	8.5
>15 Trees	0.2	99.4	98.6	0.3	5.7	6.4

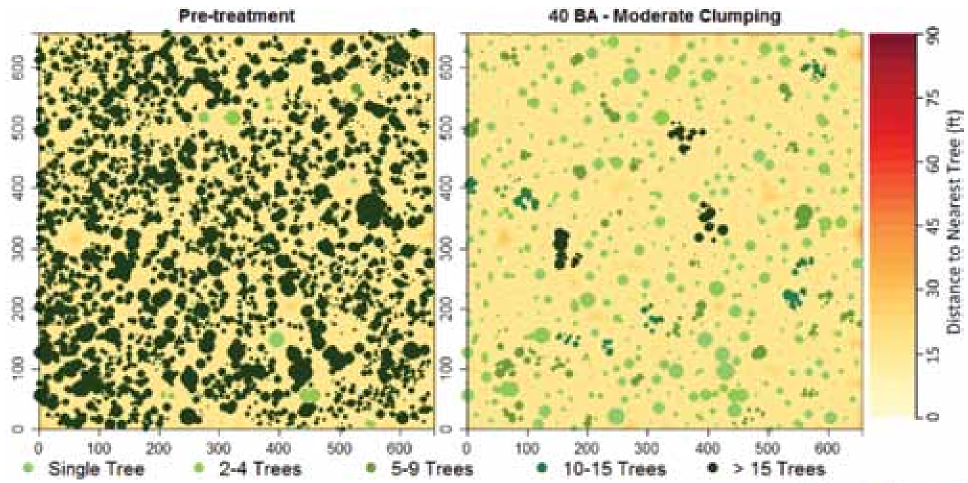


Figure 58—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

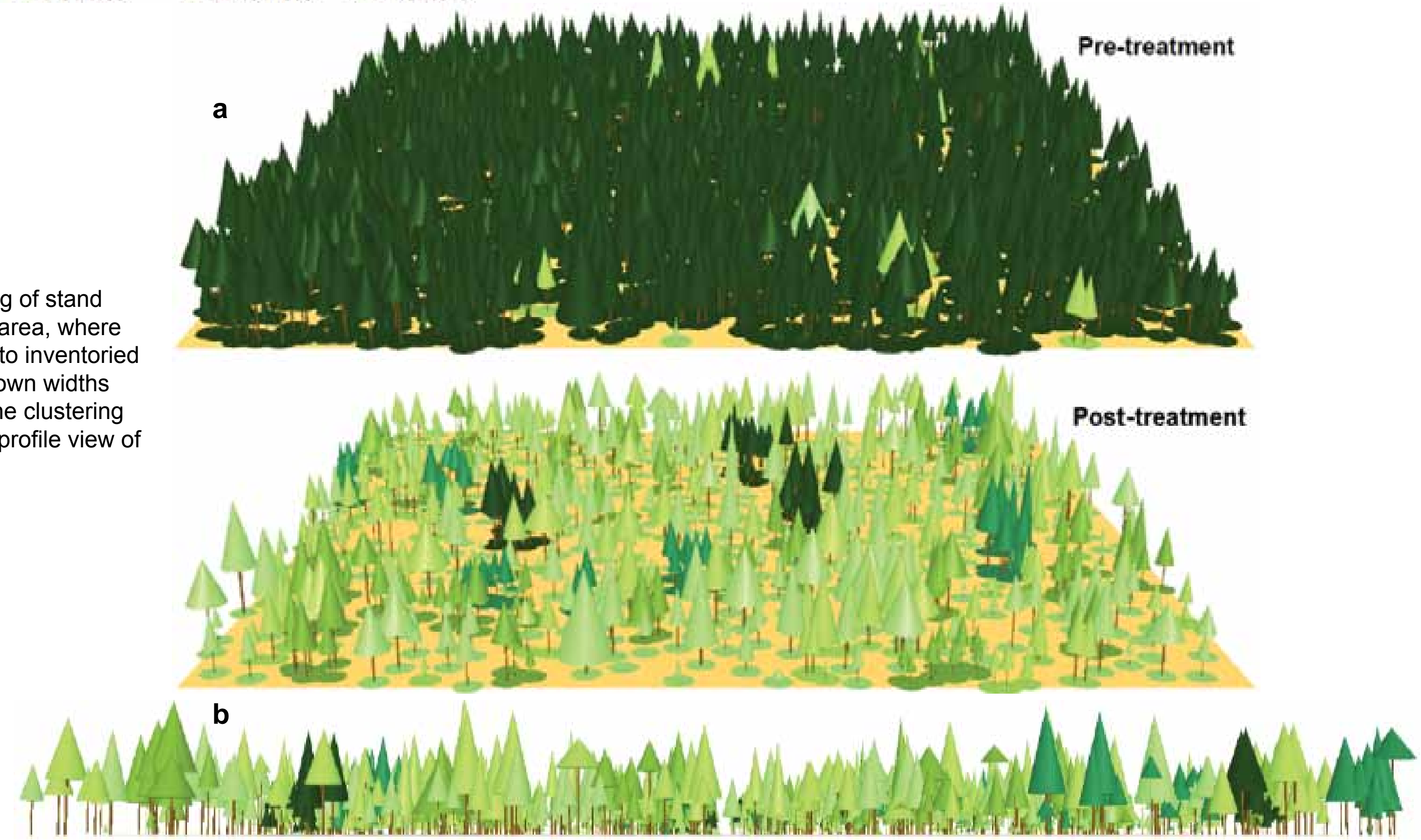


Figure 59—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 58), **b)** profile view of stand structure.

Highly Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

Under the high clumping scenario following individual, clump, and opening thinning, the goal was to distribute the stand's structure throughout the range of clump sizes. In this case, it resulted in a proportional removal of trees throughout the range of diameters (fig. 60) and no change in stand level QMD, but increased the range of local QMDs in the stand (table 36). Following completion of the thinning, the stand's canopy cover shifted from 94 to 54 percent. This treatment provided the greatest increase in local variability when all horizontal and vertical measures are considered in line with the goals of spatially explicit prescriptions.

- The stand went from being dominated by a single large clump to having a balanced distribution of clump sizes that are well spread across the stand (table 37).
- The thinning resulted in the most significant increase in number and mean size of openings, with several openings reaching radii of approximately 45 ft, or openings of approximately 1/6 acre (figs. 61 and 62).

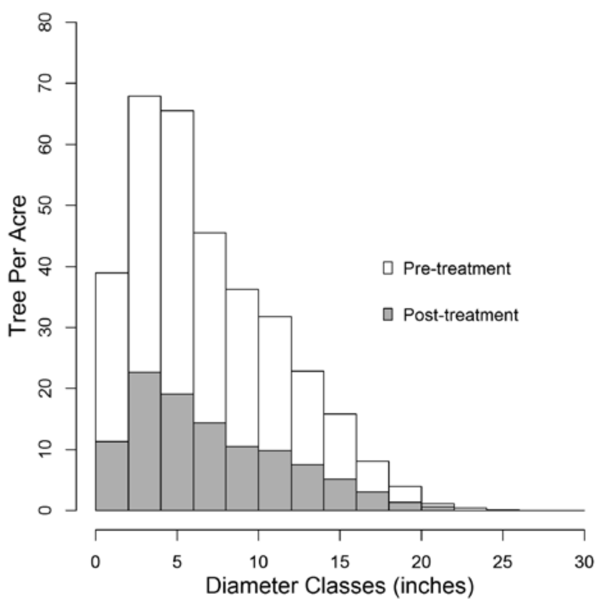


Figure 60—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the highly clumped thinning.

Table 36—Changes in stand characteristics for the moderate-high density multi-storied stand after a highly clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	338 (123–602; 31%)	106 (39–266; 40%)
BA per acre	130 ft^2 (76–326; 52%)	43 ft^2 (5.1–140; 58%)
QMD	8.6 in (5.7–17.3; 49%)	8.6 in (4.3–19.0; 27%)
Total height	36 ft (24–54; 16%)	36 ft (19– 56; 21%)
CBH	14 ft (9–21; 18%)	14 ft (7–21; 23%)
SDI	236	77
Crown biomass	15.86 tons $acre^{-1}$	5.29 tons $acre^{-1}$

Table 37—Changes in clump size distribution for the moderate-high density multi-storied stand after the highly clumped thinning treatment.

	Pre			Post		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	0.5	0.1	0.2	10.4	9.9	10.5
2–4 Trees	0.5	0.3	0.9	8.7	29.2	33.5
5–9 Trees	0.1	0.1	0.3	5.5	34.8	33.4
10–15 Trees	0.0	0.0	0.0	10.6	15.9	13.4
>15 Trees	0.2	99.4	98.6	0.6	10.2	9.1

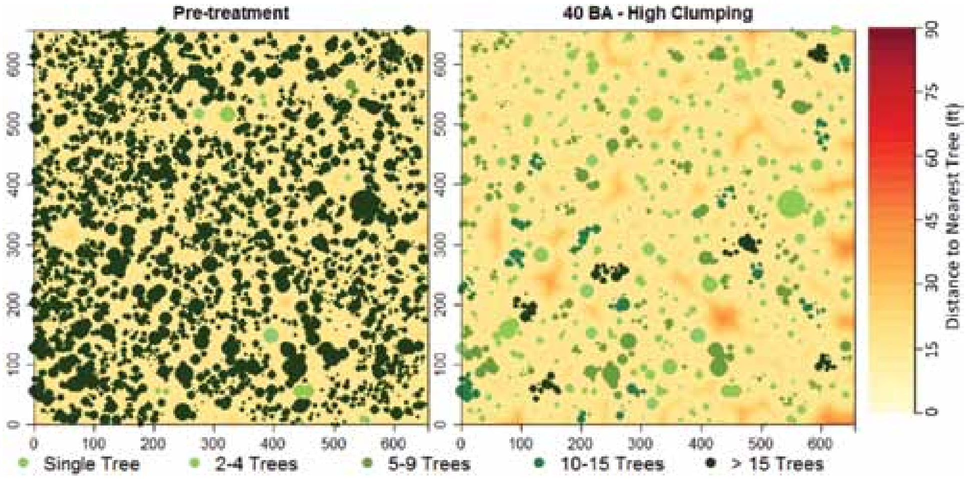


Figure 61—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

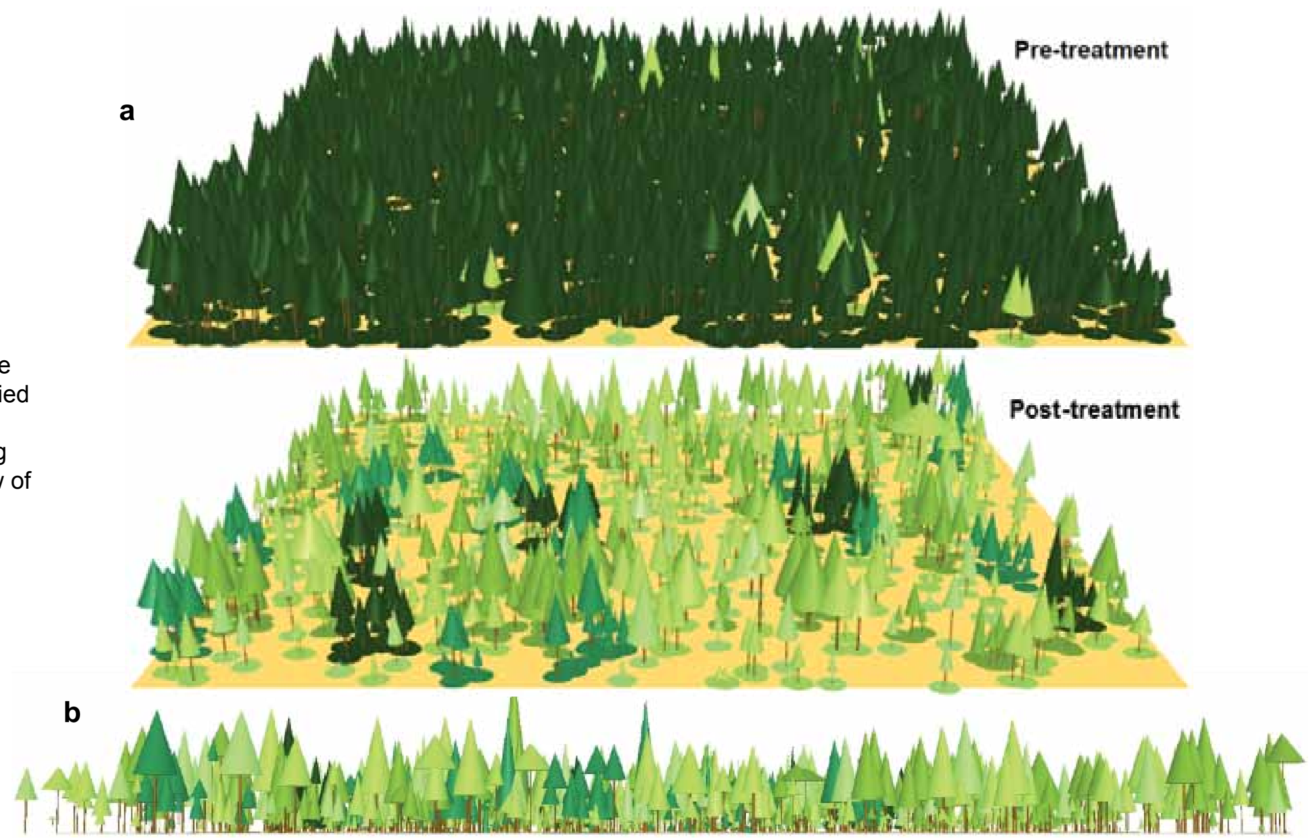


Figure 62—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clumping scheme above (fig. 61), **b)** profile view of stand structure.

Summary: Moderate-High Density Multi-Storied Stand

Prior to treatment, this stand had regions of significant density (>600 trees per acre) and horizontal continuity, with a single cluster containing more than 13,200 trees. The stand was dominated by trees less than 8 inches d.b.h. (64 percent of trees) and had a QMD of 8.6 inches (table 38). The stand also had only one opening that would meet the 20 ft requirement for stand openings (figs. 63–65).

- Following the simulated treatments, mean stand density was greatly reduced while increasing the relative variability of tree density in all but the thin from below simulations. This increase in variability is an important indicator of meeting horizontal heterogeneity treatment objectives.
- The moderate clumping treatment struggled to meet both the basal area prescription and the allocation of trees into the prescribed clump sizes, potentially indicating that multiple entries may be needed to meet stand objectives.

Table 38—Changes in stand characteristics for the moderate-high density multi-storied stand after various thinning treatments. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment	Thin from below	Random thinning	Moderately clumped	Highly clumped
Trees per acre	338 (123–602)	24 (0–52)	99 (26–188)	96 (39–188)	106 (39–266)
BA per acre	130 ft^2 (76–326)	40 ft^2 (0–259)	40 ft^2 (9–149)	41 ft^2 (10–139)	43 ft^2 (5–140)
QMD	8.6 in (5.7–17.3)	16.8 in (0–32.4)	8.7 in (4.7–21.7)	8.9 in (5.9–18.1)	8.6 in (4.3–19.0)
Mean tree height	36 ft (24–54)	65 ft (48–104)	36 ft (22–65)	36 ft (24–54)	36 ft (19–56)
Canopy base height	14 ft (9–21)	24 ft (12–41)	14 ft (7–29)	14 ft (8–21)	14 ft (7–21)
Crown biomass	15.86 tons $acre^{-1}$	4.77 tons $acre^{-1}$	4.83 tons $acre^{-1}$	5.10 tons $acre^{-1}$	5.29 tons $acre^{-1}$

Table 39—Changes in clump size distribution for each of the thinning treatments for the moderate-high density multi-storied stand.

	Pre-treatment			Thin from below			Random thinning			Moderately clumped			Highly clumped		
Clump size	#/Acre	%TPA	%BA	#/Acre	%TPA	%BA	#/Acre	%TPA	%BA	#/Acre	%TPA	%BA	#/Acre	%TPA	%BA
Single tree	0.5	0.1	0.2	11.3	47.9	44.0	7.2	7.2	11.0	27.2	28.5	31.8	10.4	9.9	10.5
2–4 Trees	0.5	0.3	0.9	4.6	52.1	56.0	6.3	17.5	20.8	10.3	32.4	31.2	8.7	29.2	33.5
5–9 Trees	0.1	0.1	0.3	0.0	0.0	0.0	2.7	17.5	19.4	2.9	22.4	22.2	5.5	34.8	33.4
10–15 Trees	0.0	0.0	0.0	0.0	0.0	0.0	0.5	5.6	5.8	0.8	10.9	8.5	10.6	15.9	13.4
>15 Trees	0.2	99.4	98.6	0.0	0.0	0.0	1.4	52.1	43.1	0.3	5.7	6.4	0.6	10.2	9.1

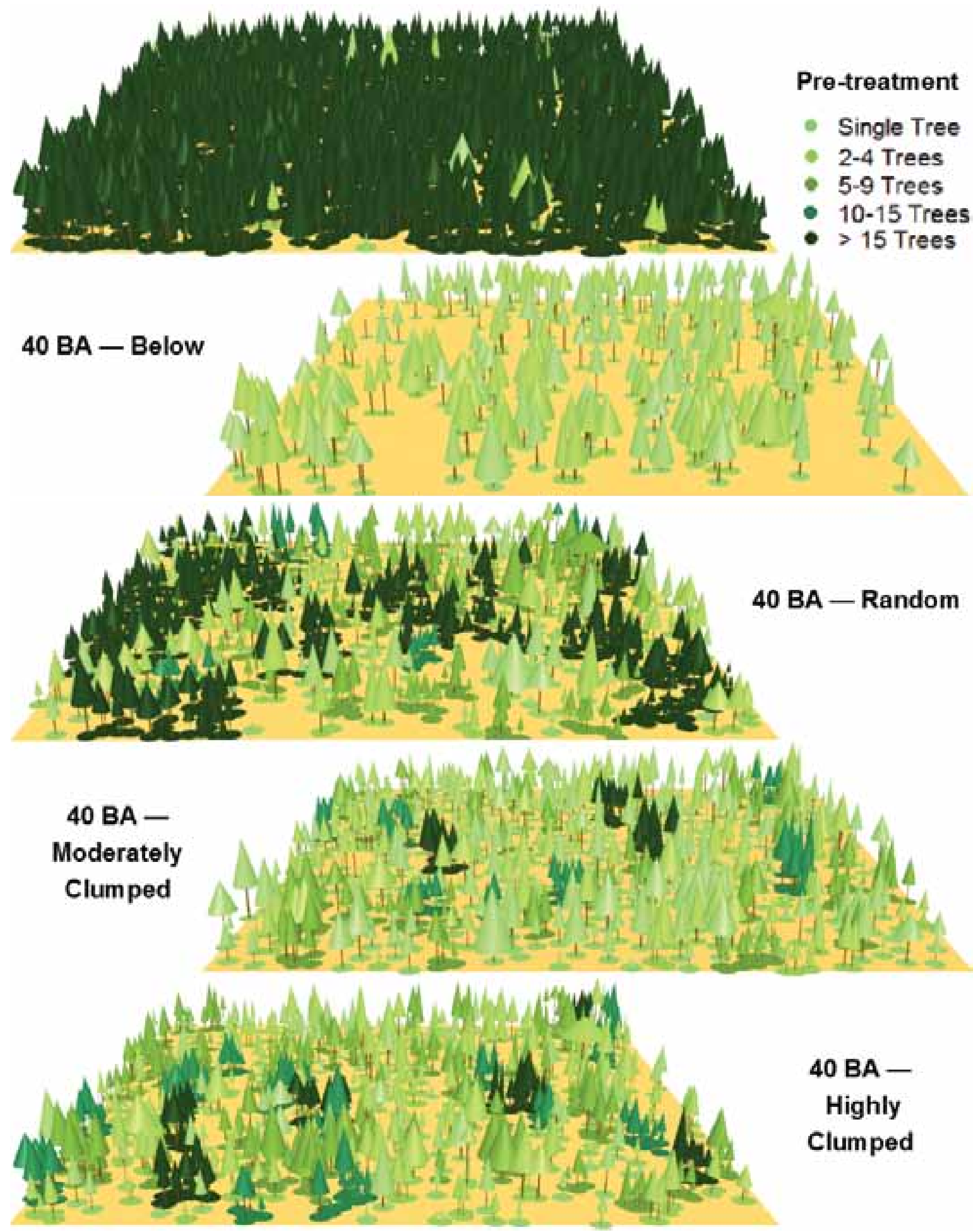


Figure 63—Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths.

The pre-treatment stand condition placed most of the trees into a single very large and continuous cluster of trees, containing more than 98 percent of the stand's trees and basal area (table 39).

- The thin from below simulations drastically shifted the stand toward Single tree or small clumps, while the random thinning left a majority of the stand (>50 percent) in clumps of more than 15 trees.

- Following the simulated treatments (Moderately and Highly Clumped), the structures within the stand were reallocated throughout all of the tree clump sizes, providing a balance of these structures to help meet many restoration, wildlife, and fuels treatment objectives.
- The two treatments differ in that the moderate clumping scenario resulted in less local variability in tree density, size, and vertical structure than the highly clumped treatment.

Prior to treatment, only 3 percent of the stand was classified in openings (>6 m from a tree) with the largest opening being approximately 1/50 acre (figs. 64 and 65; table 40).

- Thin from below had the greatest shift in distribution, putting 54 percent of the stand into openings, which was dominated by a 6.2 acre opening that snakes throughout the stand. Additionally, it led to the most simplistic vertical structure.
- The moderate clumping treatment resulted in the smallest shift in opening distribution with only about 13 percent of the stand being in openings.
- Both random thinning and high clumping resulted in similar distributions of stand openings, with about 19 percent of the stand being within openings. The differences in these treatments is that the random thinning left over 50 percent of the trees in the stand in clumps of more than 15 trees and had a smaller range of opening sizes. The high clumping treatment distributed the remnant stand structures throughout all of the clump sizes and created a greater diversity of opening sizes.

Table 40—Changes in clump and opening area for each of the thinning treatments for the moderate-high density multi-storied stand.

	Clump area (acres)				
		Mean	Median	Min	Max
Pretreatment		0.63	0.01	0.007	7.84
Below		0.015	0.014	0.007	0.026
Random		0.038	0.019	0.007	0.481
Moderate		0.017	0.014	0.007	0.070
High		0.018	0.015	0.007	0.064
	Opening area (acres)				
	n	**Mean**	**Median**	**Min**	**Max**
Pretreatment	2	–	–	0.019	0.019
Below	10	0.715	0.086	0.019	6.232
Random	24	0.065	0.058	0.019	0.150
Moderate	10	0.031	0.029	0.012	0.055
High	23	0.083	0.067	0.019	0.230

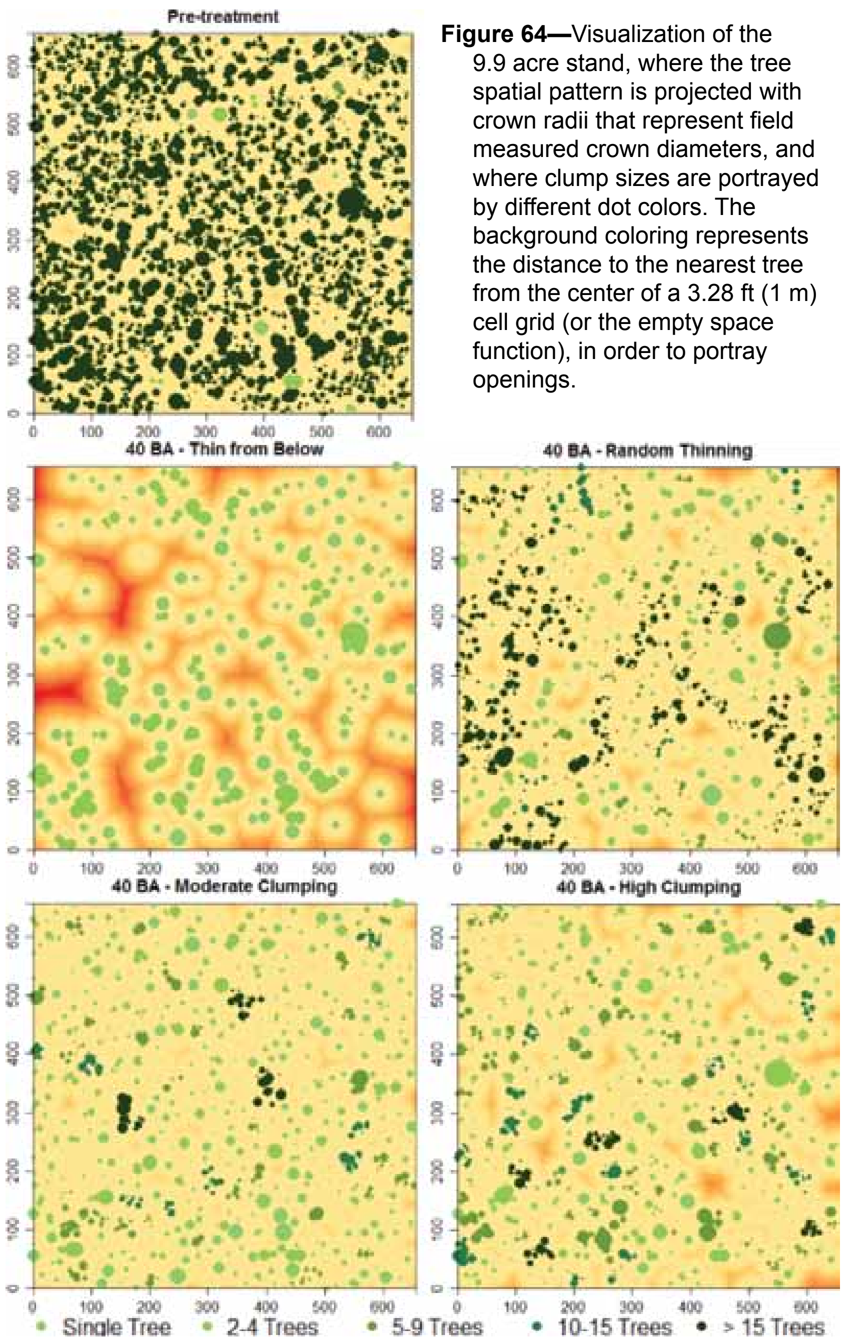


Figure 64—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function), in order to portray openings.

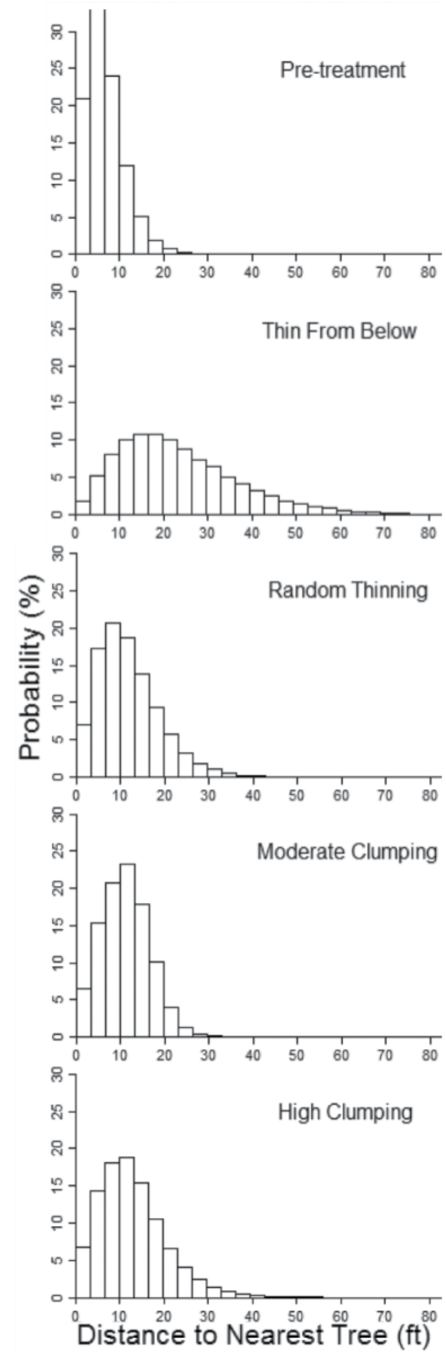


Figure 65—Treatment effects on the distribution of the distance to the nearest tree.

Pre-treatment: High Density Multi-Storied Stand

This stand was composed of 87 percent ponderosa pine, with small portions of the stand occupied by Colorado blue spruce, quaking aspen, and Gambel oak. The site is typical of many mid-elevation (about 8,400 ft above sea level) ponderosa pine stands with a site index of 90 ft at a base age of 100 (fig. 66). Prior to treatment, the stand was largely occupied by trees between 2 and 8 inches d.b.h. (fig. 67) and had a QMD of 11.4 inches with a canopy base height of 20 ft (table 41). This stand was at a moderately high density of 204 trees per acre but with regions of significant density (>500 trees per acre) and horizontal continuity, with a single clump containing more than 450 trees (table 42). Only 5 percent of the stand would be considered in openings with a radius greater than 20 ft (figs. 68 and 69). The stand underwent 4 simulated thinnings to a residual basal area of 40 ft^2 $acre^{-1}$ (9.18 m^2 ha^{-1}).

Figure 66 —Pre-treatment forest structure of a high density multi-storied stand (photo: Emma Vakili, U.S. Forest Service).

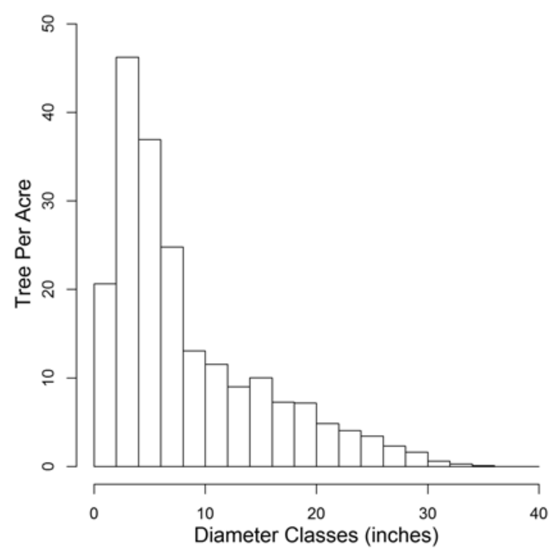


Figure 67—Pre-treatment distribution of trees per acre by 2-inch d.b.h. size classes of a high density multi-storied stand.

Table 41—Pre-treatment stand characteristics for the high density multi-storied stand. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment
Trees per acre	204 (58–537; 48%)
BA	131 ft^2 (15–249; 53%)
QMD	11.4 in (5.2–20.1; 53%)
Tree height	40 ft (24–72; 24%)
Canopy base height	20 ft (13–38; 25%)
Crown biomass	15.21 tons $acre^{-1}$

Table 42—Pre-treatment clump size distribution for the high density multi-storied stand.

Clump size	#/Acre	% TPA	% BA
Single tree	3.6	1.8	4.4
2–4 Trees	3.6	4.7	8.9
5–9 Trees	1.1	3.5	3.7
10–15 Trees	0.6	3.7	7.5
>15 Trees	2.1	86.3	75.5

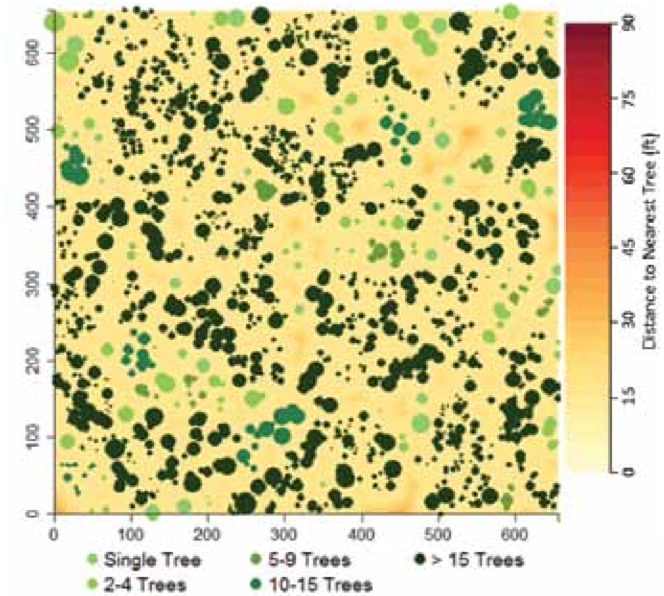


Figure 68—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

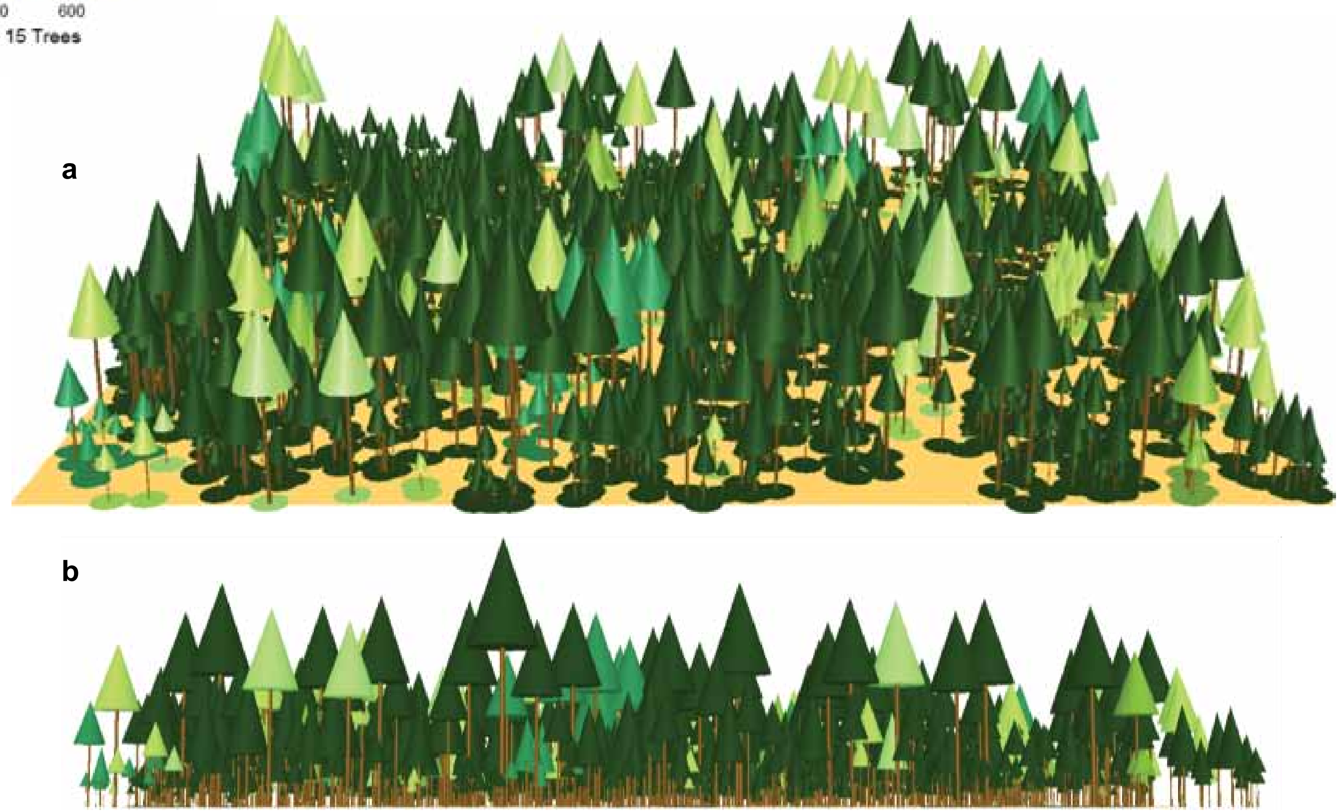


Figure 69—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 68), **b)** profile view of stand structure.

Thin From Below to 40 ft^2 ac^{-1} of Basal Area

Thin from below approaches tend to homogenize stand structure and in this case resulted in all trees less than 20 inches d.b.h. being removed (fig. 70) and an increase in stand level QMD from 11.4 to 20.1 inches (table 43), significantly reducing the local variation in QMD. Following completion of the thinning, the stand's canopy cover shifted from 94 to 49 percent. There was also a general reduction in the level of local variation in horizontal and vertical forest structures.

- Single tree and 2–4 Tree clumps went from being represented by 6.5 to 100 percent of the trees in the stand, with no clumps larger than 4 trees remaining after the treatment (table 44).
- The thinning also resulted in an increase in the number of and mean size of stand openings, with openings now reaching more than 100 ft in radius or an opening of 3/4 of an acre in size (figs. 71 and 72).

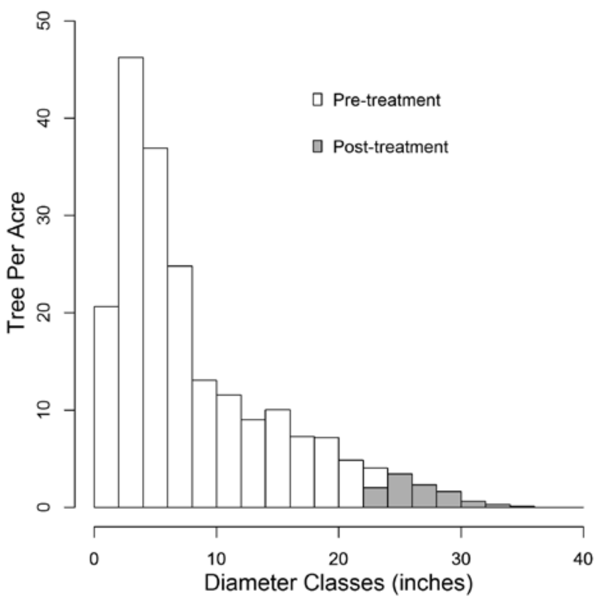


Figure 70—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the thin from below treatment.

Table 43—Changes in stand characteristics for the high density multi-storied stand after a thin from below treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	204 (58–537; 48%)	11 (0–45; 63%)
BA per acre	131 ft^2 (15–249; 53%)	41 ft^2 (0–193; 14%)
QMD	11.4 in (5.2–20.1; 53%)	20.1 in (0.0–31.9; 14%)
Total height	40 ft (24–72; 24%)	102 ft (76–129; 12%)
CBH	20 ft (13–38; 25%)	55 ft (18–76; 28%)
Crown biomass	15.21 tons $acre^{-1}$	4.62 tons $acre^{-1}$

Table 44—Changes in clump size distribution for the high density multi-storied stand after the thin from below treatment.

	Pre			Post		
Clump size	#/Acre	% TPA	% BA	#/Acre	% TPA	% BA
Single tree	3.6	1.8	4.4	7.7	73.8	74.3
2–4 Trees	3.6	4.7	8.9	1.1	26.2	25.7
5–9 Trees	1.1	3.5	3.7	0	0	0
10–15 Trees	0.6	3.7	7.5	0	0	0
>15 Trees	2.1	86.3	75.5	0	0	0

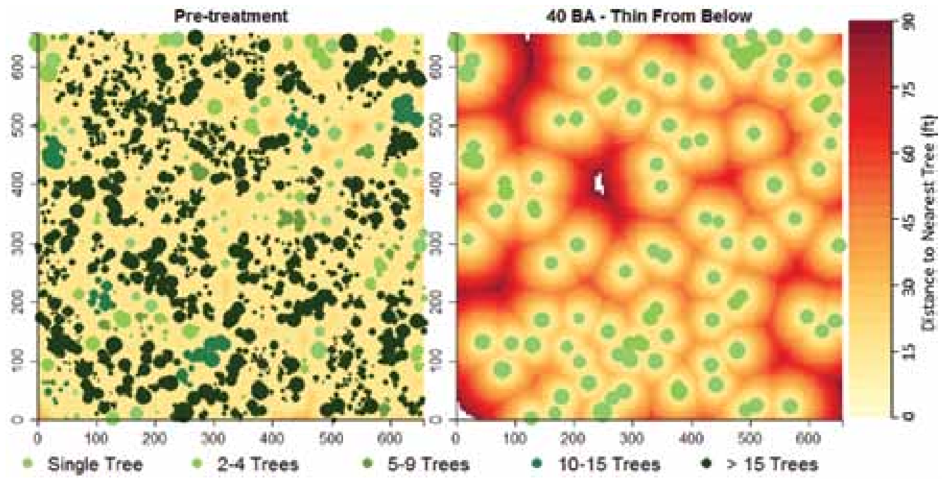


Figure 71—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

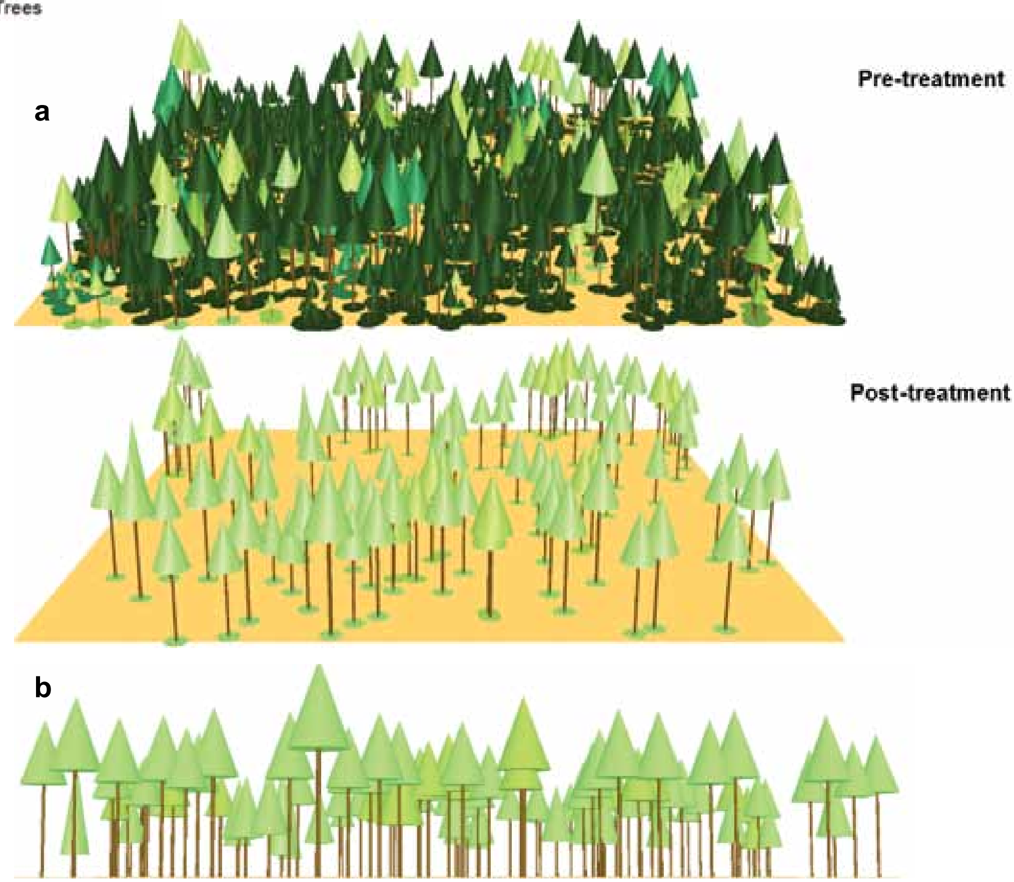


Figure 72—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 71), **b)** profile view of stand structure.

Random Thinning to 40 ft^2 ac^{-1} of Basal Area

Proportional thinning throughout the diameter range or random thinning approaches tend to preserve the pre-existing stand structure and in this case removed about 67 percent of trees from each diameter class (fig. 73), slightly shifting stand level QMD from 11.4 to 10.9 inches and a decrease in local variation in QMD (table 45). Following completion of the thinning, the stand's canopy cover shifted from 94 to 57 percent, and increases to both local horizontal and vertical forest structure variability were observed.

- The stand went from being dominated by very large clumps (>200 trees) to having a wide range of structures from Single trees to clumps of more than 15 trees (table 46).
- Half of the post-treatment trees were placed into 1–4 tree clumps, yet accounted for more than 70 percent of the basal area, indicating that smaller trees were allocated to clumps of 5–20 trees (table 46).
- The thinning increased the number and mean size of openings, with openings now reaching 50 ft in radius or 1/5 of an acre in size (figs. 74 and 75).

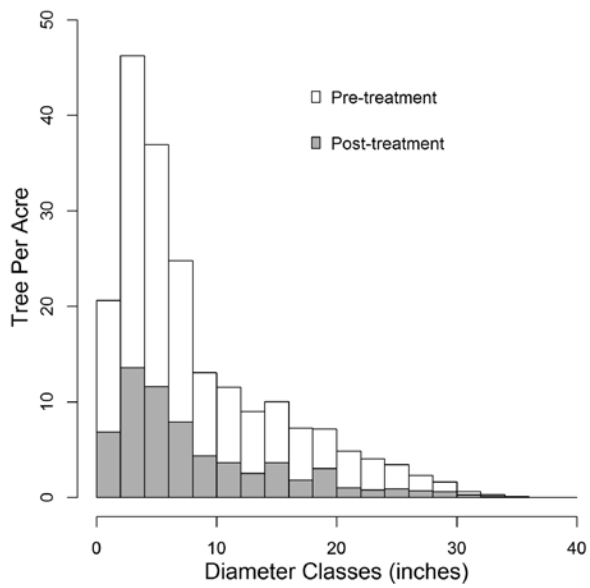


Figure 73—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the random thinning treatment.

Table 45—Changes in stand characteristics for the high density multi-storied stand after a random thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	204 (58–537; 48%)	63 (0–188; 51%)
BA per acre	131 ft^2 (15–249; 53%)	40 ft^2 (0–124; 77%)
QMD	11.4 in (5.2–20.1; 53%)	10.9 in (0.0–24.1; 35%)
Total height	40 ft (24–72; 24%)	40 ft (21–89; 51%)
CBH	20 ft (13–38; 25%)	21 ft (10–46; 34%)
Crown biomass	15.21 tons $acre^{-1}$	4.76 tons $acre^{-1}$

Table 46—Changes in clump size distribution for the high density multi-storied stand after the random thinning treatment.

	Pre			Post		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	3.6	1.8	4.4	10.3	16.3	29.8
2–4 Trees	3.6	4.7	8.9	8.9	37.2	41.1
5–9 Trees	1.1	3.5	3.7	1.1	12.3	10.8
10–15 Trees	0.6	3.7	7.5	0.8	15.0	9.8
>15 Trees	2.1	86.3	75.5	0.4	19.3	8.5

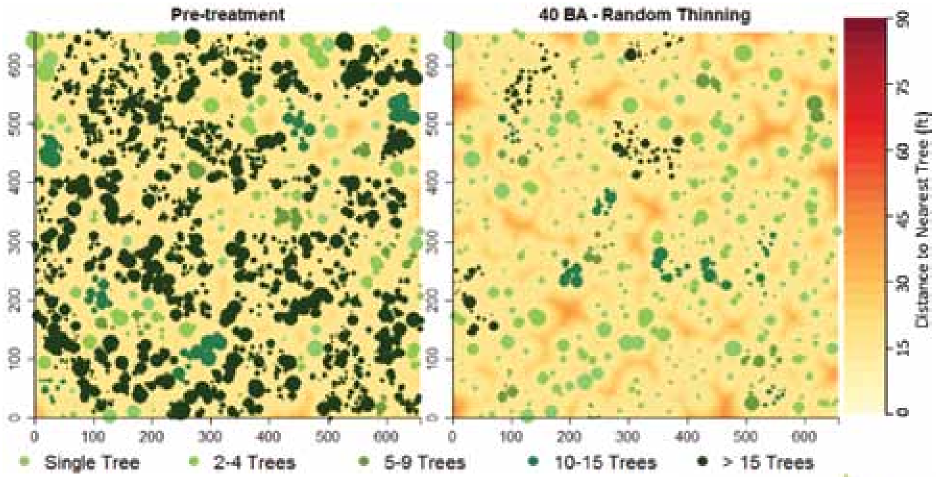


Figure 74—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

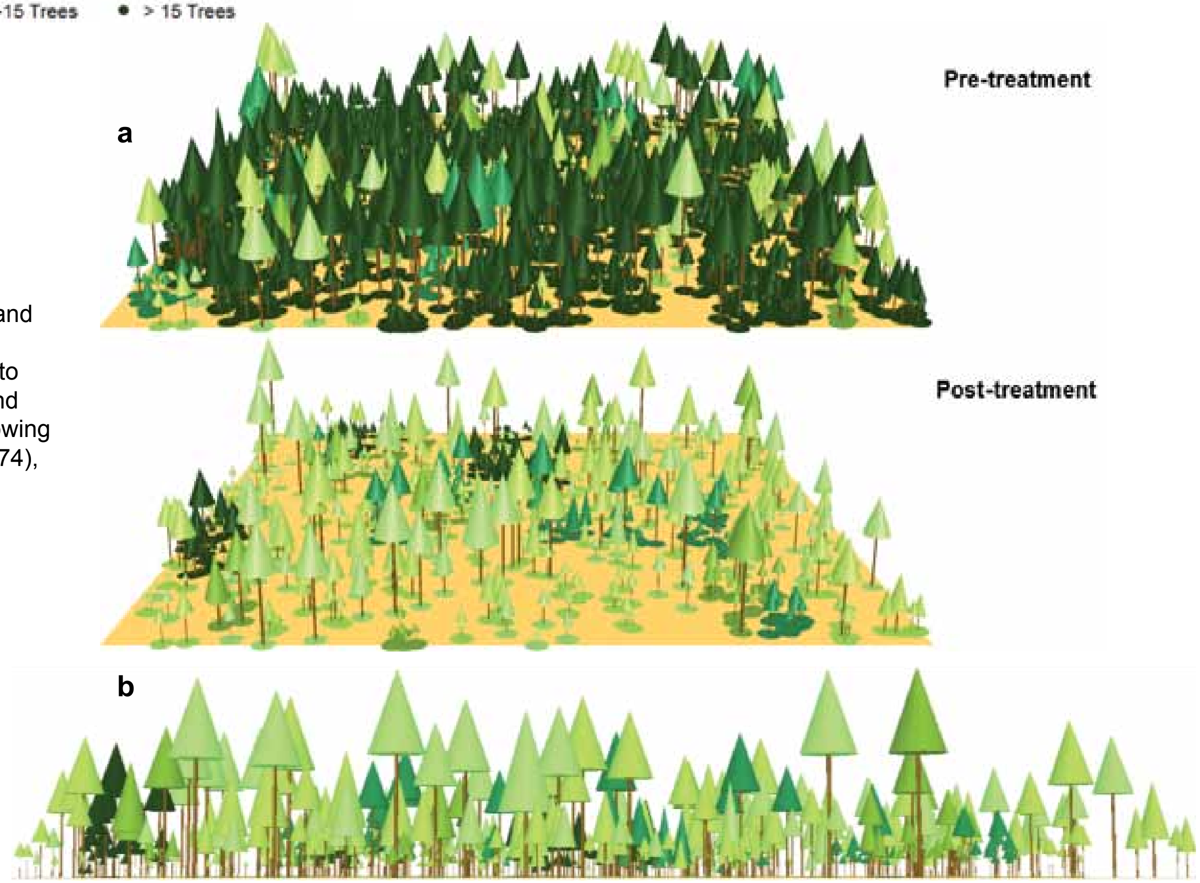


Figure 75—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 74), **b)** profile view of stand structure.

Moderately Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

A moderate clumping scenario following individual, clump, and opening thinning approach attempts to increase the number of small clumps, and in this case it resulted in a proportional removal of trees throughout the range of diameters (fig. 76) and a small increase in stand level QMD from 11.4 to 11.9 inches, but it increased the variability in local QMDs (table 47). Following completion of the thinning, the stand's canopy cover shifted from 94 to 54 percent and all measures of local horizontal and vertical forest structure increased, which is in line with the goals of spatially explicit prescriptions.

- The stand went from being dominated by large clumps to having Single tree and clumps from 2–9 trees representing the majority of the stand (table 48).
- The thinning also resulted in an increase in the number and mean size of stand openings, with many long sinuous openings now reaching radii of more than 50 ft or openings of approximately 1/5 to 1/3 acre in size (figs. 77 and 78).

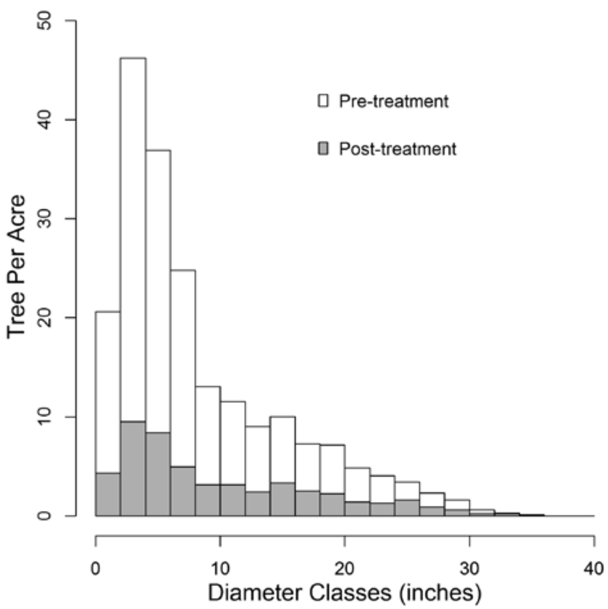


Figure 76—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the moderately clumped thinning treatment.

Table 47—Changes in stand characteristics for the high density multi-storied stand after a moderately clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees acre	204 (58–537; 48%)	51 (7–142; 60%)
BA per acre	131 ft^2 (15–249; 53%)	48 ft^2 (0.5–193; 64%)
QMD	11.4 in (5.2–20.1; 53%)	11.9 in (1.6–20.5; 64%)
Total height	40 ft (24–72; 24%)	43 ft (14–74; 32%)
CBH	20 ft (13–38; 25%)	22 ft (9–40; 34%)
Crown biomass	15.21 tons $acre^{-1}$	5.04 tons $acre^{-1}$

Table 48—Changes in clump size distribution for the high density multi-storied stand after the moderately clumped thinning treatment.

	Pre			Post		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	3.6	1.8	4.4	16.6	32.6	28.3
2–4 Trees	3.6	4.7	8.9	5.3	28.6	33.8
5–9 Trees	1.1	3.5	3.7	1.5	19.9	16.0
10–15 Trees	0.6	3.7	7.5	0.5	11.7	16.2
>15 Trees	2.1	86.3	75.5	0.2	7.2	5.8

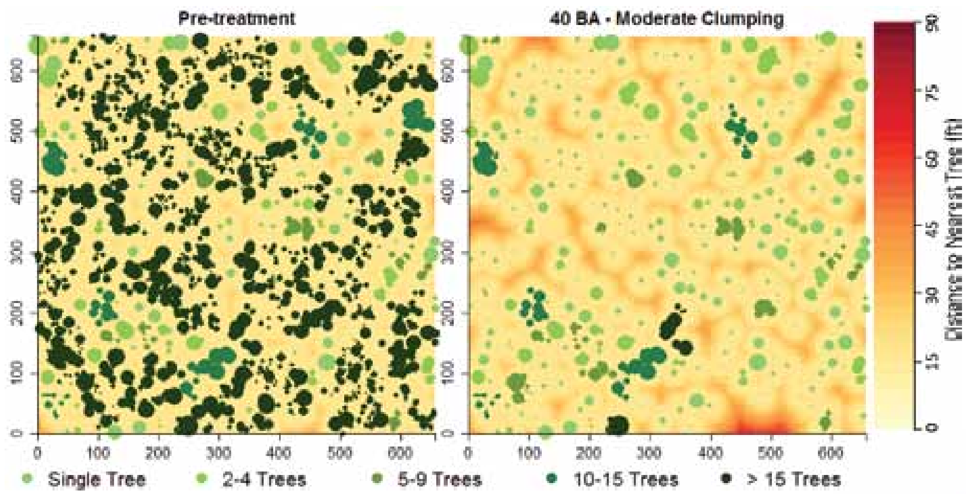
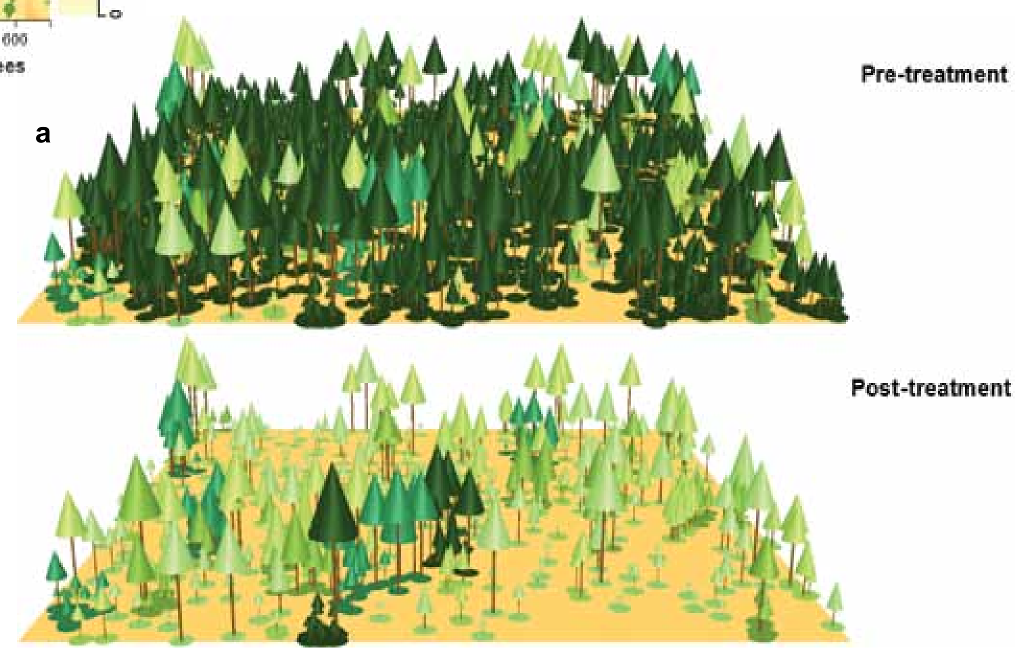


Figure 77—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

a



b

Figure 78—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clustering scheme above (fig. 77), **b)** profile view of stand structure.

Highly Clumped Thinning to 40 ft^2 ac^{-1} of Basal Area

Under the high clumping scenario following individual, clump, and opening thinning, the goal was to distribute the stand's structure throughout the range of clump sizes. In this case, it resulted in a proportional removal of trees throughout the range of diameters (fig. 79) and a small decrease in stand level QMD but provided the greatest increase to local variability of QMDs (table 49). Following completion of the thinning, the stand's canopy cover shifted from 94 to 54 percent and resulted in the highest level of local variability in trees and basal area per acre.

- The stand went from being dominated by large clumps to having a balanced distribution of clump sizes (table 50).
- The thinning resulted in a significant increase in the number and mean size of openings, with several reaching radii of more than 80 ft or openings of approximately 1/2 to 3/4 acre in size (figs. 80 and 81).

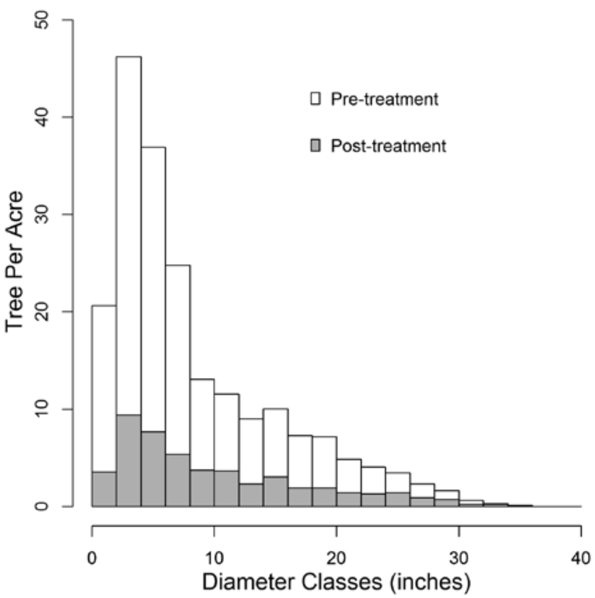


Figure 79—Comparison of trees per acre distribution within 2-inch d.b.h. size classes for the highly clumped thinning treatment.

Table 49—Changes in stand characteristics for the high density multi-storied stand after a highly clumped thinning treatment. Stand level mean with min, max, and coefficient of variation in parentheses calculated from 64 plots of 6.5-tenths x 6.5 tenths acre (82 x 82 ft).

	Pre	Post
Trees per acre	204 (58–537; 48%)	48 (0–136; 67%)
BA per acre	131 ft^2 (15–249; 53%)	44 ft^2 (0–193; 76%)
QMD	11.4 in (5.2–20.1; 53%)	10.2 in (0.0–26.2; 76%)
Total height	40 ft (24–72; 24%)	44 ft (24–85; 34%)
CBH	20 ft (13–38; 25%)	21 ft (3–40; 33%)
Crown biomass	15.21 tons $acre^{-1}$	4.80 tons $acre^{-1}$

Table 50—Changes in clump size distribution for the high density multi-storied stand after the highly clumped thinning treatment.

	Pre			Post		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	3.6	1.8	4.4	4.6	9.8	15.5
2–4 Trees	3.6	4.7	8.9	5.4	30.6	31.9
5–9 Trees	1.1	3.5	3.7	2.5	36.2	23.8
10–15 Trees	0.6	3.7	7.5	0.6	15.7	22.5
>15 Trees	2.1	86.3	75.5	0.2	7.7	6.3

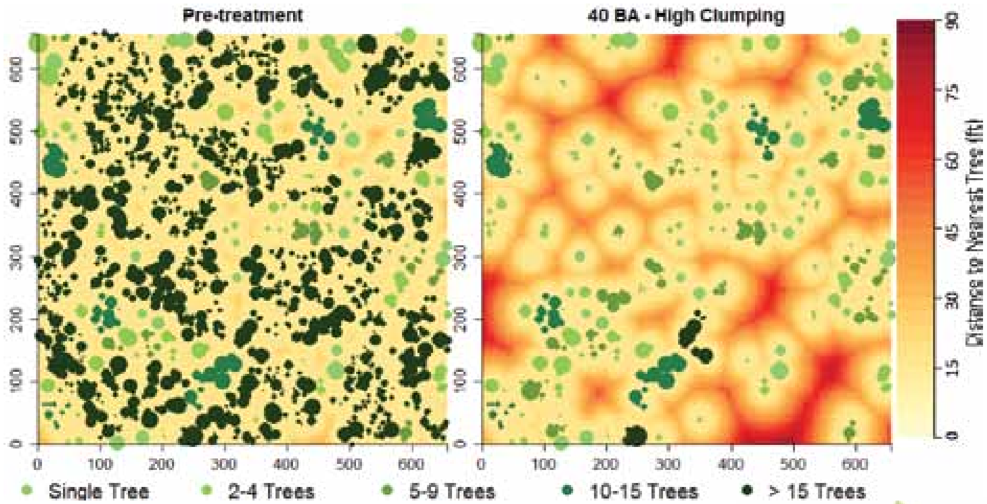


Figure 80—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function).

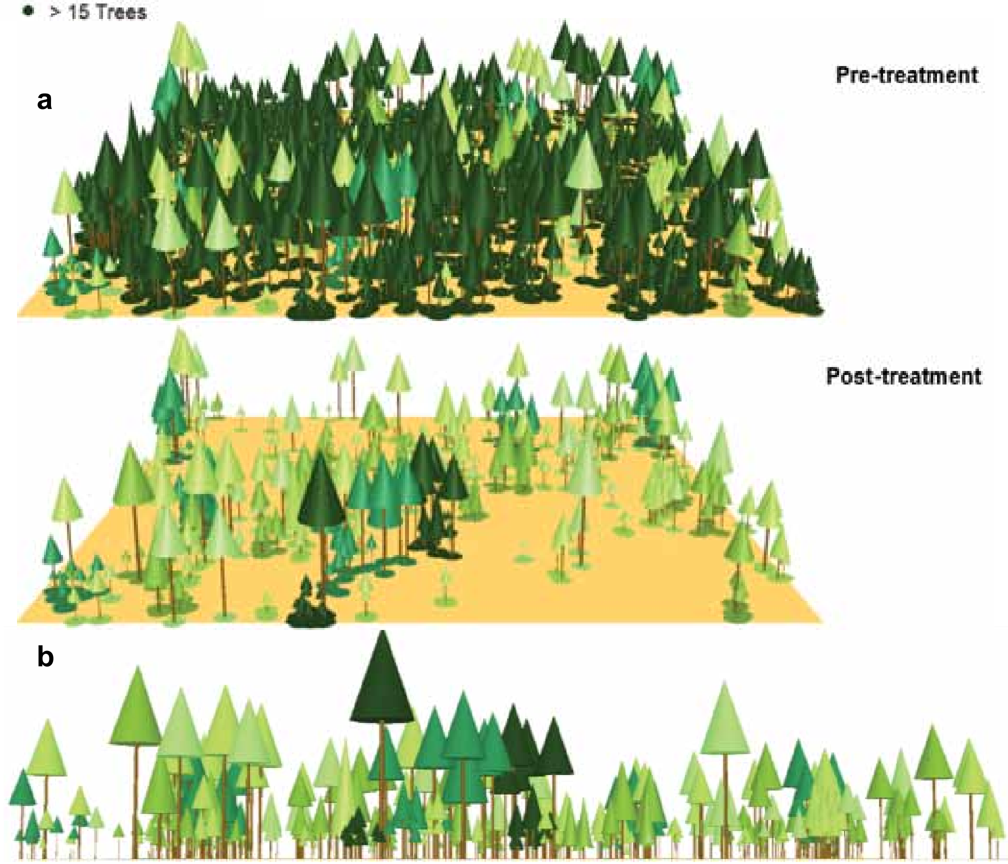


Figure 81—a) Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths and are colored following the clumping scheme above (fig. 80), **b)** profile view of stand structure.

Summary: High Density Multi-Storied Stand

Prior to treatment, this stand had regions of significant density (>500 trees per acre) and horizontal continuity. The stand was dominated by trees less than 8 inches d.b.h. (65 percent of trees) and had a QMD of 11.4 inches. Outside of a few smaller pre-existing openings, most canopy openings were less than 13 ft in radius (table 51; fig. 82).

- Following all of the simulated treatments, mean stand density was greatly reduced while increasing the relative variability of tree density in all but the thin from below simulations. This increase in variability is an important indicator of meeting horizontal heterogeneity treatment objectives.
- Under all of the simulations, except the thin from below, we also see significant increases in the relative level of vertical heterogeneity throughout the stand.

Table 51—Changes in stand characteristics for the high density multi-storied stand after various thinning treatments. Stand level mean with min and max in parentheses from 64 plots of 6.5 tenths x 6.5 tenths acre (82 x 82 ft).

	Pre-treatment	Thin from below	Random thinning	Moderately clumped	Highly clumped
Trees per acre	204 (58–537)	11 (0–45)	63 (0–188)	51 (7–142)	48 (0–136)
BA per acre	131 ft^2 (15–249)	41 ft^2 (0–193)	40 ft^2 (0–124)	48 ft^2 (0.5–193)	44 ft^2 (0–193)
QMD	11.4 in (5.2–20.1)	20.1 in (0.0–31.9)	10.9 in (0.0–24.1)	11.9 in (1.6–20.5)	10.2 in (0.0–26.2)
Mean tree height	40 ft (24–72)	102 ft (76–129)	40 ft (21–89)	43 ft (14–74)	44 ft (24–85)
Canopy base height	20 ft (13–38)	55 ft (18–76)	21 ft (10–46)	22 ft (9–40)	21 ft (3–40)
Crown biomass	15.21 tons $acre^{-1}$	4.62 tons $acre^{-1}$	4.76 tons $acre^{-1}$	5.04 tons $acre^{-1}$	4.80 tons $acre^{-1}$

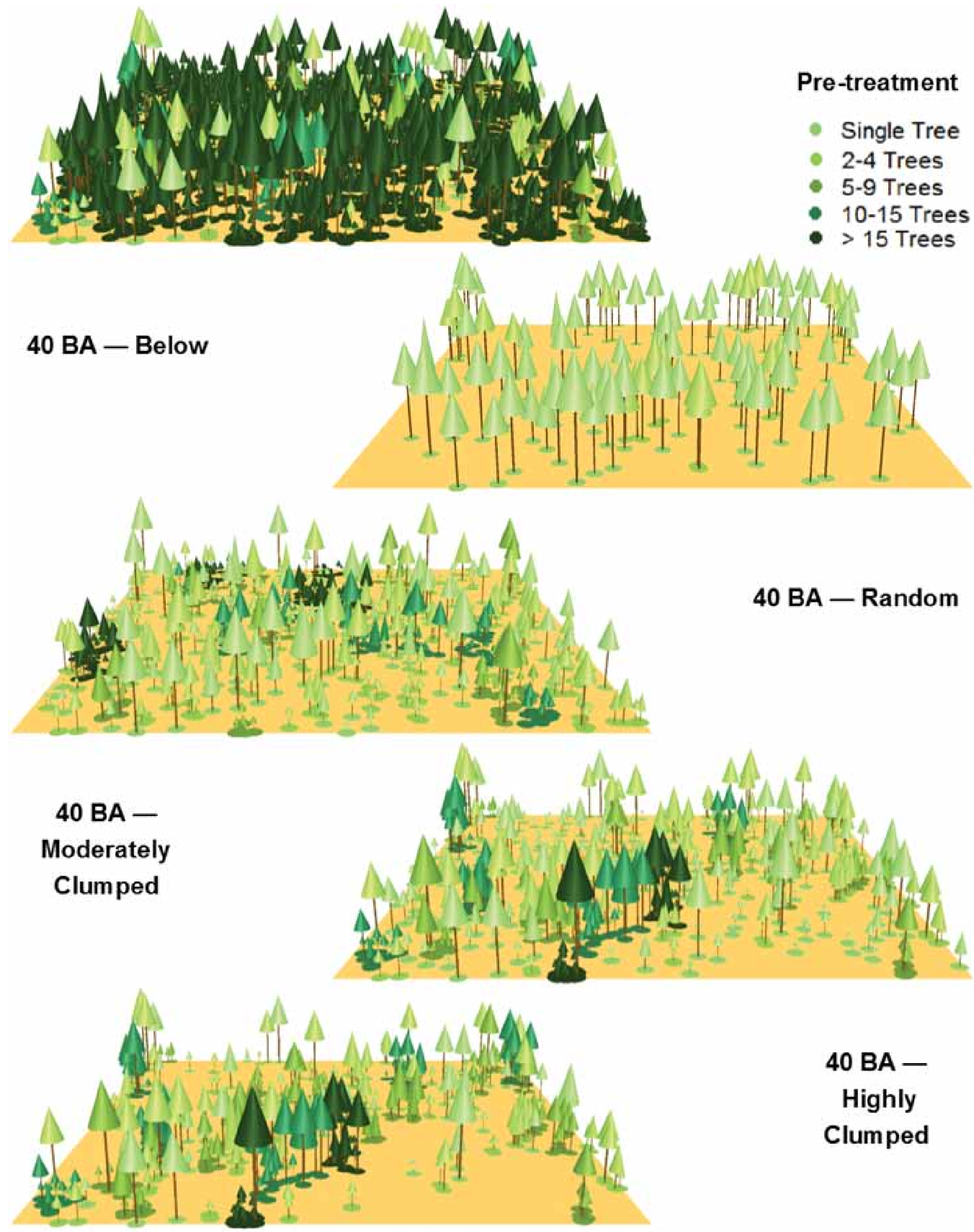


Figure 82—Virtual rendering of stand structure over the 9.9 acre area, where trees are scaled according to inventoried height, d.b.h., CBH, and crown widths.

The pre-treatment stand condition placed most of the trees into a few very large and continuous clump of trees, containing more than 85 percent of the stands trees and 75 percent of the basal area (table 52).

- The thin from below and random thinning simulations shifted most of the stand into Single tree or small clumps (>70%).
- Following the simulated spatially explicit treatments (Moderately and Highly Clumped), the structures within the stand were reallocated throughout all of the tree clump sizes, providing a balance of these structures to help meet many restoration, wildlife, and fuels treatment objectives.

Table 52—Changes in clump size distribution for each of the thinning treatments for the high density multi-storied stand.

	Pre-treatment			Thin from below			Random thinning			Moderately clumped			Highly clumped		
Clump size	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**	**#/Acre**	**% TPA**	**% BA**
Single tree	3.6	1.8	4.4	7.7	73.8	74.3	10.3	16.3	29.8	16.6	32.6	28.3	4.6	9.8	15.5
2–4 Trees	3.6	4.7	8.9	1.1	26.2	25.7	8.9	37.2	41.1	5.3	28.6	33.8	5.4	30.6	31.9
5–9 Trees	1.1	3.5	3.7	0	0	0	1.1	12.3	10.8	1.5	19.9	16.0	2.5	36.2	23.8
10–15 Trees	0.6	3.7	7.5	0	0	0	0.8	15.0	9.8	0.5	11.7	16.2	0.6	15.7	22.5
>15 Trees	2.1	86.3	75.5	0	0	0	0.4	19.3	8.5	0.2	7.2	5.8	0.2	7.7	6.3

Prior to treatment, only 8 percent of the stand was within openings (>6 m from a tree), with the largest opening being less than 1/10 acre (Figs. 83 and 84; table 53).

- Following treatment, all of the stands experienced a significant shift toward more open conditions and larger opening sizes.
- Thin from below simulation created the greatest shift in distribution, so that 76 percent of the stand area was considered to be an opening. To achieve this opening distribution, it was necessary to thin the stand to 11 trees per acre.
- Both random thinning and moderate clumping simulations provided more moderate shifts in the distribution of stand openings, with about 27 percent of the stands being within openings and the median opening size doubling.
- The high clumping simulation provided a balance between shifting the distribution and creating heterogeneous forest structures, with 53 percent of the stand being within openings and median opening size tripling the pre-treatment condition

Table 53—Changes in clump and opening area for each of the thinning treatments for the high density multi-storied stand.

	Clump area (acres)				
		Mean	Median	Min	Max
Pre-treatment		0.077	0.018	0.008	1.112
Below		0.014	0.013	0.010	0.027
Random		0.022	0.015	0.007	0.175
Moderate		0.018	0.014	0.007	0.068
High		0.019	0.014	0.008	0.068
	Opening area (acres)				
	n	**Mean**	**Median**	**Min**	**Max**
Pre-treatment	9	0.048	0.043	0.029	0.089
Below	3	–	0.140	0.024	8.816
Random	28	0.123	0.072	0.019	0.449
Moderate	25	0.200	0.085	0.19	0.790
High	8	0.842	0.123	0.029	5.873

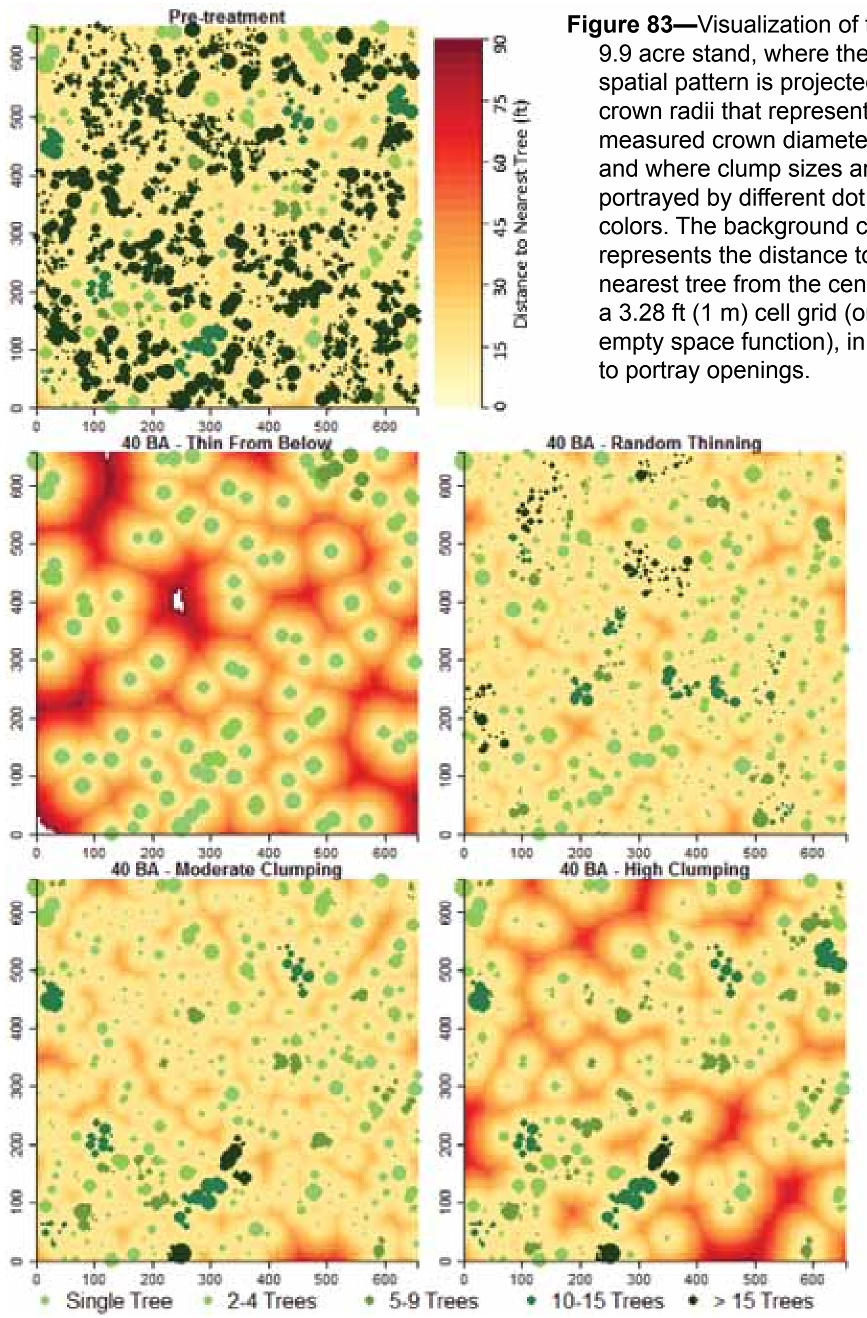
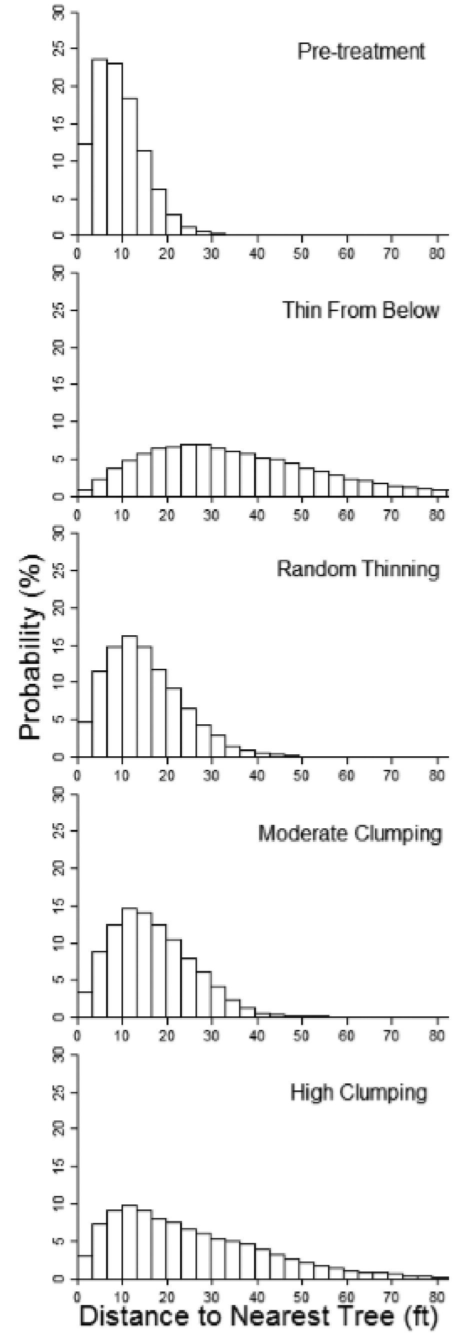


Figure 83—Visualization of the 9.9 acre stand, where the tree spatial pattern is projected with crown radii that represent field measured crown diameters, and where clump sizes are portrayed by different dot colors. The background coloring represents the distance to the nearest tree from the center of a 3.28 ft (1 m) cell grid (or the empty space function), in order to portray openings.

Figure 84—Treatment effects on the distribution of the distance to the nearest tree.



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