From:	Joe Trudeau
To:	FS-4FRI Comment Database
Cc:	Souther, John - FS
Subject:	CBD DEIS Comments attachements
Date:	Friday, January 17, 2020 9:50:07 AM
Attachments:	4FRI Planning Workgroup - September 7, 2016 meeting minutes.pdf 2018.10.15 CBD Field Report - Little Timber Sale Old Growth Logging.pdf Briefing paper on Krofcheck et al 2019.pdf FSH 2509.25_10 Watershed Conservation Practices Handbook.doc FSH_1909.12_zero_code.docx FSM 2020.docx Hampton et al., 2011 - 4FRI regional wood supply study [JoF].pdf Iniguez et al 2019_tree spatial patterns openings old growth Arizona pon....pdf Kolb et al 2007 - Perpetuating old PIPO [FEM].pdf Krofcheck_et_al-2019-Journal_of_Geophysical_Research__Biogeosciences.pdf O"Donnell et al. 2018_Forest restoration as a strategy to mitigate clima....pdf Sesnie et al 2010 - Stakeholders landscape restoration strategy.pdf SPLYT final decision 4FRI Planning Workgroup - August 9 2017 meeting min....pdf 2019_Riling_etal_Diameter_Age_BNF.pdf

Hello,

This email contains attachments cited in our Rim Country comments submitted on 1/16/2019.

Thank you,

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4FRI Planning Workgroup

Wednesday September 7, 2016 Meeting Minutes
10:00 am to 12:00 pm
Coconino National Forest Supervisor Office – Flagstaff
Conference Call (877) 820-7831, access code 691102#

1) **Welcome and introductions / additions to agenda.**

Attendance included Annette Fredette , Mark Nigrelli, Randy Fuller, Travis Wooley, Ann DeMarco, Ethan Aumack, Travis Bruner, Todd Schulke, Steve Rosenstock, Audrey Owens, Paul Watson, Brad Worsley, Sharon Adams, Dave Dorum, Amy Waltz, Joe Miller, Pascal Berlioux.

No addition to agenda.

2) **Approval of Minutes of August 2 and 9, 2016 field trip & meeting minutes**

The minutes of the August 2, 2016 field trip and August 9, 2016 meeting were approved with one modification. A fourth criterion, "slope position" was added for the definition of SPLYTs bio-physical characterization. See attached.

3) **"Stands with Preponderance of Large Young Trees," or "High Quality Canopy Habitat," or "Stands with Preponderance of Large Young Trees with High Quality Canopy Habitat"?**

The group discussed at length and decided to focus on "Stands with Preponderance of Large Young Trees with High Quality Canopy Habitat."
Ethan proposed to formalize the objective of the workgroup as: "*Retain and enhance some proportion of areas with a preponderance of large trees to achieve structural heterogeneity at a landscape scale and ensure that old growth is maximally recruited through the restoration process*."

4) **Report on USFS mapping using matrix defined on August 9.**

Mark presented the results of running the four criteria adopted at the August 9 meeting (see tables and maps attached):

1. Site Index (SI) - capturing the notion of tree diameter and tree height - greater than 50%.
2. Basal Area (BA) – for trees larger than 16" DBH - higher than 60.
3. Quadratic Mean Diameter (QMD) – averaging the diameter of the top 20 trees - toward the higher end.
4. Stand Density Index (SDI) toward the lower end.

Mark stated that these criteria do not allow for the identification of (large) young trees.

5) **Modification of matrix?**

Mark and Randy proposed to continue to refine the criteria and to run several iterations based on:

- Iterations of QMD Top 20 trees

- Iterations of basal area for trees larger than 16”
- Iterations of Site Class (SC) rather than Site Index (SI)
  (Note: SC 1 = SI > 75; SC 2 = 55 < SI < 75; SC 3 = 40 < SI < 55; SC 4 = SI < 40.)
- Binning of acreage based on: Non-MSO; MSO Recovery; MSO PAC

6) Action items / Next meeting & conf call:

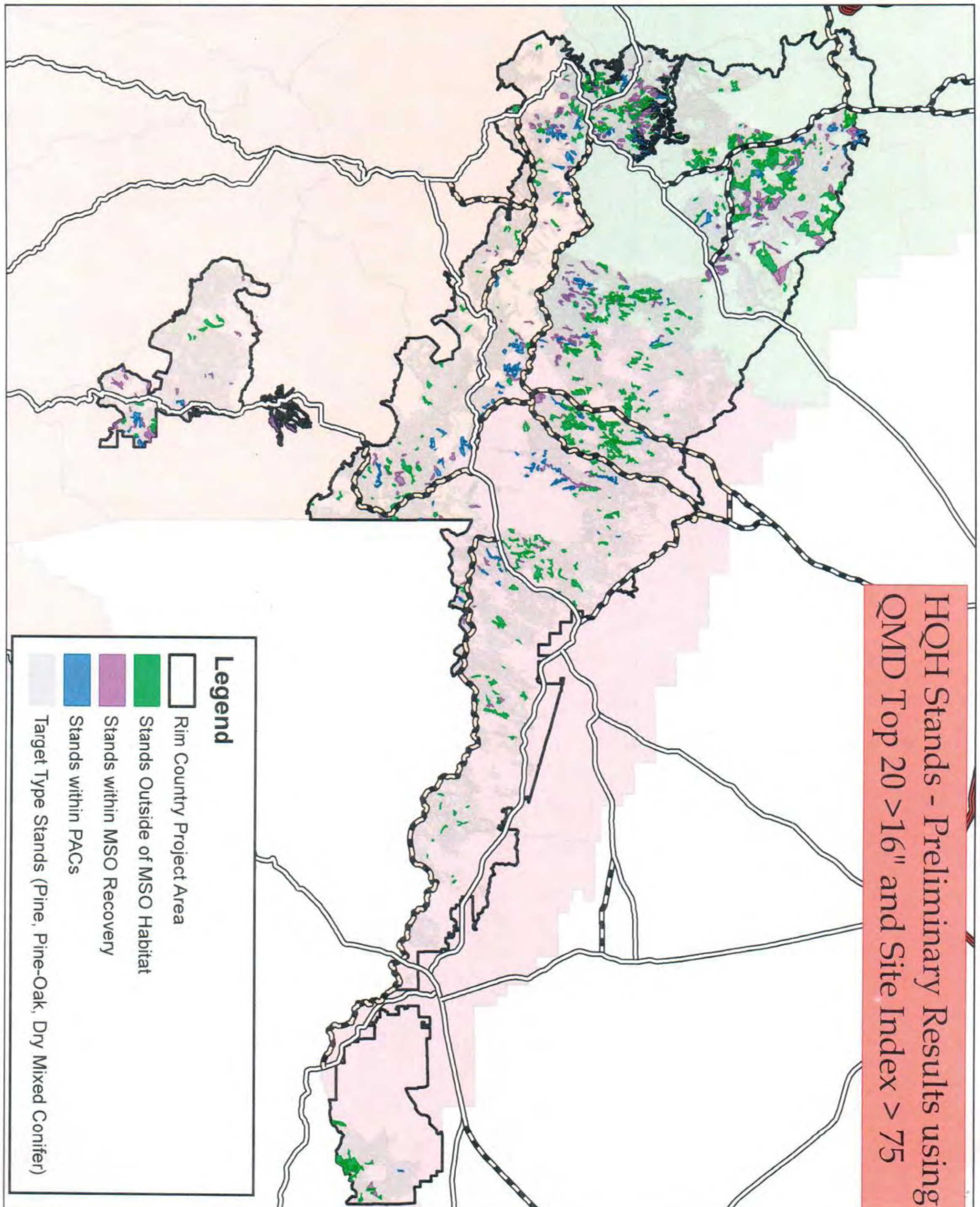
The workgroup agreed that a field trip to several locations identified by the proposed matrix will be necessary to validate the matrix.

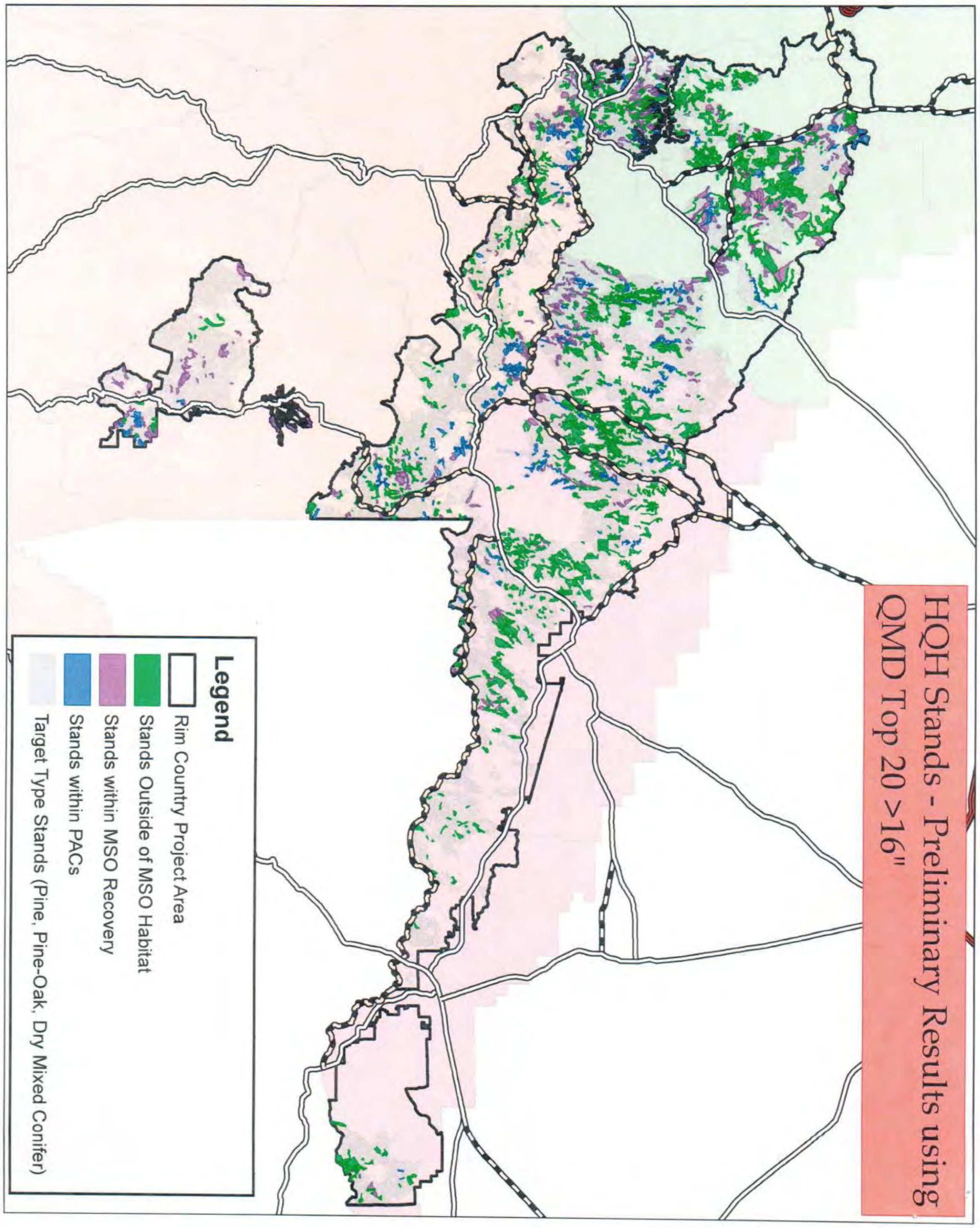
- **Next planned conference call: Thursday September 15, from 2:00 to 3:00 PM.**
- **Next meeting: Wednesday October 5, 10:00 am to 12:00 place TBD.**

Based on a very small sample size (60 Reference and 89 imputed stands) here are the attributes that seem to separate out the stands. The SHG had asked for Site Index, QMD, BA, TPA, SDI. The attributes in **GREEN** seem to have the highest value in isolating these stands. The attributes in **TAN.** The values in **RED** do not help separate out the stands and are should not be encouraged.

Preferred	Let's work around these metrics to see if there are acceptable thresholds.
Secondary	We can look at these to see if they offer any more sensitivity than the green
Don't Use	

Reference + Imputed Stands				Reference Stands Only		
QMD Stand Age	100		For P pine and P pine/Gambel oak use the PP elements only.	QMD Stand Age		
			For MCD use All Trees elements.			
4TPA (PP only)	54.5		Because of the amount of uneven-aged stands, we should use the SDI_SUM figures. There will be more accurate (ask if you don't know why).	4TPA (PP only)	55	
5TPA (PP only)	20.2			5TPA (PP only)	18	
6TPA (PP only)	4.6			6TPA (PP only)	2	
	79.3	AVERAGE			75	Average
TPA > 16" (PP only)	35		Preferred metric	TPA >16" (PP only)	33	
4BA (PP only)	65.2			4BA (PP only)	66	
5BA (PP only)	45.8			5BA (PP only)	41	
6BA (PP only)	19.9			6BA (PP only)	11	
	130.9	Average			118	Average
BA >16" (PP only)	74.5	45% of Total	Preferred metric	PP BA >16"	63	
cc	63.60%	48.90%	Not sensitive: all of our stands are mostly closed canopy	cc	50	
SDI (Rineke)	392	87%	Designed for EVEN-AGED stands only	SDI (Rineke)	414	90%
SDI_Sum (Zeide-Shaw)	275	61%	More accurate for even & uneven-aged stands	SDI_SUM	280	63%
QMD	6.4	all trees	Biased towards the abunance of small trees	QMD	5.9"	All Trees
QMD Top 20 Trees	15.3"		Metric is for ALL TREES	QMD Top 20 Trees	15.5"	All Trees
BA_WT.DIA	16.7"		Indirectly affirms QMD Top 20	BA_WT.DIA	16.4"	
Stand Height	76.5'		Because of the high site index I'd expect this to be higher??? SEE Stand Age	Stand Height	76	
Site Index	83			Site Index	83	
Stand DMR	0.27			Stand DMR	0.2	
Total BA	167			Total BA	173	
ba go>5"	17.4		Not absolute, but an indicator if present	ba go>5"	19	
Storeydness	Not a factor			Storeydness	ss=60%	ms=40%


HQH Stands - Preliminary Results using
QMD Top 20 >16" and Site Index > 75
Legend
Rim Country Project Area
Stands Outside of MSO Habitat
Stands within MSO Recovery
Stands within PACs
Target Type Stands (Pine, Pine-Oak, Dry Mixed Conifer)


HQH Stands - Preliminary Results using QMD Top 20 >16"
Legend
Rim Country Project Area
Stands Outside of MSO Habitat
Stands within MSO Recovery
Stands within PACs
Target Type Stands (Pine, Pine-Oak, Dry Mixed Conifer)

Stands where the QMD of the Top 20 Trees is Greater than 16"	Acres	
	Site Index >=75	Any Site Index
Stands including all MSO habitat	67,719	148,493
Stands excluding PACs	58,551	131,366
Stands excluding all MSO habitat	40,156	95,124

Center for Biological Diversity Post-Logging Rapid Survey

Unit 10, Little Timber Sale, Apache-Sitgreaves National Forests

Prepared by Joe Trudeau for 4FRI-SHG Little Timber Sale tour, 9/25/2018. Revised 10/15/2018.
Direct comments or questions to: jtrudeau@biologicaldiversity.org

Introduction

Between June 30 and July 2, 2018, a Facebook user posted a series of images of large diameter stumps, decks of large and old logs, and other photos and comments that called into question thinning activities underway at the Little Timber Sale on the Apache-Sitgreaves National Forest near Luna Lake, Arizona. In these posts, the author suggested that the public had been 'duped' by the Forest Service's claims that thinning under the Four Forest Restoration Initiative (4FRI) would be focused on small diameter trees. The revelation of these disturbing images of felled old growth and large diameter trees led to a series of visits to the site by a number of 4FRI stakeholders. This includes Center for Biological Diversity staff participating in a field trip to the timber sale with the Forest Service on August 28, 2018. Between August 27 and 31, 2018, Center for Biological Diversity conducted a rapid quantitative survey of a randomly selected unit where thinning had been completed (Unit 10). The purpose was to conclude if old growth was removed, and if so to estimate the amount cut. The methods and results of that survey are presented on the next two pages of this report, and discussed below.

Discussion

An additional field trip to the Little Timber Sale was requested by 4FRI Stakeholders and occurred on September 26, 2018. Approximately 45 Stakeholders and Forest Service employees attended. By request, the fifth stop of the itinerary was at Unit 10, where Center for Biological Diversity presented the results of this survey as well as an interpretation on how these observations fit into a broader - and concerning - narrative within 4FRI; that there appears to be a discernable shift away from core forest restoration principles and methodologies in southwestern ponderosa pine forest restoration, including pushing the boundaries of what has come to be known as the "social consensus" around cutting of large and old trees. The following results of our survey support this concern:

•The stand was thinned below the low end of the desired range. The desired basal are for this unit was 40-60 ft^2/acre, but our results found the units thinned to approximately 36 ft^2/acre. This supports our observation that the Forest Service tends to thin to the low end or below desired density ranges.

• Stump tallies and ring counts showed that more old growth trees (>150 years old) were cut than were retained. Removal of groups of old trees accounted for most of the reduction in this age class, with two 1-acre plots each having twenty probable old growth stumps. Despite Forest Service claims that these were predominantly large young trees, we found concrete evidence that trees well above 200 years old were cut, and that old trees may often be < 18" DBH (see photos on next page). Our sampling indicates that more than 1,300 old growth trees were cut in just this 200-acre unit. Even if our tree aging was 50% wrong, there would still be a very alarming result.

•Large trees were disproportionately targeted for removal, with nearly half of basal area reduction made in trees larger than 18" DBH, and the overall mean diameter of ponderosa pine at the stand level dropped by 2.3". Proportion of small to large trees, as measured by sampling frequency, was maintained pre- to post-logging. These results confirm that thinning was not focused on removal of small diameter trees.

•Stand exam data that we obtained showed that less than 6% of sampled ponderosa pine trees had mistletoe infections that would warrant removal under the stand thinning prescription. That prescription also stated plainly that "the stands have a low infection of dwarf mistletoe in the ponderosa pine." While is it difficult to determine the level of mistletoe infection of removed trees, our observations suggested that old tree removal was more focused on basal area reduction than severe disease infection. Based on our field survey results, target basal area of 40-60 ft^2/acre could have been met even without cutting any old trees at all.

Conclusion

Though the West Escudilla project was authorized under a separate NEPA analysis, it is part of 4FRI, being counted toward restoration targets within the 4FRI umbrella. The Center considers the observations reported here to be a troubling departure from Stakeholder-developed guidance for protection of large and old trees.

Center for Biological Diversity Post-Logging Rapid Survey (page 2)

Unit 10, Little Timber Sale, Apache-Sitgreaves National Forests

Prepared by Joe Trudeau for 4FRI-SHG Little Timber Sale tour, 9/25/2018. Revised 10/15/2018.

Inventory Specifications

18 plot centers located on August 27 and 31, 2018.
At each point, data from 3 plots were recorded:

Plot a) 10-factor prism

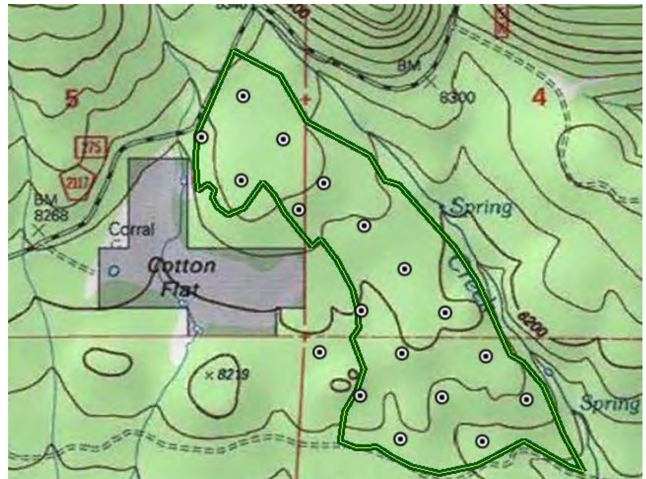
- in/out tally to determine basal area

Plot b) $1/10^{th}$ acre fixed radius (37.2' radius)

- tree status (live, snag, stump), species, and DBH
- random sample first tree from North: determine age and record diameter at stump height

Plot c) 1 acre fixed radius (117.8' radius)

- tallied live trees of all species over 4.5' tall
- tallied live old growth (>150 years) and recent cut old growth stumps



Plots located on 10-chain grid (660'). One plot was moved due to fenceline and edge of unit.

Live Tree Results

Plot a) 10-factor prism (generous with "in" trees, no limiting distances checked)

- basal area: **37.8 ft^2/acre** (includes all species, any tree over 4.5' tall)

Plot b) $1/10^{th}$ acre fixed radius (37.2' radius)

- 139 sample trees measured: PIPO (n=71), QUGA (n=67); JUDE (n=1)
- PIPO basal area: **30.5 ft^2/acre**
- All species basal area: **33.7 ft^2/acre** (~10% of BA in QUGA)
- 16 of 18 plots had live PIPO trees (~10% in "regen openings")
- PIPO basal area excluding 2 plots with no live trees (exclude "regen openings"): **34.3 ft^2/acre**
- Trees/acre: **39.4 TPA** (PIPO), 77 TPA (all species >4.5' tall)
- Average diameter of live trees (all species): 7.1"
- Average diameter of live trees (PIPO only): 10.3"
- Average age of sample tree: 117 years
- Tree taper ratio: 0.8227 (DBH/DSH on first sample tree)

mean BA=35.75 ft^2/acre

Plot c) 1 acre fixed radius (117.8' radius)

- Average TPA Tally: 50.4 trees per acre (includes all species, any tree over 4.5' tall)
- 103 likely live old growth trees tallied (3 top plots account for over 50% of total)
- 118 likely old growth stumps tallied (3 top plots account for nearly 50% of total)

Cut Tree Results (recent stumps on 1/10 acre plot, DBH estimated by applying site-specific taper ratio)

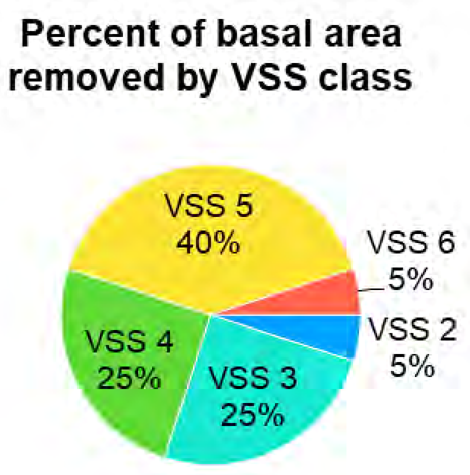
- 72 sample stumps measured (does not include stumps predating the Little sale)
- Average diameter at stump height (DSH) of recent cut trees 14.6"
- Estimated average DBH of recent cut trees 12.2"
- Estimated 37 ft^2/acre removed by recent thinning
- 18% of total trees and 45% of basal area removed was in VSS5 and VSS6 trees
- 1 snag recorded across all 18 plots (Forest Plan DC's aims for 2 snags/acre)

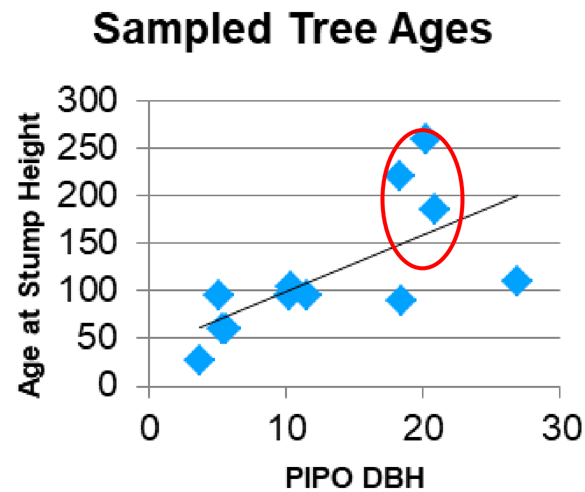
Center for Biological Diversity Post-Logging Rapid Survey (page 3)

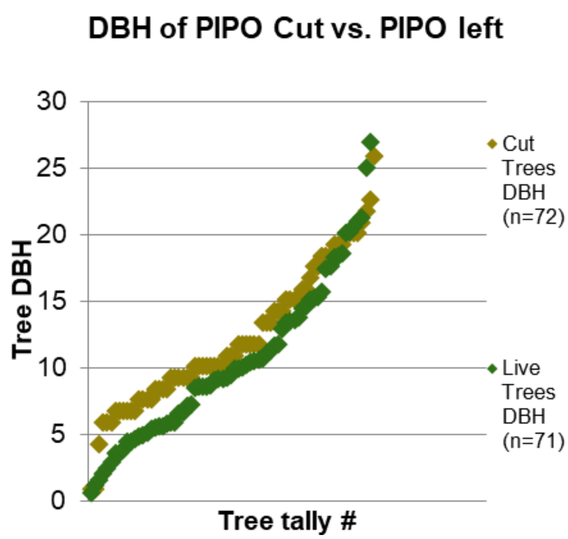
Unit 10, Little Timber Sale, Apache-Sitgreaves National Forests

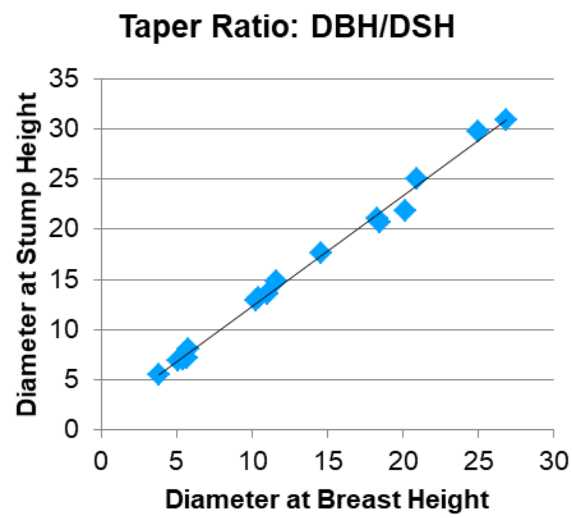
Prepared by Joe Trudeau for 4FRI-SHG Little Timber Sale tour, 9/25/2018. Revised 10/15/2018.

Supplemental Information









16" DSH (13.2" DBH)
230 years old at stump via ring count

22" DSH (18" DBH)
170 years old at stump via increment borer

26" DSH (21.3" DBH)
6" DBH leave tree has DMR score of 5

Center for Biological Diversity Post-Logging Rapid Survey (page 4)

Unit 10, Little Timber Sale, Apache-Sitgreaves National Forests

Prepared by Joe Trudeau for 4FRI-SHG Little Timber Sale tour, 9/25/2018. Revised 10/15/2018.

Supplemental Photos

Four 170-year old stumps (one not visible) surround a suppressed 6” DBH tree that is more than 60 years old. It is extremely unlikely that the old growth trees were severely infected with mistletoe while the small tree was uninfected.

Center for Biological Diversity Post-Logging Rapid Survey (page 5)

Unit 10, Little Timber Sale, Apache-Sitgreaves National Forests

Prepared by Joe Trudeau for 4FRI-SHG Little Timber Sale tour, 9/25/2018. Revised 10/15/2018.

Supplemental Photos

A 36"diameter ponderosa pine stump, approximately 160 years old. At the cusp of being a large young tree, this tree was presumably removed because of heart rot, likely visible in a broken top. Such trees are valued wildlife habitat.

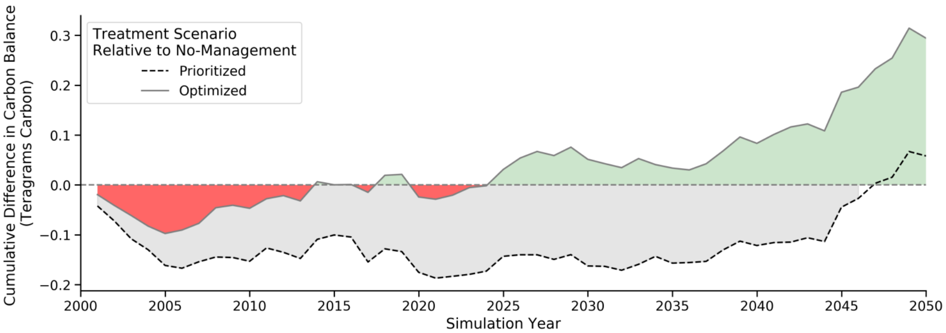
Supplemental Photos

A tree that, based on bark character, was undeniably an old growth tree. As open as this area is, it's hard to reconcile that the tree had to be removed to meet restoration objectives. Nearby old trees showed no signs of mistletoe infection.

Supplemental Photos

A 32" diameter stump, aged at >160 years old, in the most aggressively thinned portion of Unit 10. The West Escudilla EA defined old trees as those >150 years, and claimed that removal would be rare except in cases of severe mistletoe. Inspection of slash piles failed to reveal troves of mistletoe infected branches.

Earth Systems Ecology Lab



Cumulative net ecosystem carbon balance (NECB) of the prioritized (dashed black) and optimized (solid gray) scenarios, relative to the no-management scenario (0 line). Positive values indicate the landscape is taking-up more carbon than the no-management scenario. NECB accounts for carbon up-take by plants, losses from thinning, and emissions from prescribed fire and wildfire

Optimal Treatment Placement Reduces High-Severity Wildfire Risk with Less Area Thinned

Hotter, larger wildfires are becoming commonplace in the Western US and the area burned is likely to increase with additional climate warming. This is exacerbating the forest conditions that have resulted from a century of fire suppression. Restoring regular surface fires often requires first implementing expensive mechanical treatments. Given the size of the area in need of restoration treatments, optimally allocating treatments is a necessity. We ran simulations of the Santa Fe Fireshed to understand how optimizing mechanical treatment placement based on the risk of high-severity wildfire could reduce the frequency of high-severity wildfire and carbon losses under projected climate change and more severe fire weather.

We found that mechanically treating areas with the highest risk of high-severity wildfire and using prescribed fire to treat the unthinned areas (optimized scenario), we could reduce the area mechanically treated when all operable areas were thinned (prioritized scenario) by 54%. This outcome required a 27% increase in the area treated with prescribed burning. Both scenarios reduced high-severity wildfire when compared to the no-management scenario, as well as a significant reduction in wildfire carbon emissions. However, the optimized scenario did so at a considerable carbon savings in the short term, yielding a significant reduction in carbon lost from the system (see figure). Both of our scenarios achieved a reduction in high-severity fire and stabilized the remaining carbon. However, in both the management scenarios, maintaining carbon stability under changing climate and increasingly severe fire weather was contingent on the regular application of prescribed fire at return intervals that are consistent with historic fire regimes.

Management Implications

Prioritizing the allocation of thinning treatments to areas with the greatest chance of burning under high-severity wildfire and treating the rest of the landscape with prescribed burning, can substantially reduce the area requiring thinning.

Optimally locating thinning treatments can result in greater carbon storage across the landscape, with less risk of stand-replacing wildfire. The benefits of treatment optimization persist even as fire weather becomes more severe with changing climate.

Restoring high-frequency fire regimes is critical for reducing the risk of high-severity wildfire and stabilizing carbon.

Publication:

Krofcheck DJ, CC Remy, AR Keyser, MD Hurteau. 2019. Optimizing forest management stabilizes carbon under projected climate and wildfire. JGR Biogeosciences, doi:10.1029/2019JG005206.

Funded by: USDA NIFA & New Mexico State Chapter of The Nature Conservancy

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United States Department of Agriculture

National Institute of Food and Agriculture

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FOREST SERVICE HANDBOOK
ROCKY MOUNTAIN REGION (REGION 2)
DENVER, CO

FSH 2509.25 – WATERSHED CONSERVATION PRACTICES HANDBOOK

CHAPTER 10 – MANAGEMENT MEASURES AND DESIGN CRITERIA

Amendment No.: 2509.25-2006-2

Effective Date: May 5, 2006

Duration: This amendment is effective until superseded or removed.

Approved: RICK D. CABLES
Regional Forester

Date Approved: 04/20/2006

Posting Instructions: Amendments are numbered consecutively by Handbook number and calendar year. Post by document; remove entire document and replace with this amendment. Retain this transmittal as the first page(s) of this document. The last amendment to this Handbook was 2509.25-2006-1 to 2509.25 Zero Code.

New Document(s):	2509.25_10	29 Pages
Superseded Document(s) by Issuance Number and Effective Date	2509.25_10_contents (Amendment 2509.25-96-1, 12/26/1996) 2509.25_10 (Amendment 2509.25-2001-1, 12/18/2001)	1 Page 23 Pages

Digest:

11.1 – Revises the caption from “Standard” to “Management Measure”. Adds explanation regarding managing changes in streamflow from natural and anthropogenic disturbance. Adds direction for minimizing Connected Disturbed Areas.

11.2 – Revises the caption from “Standard” to “Management Measure”. Revises direction to manage ground cover in an “activity area” rather than a “land unit”. Adds direction that amount of ground cover needed is commensurate with site potential.

12 – Revises the caption from “Riparian Areas” to “Riparian Areas and Wetlands”.

Digest continued:

12.1 – Revises the caption from "Standard" to "Management Measure". Revises direction for management of livestock grazing in riparian areas and wetlands. Adds direction to emphasize natural processes when restoring streambanks.

12.2 – Revises the caption from "Standard" to "Management Measure". Adds direction that certain situations may require an exception to direction to provide free movement of aquatic life at stream crossings.

12.3 – Revises the caption from "Standard" to "Management Measure". Removes direction to manage toward "robust stream health", but rather to "maintain or improve long-term stream health".

12.4 – Revises the caption from "Standard" to "Management Measure". Removes reference to "404 regulations" in the Management Measure.

12.5 – Revises the caption from "Standard" to "Management Measure". Revises direction from "Return and/or maintain sufficient" to "Manage" stream flows.

12.6 – Revises the caption from "Standard" to "Management Measure". Revises direction for mitigation of water imports to include water disposal and to "maintain or improve long-term stream health" from "is at least 80% of reference conditions". Adds direction for maintenance and operation of water conveyance ditches and pipelines. Adds direction for snow management.

13.1 – Revises the caption from "Standard" to "Management Measure". Revises direction for ground skidding to avoid "sustained" slopes steeper than 40% and "moderate to severely burned sustained slopes greater than 30%". Adds direction to retain drainages and remove outside berms on outsloped roads. Adds direction for location and construction of log landings.

13.2 – Revises the caption from "Standard" to "Management Measure".

13.3 – Revises the caption from "Standard" to "Management Measure". Adds direction regarding operation and maintenance of roads in the winter to protect water quality from de-icers and sedimentation. Adds direction for road surface stabilization and dust abatement to protect water quality.

13.4 – Revises the caption from "Standard" to "Management Measure". Adds direction to restore cuts and fills to the original slope contours where practicable. Adds direction to establish effective ground cover on disturbed sites.

14 – Revises the caption from "Soil Productivity" to "Soil Quality".

Digest continued:

14.1 – Revises the caption from "Standard" to "Management Measure". Revises direction from "limit the sum of severely burned and detrimentally compacted, eroded, and displaced land to no more than 15% of any land unit" to "limit the sum of severely burned soil and detrimentally compacted, eroded, and displaced soil to no more than 15% of any activity area". Removes reference to wildfire and adds emphasis on restoration to the explanation of the Management Measure. Adds direction to consider snow depths when managing dispersed winter motorized recreation.

14.2 – Revises the caption from "Standard" to "Management Measure". Revises direction for slash retention in harvest units to protect soil quality.

15.1 – Revises the caption from "Standard" to "Management Measure". Adds direction for location of temporary camps to protect water quality.

15.2 – Revises the caption from "Standard" to "Management Measure". Adds direction to prepare Spill Prevention Control and Countermeasure Plans for vehicle service and refueling areas, chemical storage and use areas, and waste dumps. Adds direction to require removal or encapsulation of mine waste material before site reclamation is accepted as final. Adds direction to prevent contaminated runoff from mine waste dumps and tailings piles from reaching surface or ground water. Adds direction to report and clean-up spills in accordance with applicable state and federal laws, rules and regulations.

15.3 – Revises the caption from "Standard" to "Management Measure".

Table of Contents

Management measures are environmental goals to protect soil, aquatic, and riparian systems. Design criteria are specific practices to attain the management measures using current knowledge and technology. Notes following the design criteria cite the effectiveness of the design criteria. The five areas covered are hydrologic function, riparian areas and wetlands, sediment control, soil quality, and water purity.

A 1985 agreement between the Forest Service and the Environmental Protection Agency mandated the Water Resource Evaluation of Nonpoint Silvicultural Sources (WRENSS) as official guidance to control nonpoint sources of water pollution. Its controls were used to construct many management measures and design criteria. Others are adapted from Federal and State BMPs and work of other Regions and agencies. "Best Management Practices" are, by definition, the most effective, practicable means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals (CDPHE, 2001; WY DEQ, 2001).

11 - HYDROLOGIC FUNCTION

Hydrologic function is the ability of a watershed to infiltrate precipitation and naturally regulate runoff so streams are in dynamic equilibrium with their channels and floodplains. Management measures and design criteria to protect hydrologic function apply to all actions that may impact the "sponge and filter" qualities of watersheds. Hydrologic function is protected by maintaining good vegetation and ground cover and by minimizing connected disturbed areas.

11.1 - Management Measure (1)

Manage land treatments to conserve site moisture and to protect long-term stream health from damage by increased runoff.

Land treatments that reduce the evapotranspiration of a watershed or reduce the ability of the watershed to infiltrate and store water will result in an increase in runoff. Land treatments should be implemented in consideration of the ability of the stream to absorb increases in runoff given the effects of the proposed activity in conjunction with other natural or anthropogenic disturbances in the watershed. The ability of a particular stream to be able to accommodate increases in runoff and sediment transport without being damaged depends upon stream type, past disturbances and current stream condition.

Any disturbance that reduces the density of live vegetation cover will increase runoff from forested watersheds. These disturbances can be natural, such as a wildfire or insect and disease outbreaks, or anthropogenic like timber harvest or fuels treatments. In snow dominated areas, flow increases occur mostly during spring runoff on the rising limb of the hydrograph, and are not measurable until about 25 percent of the basal area of a forested watershed is affected. The increase in the size of peak flows is proportional to the amount of basal area affected. However, any reduction in forest cover will have a progressively smaller effect on peak flows with increasing flow magnitude or recurrence interval. Also, increases in runoff are generally proportional to annual precipitation, that is, greater increases occur in wetter areas. And, the increase in runoff declines over time with vegetation regrowth. Conversely, large openings (opening diameter greater than 15 times the height of surrounding trees) can be subjected to snow scour that can actually reduce site moisture and runoff. (EPA, 1980; MacDonald and Stednick, 2003; Ice and Stednick, 2004).

Increased runoff and sediment caused by soil disturbances are the major source of stream impacts. Roads and other soil disturbances can impair the ability of the land to absorb water and filter sediment. Roads, soil disturbances and vegetation treatments can increase small peak flows and channel erosion, but stream health is not damaged if watershed conservation practices are used. Connected disturbed areas are the main source of damage in all regions (Jones and Grant 1996; Troendle and Olsen 1994; Ziemer 1981).

1. Design Criteria.

a. In each watershed containing a 3-rd order and larger stream, limit connected disturbed areas so the total stream network is not expanded by more than 10%. Progress toward zero connected disturbed area as much as practicable. Where it is impossible or impracticable to disconnect a particular connected disturbed area, minimize the areal extent of the individual connected disturbed area as much as practicable. In watersheds that contain stream reaches in diminished stream health class, allow only those actions that will maintain or reduce watershed-scale Connected Disturbed Area.

NOTE: Connected disturbed areas discharge surface water into streams singly or in combination; this measure avoids stream damage from peak flows (Wemple 1994). Stream order is based on the total network of all streams.

b. Design the size, orientation, and surface roughness (that is. slash and other features that would trap and hold snow on site) of forest openings to prevent snow scour and site desiccation.

NOTE: WRENSS (III.12 through III.19).

2. Monitoring. Check size and orientation of openings, extent of connected disturbed areas, and stream health (channel widths-depths, substrate, bank stability) of sensitive stream reaches.

3. Restoration. Disconnect disturbed areas from stream networks. Reclaim areas that contribute to excessive runoff and peak flows. Revegetate using certified local native plants as practicable; avoid persistent or invasive exotic plants.

11.2 - Management Measure (2)

Manage land treatments to maintain enough organic ground cover in each activity area to prevent harmful increased runoff.

Organic ground cover (plants, litter, and humus) is vital to maintain hydrologic function. Reduced ground cover decreases infiltration of water and increases surface runoff and peak flows. Continued or severe loss of ground cover often results in the formation of pedestals, rills, and gullies that greatly concentrate runoff, increase peak flows, and damage streams.

1. Design Criteria.

   a. Maintain the organic ground cover of each activity area so that pedestals, rills, and surface runoff from the activity area are not increased. The amount of organic ground cover needed will vary by different ecological types and should be commensurate with the potential of the site.

      NOTE: Such ground cover allows for prescribed fire and site preparation without increasing surface runoff from a 10-year storm (WRENSS II.60; USFS 1966).

   b. Restore the organic ground cover of degraded activity areas within the next plan period, using certified local native plants as practicable; avoid persistent or invasive exotic plants.

      NOTE: Field studies show this to be a reasonable recovery period over a wide range of environments to bring each activity area into compliance.

2. Monitoring. Observe evidence of pedestals, rills, and surface runoff. Compare average organic ground cover of treated activity areas with reference areas, using ocular methods, rooted nested frequency method, cover-frequency method (USFS, 1996a), soil pedon data, pace transects, or other accepted monitoring methods.

3. Restoration. Apply watershed restoration along with land-use controls on degraded lands to disperse runoff and restore organic ground cover with minimum long-term maintenance needs. Reclamation treatments and changes in management may be required. Revegetate using certified local native plants as practicable; avoid persistent or invasive exotic plants.

12 - RIPARIAN AREAS AND WETLANDS

Vegetation next to water bodies plays a major role in sustaining the long-term integrity of aquatic systems (Hynes 1970; Odum 1971). Values provided include shade, bank stability, fish cover, woody debris input, storage and release of sediment, surface-ground water interactions, and habitat for terrestrial and aquatic plants and animals. Riparian zones and wetlands must be managed with care to protect these values.

12.1 - Management Measure (3)

In the water influence zone next to perennial and intermittent streams, lakes, and wetlands, allow only those actions that maintain or improve long-term stream health and riparian ecosystem condition.

The water influence zone (WIZ) includes the geomorphic floodplain (valley bottom), riparian ecosystem, and inner gorge. Its minimum horizontal width (from top of each bank) is the greater of 100 feet or the mean height of mature dominant late-seral vegetation. The WIZ protects interacting aquatic, riparian, and upland functions by maintaining natural processes and resilience of soil, water, and vegetation systems (Reid and Ziemer 1994).

1. Design Criteria.

   a. Allow no action that will cause long-term change to a lower stream health class in any stream reach. In degraded systems (that is At-risk or Diminished stream health class), progress toward robust stream health within the next plan period.

      NOTE: Assess impacts of existing and proposed land treatments in the field before projects begin. Light treatments usually protect stream integrity (WRENSS II.65).

   b. Allow no action that will cause long-term change away from desired condition in any riparian or wetland vegetation community. Consider management of stream temperature and large woody debris recruitment when determining desired vegetation community. In degraded systems, progress toward desired condition within the next plan period.

      NOTE: Desired vegetation condition supports robust stream health (USFS 1996a).

   c. Keep heavy equipment out of streams, swales, and lakes, except to cross at designated points, build crossings, or do restoration work, or if protected by at least 1 foot of packed snow or 2 inches of frozen soil. Keep heavy equipment out of streams during fish spawning, incubation, and emergence periods.

      NOTE: This measure sustains stream and lake integrity (WRENSS II.60).

   d. Ensure at least one-end log suspension in the WIZ. Fell trees in a way that protects vegetation in the WIZ from damage. Keep log landings and skid trails out of the WIZ, including swales.

      NOTE: This measure sustains stream and riparian integrity (WRENSS II.58).

e. Locate new concentrated-use sites outside the WIZ if practicable and outside riparian areas and wetlands. Armor or reclaim existing sites in the WIZ to prevent detrimental soil and bank erosion.

NOTE: WRENSS (II.62), armored water-dependent facilities are excepted.

f. Manage livestock use through control of time/timing, intensity, and duration/frequency of use in riparian areas and wetlands to maintain or improve long-term stream health. Exclude livestock from riparian areas and wetlands that are not meeting or moving towards desired condition objectives where monitoring information shows continued livestock grazing would prevent attainment of those objectives.

g. Keep stock tanks, salt supplements, and similar features out of the WIZ if practicable and out of riparian areas and wetlands always. Keep stock driveways out of the WIZ except to cross at designated points. Armor water gaps and designated stock crossings where needed and practicable.

NOTE: This measure avoids much serious bank damage (Clary and Webster 1989).

h. Manage dry meadow and upland plant communities, including Kentucky bluegrass types, that have invaded into wetland/riparian areas in a manner that will contribute to their replacement over time by more mesic native plant communities to the extent practicable. Develop site-specific riparian stubble height standards or use the following default levels for carex and juncos species: 3-4 inches in spring-use pastures and 4-6 inches in summer or autumn use pastures; to leave adequate residual stubble height to retain effective ground cover.

NOTE: Clary and Webster (1989); USFS (1995); USFS (1996a). Riparian areas with no carex and juncos (for example bluegrass, tufted hairgrass, and so forth) require local stubble heights.

i. Do not allow livestock grazing through an entire growing season in pastures that contain in riparian areas and wetlands. Apply short-duration grazing as practicable (generally less than 20 days) to minimize re-grazing of individual plants, to provide greater opportunity for regrowth and to manage utilization of woody species and reduce soil compaction. During the hot season (mid-to-late summer) manage livestock herds to avoid concentrating in riparian areas and wetlands. Apply principles of the Grazing Response Index to livestock management (USFS, 1996a).

NOTE: USFS (1995).

j. Design grazing systems to limit utilization of woody species. Where woody species have been historically suppressed, or where the plant community is below its desired condition and livestock are a key contributing factor, manage livestock through control of time/timing, intensity, and duration/frequency of use so as to allow for riparian hardwood growth extension and reproduction. Manage woody species in riparian areas to provide for stream temperature, bank stability and riparian habitat.

NOTE: USFS (1995).

k. Maintain the extent of stable banks in each stream reach at 74% or more of reference conditions. Consider degree of livestock trampling and riparian vegetation utilization on or immediately adjacent to stream banks when timing livestock moves between units.

NOTE: USFS (1996a).

l. Adjust management in riparian areas and wetlands to improve detrimental soil compaction whenever it occurs.

NOTE: Hummocking and platy surface soil structure are good indicators of soil compaction if more detailed sampling is not available (BLM 1993, 1994; FSH 2509.18).

m. Do not excavate earth material from, or store excavated earth material in, any stream, swale, lake, wetland, or WIZ.

NOTE: Field studies show such actions can severely damage stream health.

n. Emphasize natural stabilization processes consistent with the stream type and capability (Rosgen and Proper Functioning Condition processes) when restoring damaged stream banks. Use native vegetation for stream bank stabilization whenever practicable.

2. Monitoring. Monitor streambeds and banks, aquatic habitat and biota, soil structure, and riparian vegetation composition and structure.

3. Restoration. Avoid new disturbance until vegetation recovers. Stabilize stream and lake banks with certified local native plants as practicable; avoid persistent or invasive exotic plants. Restore aquatic habitat. Relocate heavy-use sites. Disconnect or armor disturbed areas. Rest degraded areas from disturbance if needed.

12.2 - Management Measure (4)

Design and construct all stream crossings and other instream structures to provide for passage of flow and sediment, withstand expected flood flows, and allow free movement of resident aquatic life.

Corps of Engineers and Forest Service design criteria are combined to ensure that all facilities remain stable, not necessarily pass the entire flood flow. Structures must sustain long-term channel integrity, pass design flows with expected debris or be armored to withstand the design flood (not wash out) during their design life, and allow unimpeded movement of aquatic life.

Culverts often concentrate flow and increase depth and velocity to a maximum just before spilling onto the streambed. Scour pools are common below outlets and migration can be impaired if water velocity or drop is excessive. Check crossings for problems and repair them if needed.

The need for providing passage for aquatic life or creating a barrier to movement is determined on a site-specific basis. In general, in-stream structures should provide for unimpeded movement of resident aquatic life. However, in certain situations, such as to protect a genetically pure population of native fish or other aquatic species, there may be a need to restrict passage.

1. Design Criteria.

a. Install stream crossings to meet Corps of Engineers and State permits, pass normal flows, and be armored to withstand design flows.

b. Size culverts and bridges to pass debris. Engineers work with hydrologists and aquatic biologists on site design.

NOTE: WRENSS (II.61, II.65).

c. Install stream crossings on straight and resilient stream reaches, as perpendicular to flow as practicable, and to provide passage of fish and other aquatic life.

NOTE: Maintaining channel geometry and hydraulics protects fish passage (WRENSS II.60; Baker and Votapka 1990).

d. Install stream crossings to sustain bankfull dimensions of width, depth, and slope and keep streambeds and banks resilient. Favor bridges, bottomless arches or buried pipe-arches for those streams with identifiable flood plains and elevated road prisms, instead of pipe culverts. Favor armored fords for those streams where vehicle traffic is either seasonal or temporary, or the ford design maintains the channel pattern, profile and dimension.

NOTE: Temporary bridges or vented fords (fords with pipes to pass low flows) are potential options where appropriate depending upon traffic use. Temporary bridges should be installed and removed seasonally. Temporary fords should be removed when the need for the crossing no longer exists. Pipe culverts pose the most risk of channel damage, migration blockage, and sediment, while fords can impact incised channels (WRENSS II.57; Terrene Institute 1994; Bohn 1998).

e. Install or maintain fish migration barriers only if needed to protect endangered, threatened, sensitive, or unique native aquatic populations, and only where natural barriers do not exist.

NOTE: Many barriers have disrupted natural distributions of fish populations.

2. Monitoring. Check stability and grade of crossings, capacity of channels, sediment deposits in streambeds, and ability of aquatic biota to pass (40 CFR 230.23 and 230.31).

3. Restoration. Replace problem culverts with bridges, fords, or arches to provide bed and bank stability and movement of aquatic life.

12.3 - Management Measure (5)

Conduct actions so that stream pattern, geometry, and habitats maintain or improve long-term stream health.

Stream health depends much on channel widths and depths, bank stability, and quality of cover and substrate. In-channel work can directly impact stream channel morphology. Other actions, such as snowmaking or water depletions, can indirectly affect channel morphology by changing (either increasing or decreasing) flow.

1. Design Criteria.

a. Add or remove rocks, wood, or other material in streams or lakes only if such action maintains or improves stream and lake health. Leave rocks and portions of wood that are embedded in beds or banks to prevent channel scour and maintain natural habitat complexity.

NOTE: Structural complexity provided by rocks, wood, and other elements is vital to maintain channel resilience and habitat features for aquatic biota. Excessive input or removal can damage stream health (Dunne and Leopold 1978, page 709).

b. Do not relocate natural stream channels if avoidable. Return flow to natural channels where practicable. Where reconstruction of stream channels is necessary, construct channels and floodways with natural stream pattern and geometry, stable beds and banks and provide habitat complexity.

NOTE: Dunne and Leopold (1978, page 709).

2. Monitoring. Monitor channel pattern, geometry, and stability; migration barriers; and aquatic habitat and biota.

3. Restoration. Restore degraded streams to robust stream health with minimum long-term maintenance needs, as part of whole watershed restoration programs that permanently cure causes of damage. Install or remove rocks, wood, or other structures only as a last resort to restore robust stream health. Plant certified local native plants, as practicable, to restore bank stability and cover; avoid persistent or invasive exotic plants.

12.4 - Management Measure (6)

Maintain long-term ground cover, soil structure, water budgets, and flow patterns of wetlands to sustain their ecological function.

Wetlands control runoff and water quality, recharge ground water, and provide abundant and diverse biota. Natural patterns and processes must be protected. Executive Order 11990 directs that impacts to wetlands should be avoided, minimized or mitigated where practicable. The Corps of Engineers protects wetlands under Section 404 regulations, which may permit wetland impacts if mitigation measures are applied to replace wetland values in-kind.

1. Design Criteria.

a. Keep ground vehicles out of wetlands unless protected by at least 1 foot of packed snow or 2 inches of frozen soil. Do not disrupt water supply or drainage patterns into wetlands.

NOTE: Field studies show this measure protects soil structure and water regimes.

b. Keep roads and trails out of wetlands unless there is no other practicable alternative. If roads or trails must enter wetlands, use bridges or raised prisms with diffuse drainage to sustain flow patterns. Set crossing bottoms at natural levels of channel beds and wet meadow surfaces. Avoid actions that may dewater or reduce water budgets in wetlands.

NOTE: Terrene Institute (1994).

c. Avoid long-term reduction in organic ground cover and organic soil layers in any wetland (including peat in fens).

NOTE: Field studies show this measure protects vital ecological functions.

d. When practicable, keep buried utility and pipelines out of wetlands. If such a line must enter a wetland, use measures that sustain long-term wetland function.

NOTE: This measure is needed to avoid subsurface wetland damage.

e. Avoid any loss of rare wetlands such as fens and springs.

NOTE: These wetlands cannot be replaced in-kind.

f. Do not build firelines in or around wetlands unless needed to protect life, property, or wetlands. Use hand lines with minimum feasible soil disturbance. Use wetland features as firelines if practicable.

NOTE: This measure protects drainage patterns and prevents fireline scars that are often slow to heal in wetlands (USFS 1990, page II-51).

2. Monitoring. Monitor integrity of organic ground cover and organic soil layers, plant community composition and structure, soil structure, water levels, and drainage patterns.

3. Restoration. Retrofit crossings to restore water levels and drainage (Terrene Institute 1994). Reclaim wetlands to restore physical and biological functions. Revegetate using certified local native plants as practicable; avoid persistent or invasive exotic plants.

12.5 - Management Measure (7)

Manage stream flows under appropriate authorities to minimize damage to scenic and aesthetic values, fish and wildlife habitat, and to otherwise protect the environment.

Aquatic ecosystems make up only about 5% of the NFS lands in the Region, but almost half of the imperiled species are aquatic dependent. Stream flow regimes are critical to maintaining stream processes, aquatic life and habitat. Work to protect current stream flow dependent water uses and improve conditions in perennial streams where stream flow regimes have been altered.

Streamflow protection may be a condition of permitting occupancy and use of NFS lands. Cooperation with water users and others is necessary to ensure appropriate resource protection while meeting the needs of people who have valid existing water rights. State instream flow programs will be used where possible when they meet NFS needs.

1. Design Criteria.

a. Cooperate with water users and other interested parties to evaluate how to operate existing water use facilities to meet resource goals.

b. Obtain stream flows under appropriate federal and state, legal and regulatory authorities to protect stream processes, aquatic and riparian habitats and communities, and recreation and aesthetic values. Top priority is to protect imperiled native species. Generally, this will include a range of flows to support desired uses and values.

c. Upon issuance of special use authorizations for new or existing water use facilities, include permit conditions at the point of diversion or storage, if needed, to minimize impacts to water dependent resources and values. One or more of the following circumstances may be present in any given project. Water dependent resources and values not included on this list may require additional consideration.

(1) When managing for physical stream processes, including channel maintenance, evaluate each stream on which a project is planned to ascertain what flows represent the amounts and timing needed to sustain these functions. Essential attributes of a properly functioning self-maintaining channel include providing for flows to achieve the following:

(a) Move the mass and sizes of alluvial sediment supplied to the channel.

(b) Maintain channel capacity by preventing terrestrial vegetative growth in the bed of the channel.

(c) Protect and sustain channel banks and the floodplain by maintaining healthy streamside vegetation.

(d) Maintain processes that sustain the relationship between the channel and the floodplain.

(2) When managing for aquatic biota and their habitat, evaluate each stream upon which a project is planned to ascertain what flows represent the amounts and timing needed to sustain viability of existing populations of native and desired non-native vertebrate species**.** Essential flow related attributes of sustainable habitat should achieve the following:

(a) Maintain the physical, biological, and chemical processes necessary for all life-history stages of identified species and communities.

(b) Minimize the impact of dams and diversion structures on the interaction between populations.

(c) Return flows to historic habitat where reintroduction potential exists.

(3) When managing for riparian habitat and communities, evaluate each stream upon which a project is planned to ascertain what flows and timing are needed to maintain or improve riparian habitat and community structure and function. These flows should be adequate to:

(a) Maintain the physical, biological, and chemical processes necessary to ensure the sustainability and ecological integrity of identified species and communities.

(b) Maintain the magnitude, variability, and frequency of disturbance processes that affect community structure and function.

(4) When managing for aesthetic and recreational values, evaluate each stream upon which a project is planned to ascertain what flows and timing represent the amounts and period needed to sustain these values. These flows should be adequate to:

(a) Support flow dependent recreation uses (for example, rafting, kayaking, swimming).

(b) Maintain desired populations of fish species to provide for appropriate recreational experiences.

(c) Provide water for aesthetic enjoyment.

(d) Support special designations, including Wild and Scenic Rivers, where flowing water is critical to the purpose and quality of the designation.

d. Obtain water rights under federal and state law to protect stream processes, aquatic and riparian habitats and communities, and recreation and aesthetic values. Top priority is to protect imperiled native species.

NOTE: FSM 2540

2. Monitoring. Monitor stream flow, stream health, and riparian condition.

3. Restoration. In cases of noncompliance with permit conditions, pursue suspension or revocation provisions contained in the authorization. Explore joint operation plans for related water facilities to protect instream values with least impact to water users.

12.6 - Management Measure (8)

Manage water-use facilities to prevent gully erosion of slopes and to prevent sediment and bank damage to streams.

Clean Water Act Section 304(f)(2) addresses control of pollution caused by dams and flow diversion facilities. Facilities include diversion and discharge structures, ditches, and pipes. Other activities, such as coal-bed methane production or snowmaking at ski areas, can generate large volumes of water that may exceed the assimilative capacity of receiving streams. Protect slope, stream stability and aquatic habitat as much and as early as practicable (Section 319(a)).

1. Design Criteria.

a. Design all ditches, canals, and pipes with at least an 80% chance of passing high flows and remaining stable during their life.

NOTE: This measure minimizes pipe breaks and ditch failures that cause gullies and landslides which add huge sediment loads to streams.

b. Do not flush or deposit sediment from behind diversion structures into the stream below. Deposit sediment in a designated upland site. Vegetate or otherwise stabilize spoil piles.

NOTE: Adding sediment to a stream that no longer has the capacity to transport it creates long-term stream damage (40 CFR 230) that often includes bank failure.

c. Mitigate water imports and water disposal (including reservoir releases) so that the extent of stable banks, channel pattern, profile and dimensions maintain or improve long-term stream health in each receiving stream reach.

NOTE: Water imports that increase the size or duration of high flows have damaged streams through major bank erosion. This measure prevents such severe damage.

d. Maintain and operate water conveyance ditches and pipelines to carry their design volumes of water with appropriate freeboard. Keep ditches clear of vegetation, debris or other obstructions to minimize potential for ditch failures.

e. Conduct snow management, including snowmaking and snow-farming, in such a manner that prevents slope failures and gully erosion on the hillslopes and prevents adverse impacts, such as bank erosion and excessive sediment, in receiving streams.

2. Monitoring. Monitor stream health below diversion and discharge structures. Check prompt remediation of water pipeline breaks and ditch failures. Inspect each facility in the field at least once every two years to conform to the biennial reporting provisions of Clean Water Act Section 319(m).

3. Restoration. Require performance bonds for potential repair of ditches and streams. Stop operation of facilities that do not comply with design criteria until compliance occurs.

Stabilize ditch berms and gullies. Restore ground cover using certified local native plants as practicable; avoid persistent or invasive exotic plants. Remove sediment from streams. Stabilize streams to move them toward robust stream health.

13 - SEDIMENT CONTROL

Most sediment delivered from slopes to streams comes from roads and similar disturbed sites. Management measures and design criteria to control sediment come from Clean Water Act Section 404 mandatory BMPs (33 CFR 323.4), EPA and State BMPs, and WRENSS controls. The goal is antidegradation and no impairment.

13.1 - Management Measure (9)

Limit roads and other disturbed sites to the minimum feasible number, width, and total length consistent with the purpose of specific operations, local topography, and climate.

Keep the number of stream crossings and the extent of sediment sources to a practicable minimum. Avoid sediment loads that damage stream health.

1. Design Criteria.

   a. Construct roads on ridge tops, stable upper slopes, or wide valley terraces if practicable. Stabilize soils onsite. End-haul soil if full-bench construction is used. Avoid slopes steeper than 70%.

      NOTE: Roads on favorable terrain cause little sediment (WRENSS V.29, V.35).

   b. Avoid soil-disturbing actions during periods of heavy rain or wet soils. Apply travel restrictions to protect soil and water.

      NOTE: This measure reduces mobilized soil during runoff events (WRENSS II.56).

   c. Install cross drains to disperse runoff into filter strips and minimize connected disturbed areas. Make cuts, fills, and road surfaces strongly resistant to erosion between each stream crossing and at least the nearest cross drain. Revegetate using certified local native plants as practicable; avoid persistent or invasive exotic plants.

      NOTE: Cross drains near crossings, well-revegetated cuts and fills, and surfacing with large (1 to 3 inch), angular, well-graded gravel greatly reduce sediment from connected disturbed areas (Burroughs and King 1989; Kochenderfer et al. 1984; Swift 1984).

d. Construct roads where practicable, with outslope and rolling grades instead of ditches and culverts.

NOTE: Kochenderfer et al. (1984); Swift (1984).

e. Retain stabilizing vegetation on unstable soils. Avoid new roads or heavy equipment use on unstable or highly erodible soils.

NOTE: WRENSS (II.58, II.60).

f. Use existing roads unless other options will produce less long-term sediment. Reconstruct for long-term soil and drainage stability.

NOTE: Reusing old roads usually produces less sediment, but it is often best to reclaim old roads near streams and build farther upslope.

g. Avoid ground skidding on sustained slopes steeper than 40% and on moderate to severely burned sustained slopes greater than 30%. Conduct logging to disperse runoff as practicable.

NOTE: This measure promotes filtration of runoff and sediment (WRENSS II.61).

h. Designate, construct, and maintain recreational travelways for proper drainage and armor their stream crossings as needed to control sediment.

NOTE: Uncontrolled OHV and other recreational use, especially in wet conditions, can severely damage streams and riparian areas.

i. During and following operations on outsloped roads, retain drainage and remove berms on the outside edge except those intentionally constructed for protection of road grade fills.

j. Locate and construct log landings in such a way to minimize the amount of excavation needed and to reduce the potential for soil erosion. Design landings to have proper drainage. After use, treat landings to disperse runoff and prevent surface erosion and encourage revegetation.

2. Monitoring. Monitor travelway conditions, sediment movement into streams, and sediment effects on aquatic habitat and biota.

3. Restoration. Disconnect disturbed areas from streams. Stabilize slopes and surface roads. Close and reclaim roads using certified local native plants as practicable; avoid persistent or invasive exotic plants. Restore integrity of streams and their aquatic habitats.

13.2 - Management Measure (10)

Construct roads and other disturbed sites to minimize sediment discharge into streams, lakes, and wetlands.

Excessive sediment from roads and other disturbed sites can have adverse effects on aquatic habitat. Projects that avoid water bodies or discharge into filter strips are usually less expensive than those that use constructed sediment traps. Sediment control has been effective with common watershed conservation practices in all regions.

1. Design Criteria.

   a. Design all roads, trails, and other soil disturbances to the minimum standard for their use and to "roll" with the terrain as feasible.

      NOTE: Field studies show that following terrain contours reduces cuts and fills.

   b. Use filter strips, and sediment traps if needed, to keep all sand-sized sediment on the land and disconnect disturbed soil from streams, lakes, and wetlands. Disperse runoff into filter strips.

      NOTE: Burroughs and King (1989); WRENSS (II.64).

   c. Key sediment traps into the ground. Clean them out when 50% full. Remove sediment to a stable, gentle, upland site and revegetate.

      NOTE: Field studies show that good sediment traps enhance filter strips.

   d. Keep heavy equipment out of filter strips except to do restoration work or build armored stream or lake approaches. Yard logs up out of each filter strip with minimum disturbance of ground cover.

      NOTE: Field studies show this measure protects filter strip integrity.

   e. Build firelines outside filter strips unless tied into a stream, lake, or wetland as a firebreak with minimal disturbed soil. Retain organic ground cover in filter strips during prescribed fires.

      NOTE: Light burns protect the ground cover of filter strips (USFS 1990).

   f. Design road ditches and cross drains to limit flow to ditch capacity and prevent ditch erosion and failure.

      NOTE: WRENSS (II.56, II.58); Burroughs and King (1989).

2. Monitoring. Monitor sediment movement into streams and sediment effects on aquatic habitat and biota.

3. Restoration. Add cross drains and sediment traps to improve filter strips. Revegetate disturbed areas using certified local native plants as practicable; avoid persistent or invasive exotic plants. Restore integrity of streams and their aquatic habitats.

13.3 - Management Measure (11)

Stabilize and maintain roads and other disturbed sites during and after construction to control erosion.

Build erosion resistance into project design to reduce costly maintenance and restoration (Clean Water Act Sections 402(p) and 404). Mitigate concurrently with construction. Obtain stormwater (402) and 404 permits as required.

1. Design Criteria.

a. Do not encroach fills or introduce soil into streams, swales, lakes, or wetlands.

NOTE: Corps of Engineers nationwide permits (33 CFR 330) limit fill in streams.

b. Properly compact fills and keep woody debris out of them. Revegetate cuts and fills upon final shaping to restore ground cover, using certified local native plants as practicable; avoid persistent or invasive exotic plants. Provide sediment control until erosion control is permanent.

NOTE: Burroughs and King (1989); WRENSS (II.63, V.29, V.35).

c. Do not disturb ditches during maintenance unless needed to restore drainage capacity or repair damage. Do not undercut the cut slope.

NOTE: Burroughs and King (1989); WRENSS (II.56, II.58, II.63).

d. Space cross drains according to road grade and soil type as indicated below: (ex. 01). Do not divert water from one stream to another.

NOTE: Kochenderfer et al. (1984); Swift (1984); WRENSS (II.64) SDSU et. al. (2003).

e. Empty cross drains onto stable slopes that disperse runoff into filter strips. On soils that may gully, armor outlets to disperse runoff. Tighten cross-drain spacing so gullies are not created.

NOTE: Avoid streamheads, unstable soils, and highly erodible soils (Burroughs and King 1989; WRENSS II.56, II.58, II.59, II.63, II.64).

f. Armor rolling dips as needed to prevent rutting damage to the function of the rolling dips. Ensure that road maintenance provides stable surfaces and drainage.

NOTE: Burroughs and King (1989); WRENSS (II.64).

13.3 - Exhibit 01
Maximum Cross-Drain Spacing in Feet Based on Soil Types*

	Unified Soil Classification - ASTM D 2487			
Road Grade (%)	ML, SM Extr. Erodible Silts-sands with little or no binder (d.g.)	MH, SC, CL Highly Erodible Silts-sands with moderate binder	SW,SP,GM,GC Mod. Erodible Gravels + fines & sands with little or no fines	GW,GP Low Erodible Gravels with little or no fines
1-3	600	1000	1000	1000
4-6	300	540	680	1000
7-9	200	360	450	670
10-12	150	270	340	510
13-15	120	220	270	410

*Adapted from original work on the Siuslaw National Forest documented in the Transportation Engineering Handbook of the Pacific Northwest Region, 1966. Original spacings were based on rainfall intensities of 1 to 2 inches per hour falling in 15 minutes. Soil groups and spacings have been modified, based partly on ditch erosion information in WRENSS, to better represent climate and soil regimes found in the Rocky Mountain Region.

These are maximum spacings. They should be reduced if warranted by onsite factors such as expected road use, downslope stability and erosion hazards, and filter strip capability to trap runoff and sediment and conserve ground cover integrity given the extra water. Combine these spacings with common sense to place cross drains where damage to ditches, slopes, and streams will be minimized. For example, shorten or extend the spacing where needed to move a cross-drain outlet from a stream headwall to a convex slope.

g. Where berms must be used, construct and maintain them to protect the road surface, drainage features, and slope integrity while also providing user safety.

NOTE: Roadside berms can channel runoff down the road (Burroughs and King 1989). Use of shoes on snowplow blades protects surfaces.

h. Build firelines with rolling grades and minimum downhill convergence. Outslope or backblade, permanently drain, and revegetate firelines immediately after the burn. Use certified local native plants as practicable; avoid persistent or invasive exotic plants.

NOTE: WRENSS (II.56, II.61).

i. Use the minimum amount of sand, salt, and/or other de-icing substances (Mag-Chloride) as necessary to provide safe winter travel conditions. Design paved roads and parking lots to facilitate sand removal (that is curbs or paved ditches). Use filter strips or other trapping methods to reduce movement of de-icing materials into near-by water bodies. Do not deposit sediment into streams or on streambanks along roads.

j. During winter operations, maintain roads as needed to keep the road surface drained during thaws and break-ups. Perform snow removal in such a manner that protects the road and other adjacent resources. Do not use riparian areas, wetlands or streams for snow storage or disposal. Remove snow berms where they result in accumulation or concentration of snowmelt runoff on the road or erodible fill slopes. Install snow berms where such placement will preclude concentration of snowmelt runoff and will serve to rapidly dissipate melt water.

k. On roads with high/heavy traffic use, require maintenance agreements and/or use of road surface stabilization practices and dust abatement supplements. See FSH 7709.56 and FSH 7709.58.

2. Monitoring. Monitor condition of cuts, fills, and ditches, effectiveness of filter strips, and runoff and sediment dispersion below cross drains. Monitor sediment movement into streams and sediment effects on aquatic habitat and biota.

3. Restoration. Stabilize fills, ditches, and cross drains. Add cross drains. Repair and armor surfaces subject to ruts. Restore integrity of streams and their aquatic habitats.

13.4 - Management Measure (12)

Reclaim roads and other disturbed sites when use ends, as needed, to prevent resource damage.

Restoring stable grades, stable drainage, and ground cover are critical to reclaiming disturbances and protecting soil quality and stream health. Roads in riparian areas and wetlands should be the highest priority for restoration.

1. Design Criteria.

a. Site-prepare, drain, decompact, revegetate, and close temporary and intermittent use roads and other disturbed sites within one year after use ends. Provide stable drainage that disperses runoff into filter strips and maintains stable fills. Do this work concurrently. Stockpile topsoil where practicable to be used in site restoration. Use certified local native plants as practicable; avoid persistent or invasive exotic plants.

NOTE: WRENSS (II.57, II.58), USFS (1996b). One year allows revegetation in optimum seasons.

b. Remove all temporary stream crossings (including all fill material in the active channel), restore the channel geometry, and revegetate the channel banks using certified local native plants as practicable; avoid persistent or invasive exotic plants.

c. Restore cuts and fills to the original slope contours where practicable and as opportunities arise to re-establish subsurface pathways. Use certified local native plants as practicable; avoid persistent or invasive exotic plants. Obtain stormwater (402) discharge permits as required.

d. Establish effective ground cover on disturbed sites to prevent accelerated on-site soil loss and sediment delivery to streams. Restore ground cover using certified native plants as practicable to meet revegetation objectives. Avoid persistent or invasive exotic plants.

2. Monitoring. Monitor connected disturbed areas and culverts removed.

3. Restoration. Reclaim remaining sediment sources. Provide stable drainage that disconnects as much disturbed area as practicable. Revegetate using certified local native plants as practicable; avoid persistent or invasive exotic plants.

14 - SOIL QUALITY

Soil quality determines vegetation growth capability in all terrestrial ecosystems. Soil depth, structure, organic matter, and nutrients are critical to sustaining this potential. Management measures and design criteria to protect soil quality apply to all actions that may impact these soil qualities.

14.1 - Management Measure (13)

Manage land treatments to limit the sum of severely burned soil and detrimentally compacted, eroded, and displaced soil to no more than 15% of any activity area.

Severe burns kill soil biota, alter soil structure, consume litter and humus, and remove organic matter and nutrients. Severe fires occur when humus and large fuels are dry and heavy fuels near the ground conduct much heat into the soil. Recovery takes years (USFS 1990).

Soil compaction is caused by the weight of vehicles and animals on the ground. It increases soil density and reduces large pores so that water absorption and root growth are impaired. Clay and loam soils compact more than sandy soils. Soils compact more when soil moisture exceeds the plastic limit. Detrimental compaction may occur with few passes in moist soils but may take many passes in dry soils. Ground cover, deep snow, and frozen soil reduce compaction. Severe compaction can extend to two feet in roads, major skid trails, and log decks; tree growth may be greatly reduced and recovery may take decades (USFS 1990).

The 15% limit applies to all natural and human disturbances that may impact soil structure, organic matter, and nutrients in areas allocated for vegetation production (R2 FSH 2509.18). Where excessive soil impacts already exist from prior activity, the emphasis should be on preventing any additional detrimental impacts and on reclamation where practicable. As defined in the National Soil Handbook (FSH 2509.18) soil quality standards are intended for areas where management prescriptions are being applied, such as timber harvest areas and range allotments. They are not intended to apply to administrative sites or other areas with dedicated uses such as the permanent transportation system, well pads or ski areas, for example.

1. Design Criteria.

a. Restrict roads, landings, skid trails, concentrated-use sites, and similar soil disturbances to designated sites.

NOTE: FSH 2509.18; WRENSS (V.29, V.35).

b. Operate heavy equipment for land treatments only when soil moisture is below the plastic limit, or protected by at least 1 foot of packed snow or 2 inches of frozen soil.

NOTE: This measure limits compaction. Soil moisture exceeds the plastic limit if the soil can be rolled into 3 mm threads without breaking or crumbling.

c. Conduct prescribed fires to minimize the residence time on the soil while meeting the burn objectives. This is usually done when the soil and duff are moist.

NOTE: This measure prevents severe soil heating (USFS 1990, page IV-90).

d. Allow dispersed winter motorized recreation when snow depths are sufficient to protect soils. Specify a minimum unpacked snow depth of 12 inches unless a site-specific analysis shows a different snow depth is adequate to protect soils. Allow use of snowcats or grooming machines when unpacked snow depths equal or exceed 18 inches. Evaluate special use permit conditions on a site specific basis.

2. Monitoring. Monitor extent of severely burned and detrimentally compacted, displaced, and eroded soil in those activity areas with the most disturbances.

3. Restoration. Subsoil and till to mitigate detrimental compaction. Seed, fertilize, and mulch severe burns. Use certified local native plants as practicable; avoid persistent or invasive exotic plants. Close and reclaim, or permanently armor, any site that has soil pedestals or rills and is subject to concentrated use.

14.2 - Management Measure (14)

Maintain or improve long-term levels of organic matter and nutrients on all lands.

Nutrient loss occurs when organic matter and nutrients contained in leaves, limbs, litter, humus, and topsoil is moved offsite. Bole-only timber harvest and careful slash piling that keeps soil in place minimizes loss (USFS 1990).

Careless piling that moves topsoil may remove much nitrogen and other nutrients from the site. Long-term soil productivity is reduced because organic matter that supplies nutrients over time is displaced offsite (USFS 1990).

Total-tree harvest removes the whole above-stump tree from the site. Loss of nitrogen and other nutrients can be several times that with bole-only harvest (Woodard 1993). Nutrient studies show that soil productivity may be reduced by one total-tree clearcut in poor soils and repeated clearcuts in rich soils. However, total-tree harvest may be necessary to reduce fuel loadings, prevent soil damaging high severity fires and restore natural disturbance regimes.

1. Design Criteria.

   a. On soils with surface soil (A-horizon) thinner than 1 inch, topsoil organic matter less than 2%, or effective rooting depth less than 15 inches, retain 80 - 90% of the fine (less than 3 inches in diameter) post treatment logging slash in the stand after each clearcut and seed-tree harvest. Consider need for retention of coarse woody debris slash in each activity area to balance soil quality requirements and fuel loading concerns.

      NOTE: Base this measure strictly on onsite soil investigations, NRCS (SCS, 1993) rating for whole tree harvesting and slash levels. Exceptions may occur when high fire hazard overrides the need to leave slash onsite. Apply this measure to complement site regeneration.

   b. If machine piling of slash is done, conduct piling to leave topsoil in place and to avoid displacing soil into piles or windrows.

      NOTE: USFS (1990, pages II-25, II-54, IV-91).

2. Monitoring. Monitor slash and litter removal, and soil in piles and windrows.

3. Restoration. Return slash to the site, fertilize, or add sludge to restore site organic matter and nutrients; avoid persistent or invasive exotic plants.

15 - WATER PURITY

Chemicals and pathogens impact water purity. Management measures and design criteria to protect water purity intend to avoid contamination of all waters.

15.1 - Management Measure (15)

Place new sources of chemical and pathogenic pollutants where such pollutants will not reach surface or ground water.

Chemicals and pathogens can travel long distances in water. Pollutants must be filtered out before they reach surface or ground water.

1. Design Criteria.

    a. Locate pack and riding stock sites (for example corrals and loading areas), sanitary sites, and well drill-pads outside the water influence zone (WIZ).

    NOTE: This measure and those under section 12.1 minimize water pollution. Some minor bacterial input from dispersed livestock and wildlife use is unavoidable.

    b. Locate vehicle service and fuel areas, chemical storage and use areas, and waste dumps and areas on gentle upland sites. Mix, load, and clean on gentle upland sites. Dispose of chemicals and containers in State-certified disposal areas.

    NOTE: Keep such sites out of valley bottoms due to mobility of many chemicals.

    c. Locate temporary labor, spike, logging and fire camps such that surface and subsurface water resources are protected. Consideration should be given to disposal of human waste, wastewater and garbage and other solid wastes.

2. Monitoring. Monitor water quality and location of pollutant sources.

3. Restoration. Move pollutants to State-certified disposal areas. Reclaim source areas. Remove contaminated sediments from waters.

15.2 - Management Measure (16)

Apply runoff controls to disconnect new pollutant sources from surface and ground water.

Even favorably located pollutant sources need controls to trap pollutants during major runoff events. Keep discharges free from toxic pollutants in toxic amounts.

1. Design Criteria.

a. Install contour berms and trenches around vehicle service and refueling areas, chemical storage and use areas, and waste dumps to fully contain spills. Use liners as needed to prevent seepage to ground water. Prepare Spill Prevention Control and Countermeasure Plan per the requirements of 40 CFR 112.

NOTE: Standard contingency runoff control for chemical use and storage sites.

b. Reclaim each mine waste dump when its use ends, using certified local native plants as practicable; avoid persistent or invasive exotic plants. Stabilize waste dumps and tailings in non-use periods to prevent wind and water erosion. If non-use will exceed one year, perform concurrent reclamation. Require removal or encapsulation of waste material as necessary to prevent contamination of nearby water bodies before operator abandons site or reclamation is accepted as final.

NOTE: Avoid unreclaimed pollution sources throughout a watershed.

c. Prevent contaminated runoff from waste dumps and/or tailings from reaching surface and/or ground water. Potential techniques include use of lined ponds to catch runoff, diversion ditches or other runoff controls to divert runoff around waste dumps/tailings piles, capping or treating waste piles on site or off-site disposal of waste as appropriate. If ponds are used, build tailings dams with a 95% chance of containing floods (100-year event) over their design life. Permanently stabilize dams at final shaping.

NOTE: Lined ponds are a standard practice on new mines. Use clay plus synthetic liners if the pond will hold known chemicals. Geotechnical engineers must approve all designs.

d. Clean wastewater from concrete batching and aggregate operations before returning the water to streams, lakes, or wetlands.

NOTE: Needed to prevent major sediment and cementation impacts in streambeds.

e. Inspect equipment used for transportation, storage or application of chemicals daily during use period for leaks. If leaks or spills occur, report them and install emergency traps to contain them and clean them up. Refer to FSH 6709.11, chapter 60 for direction on working with hazardous materials.

NOTE: Standard practice for pesticide equipment (USFS 1990, page II-60).

f. Report spills and take appropriate clean-up action in accordance with applicable state and federal laws, rules and regulations. Contaminated soil and other material shall be removed from NFS lands and disposed of in a manner according to state and federal laws, rules and regulations.

2. Monitoring. Monitor water quality and status of runoff controls.

3. Restoration. Move pollutants to State-certified disposal areas. Reclaim source areas using certified local native plants as practicable; avoid persistent or invasive exotic plants. Remove contaminated sediments from waters.

15.3 - Management Measure (17)

Apply chemicals using methods that minimize risk of entry to surface and ground water.

Pollution risk depends on chemical mobility and persistence, application mode and rate, and distance from water (USFS 1990). Risk of entry to surface water is highest for broadcast and aerial treatments and for fine droplets. Risk of entry to ground water is highest over sandy soils and shallow water tables.

1. Design Criteria.

a. Favor pesticides with half-lives of 3 months or less when practicable to achieve treatment objectives.. Apply at lowest effective rates as large droplets or pellets. Follow the label directions. Favor selective treatment. Use only aquatic-labeled chemicals in the WIZ.

NOTE: Standard practice for pesticides (USFS 1990, pages II-55 to II-60).

b. Use non-toxic, non-hazardous drilling fluids when practicable.

NOTE: Standard practice for oil and gas drilling operations. Oil-based drilling fluids are required for deep wells.

2. Monitoring. Monitor vegetation near water and chemicals in water.

3. Restoration. Remove or neutralize contaminants or avoid further application.

FSH 1909.12 - LAND MANAGEMENT PLANNING HANDBOOK
CHAPTER - ZERO CODE

Table of Contents

This Handbook provides procedural guidance for implementing land management planning direction for the 2012 Planning Rule (77 FR 21165, April 9, 2012). The primary use is for interdisciplinary team members and Line Officers responsible for planning.

01 – AUTHORITY

The Forest and Rangeland Renewable Resources Planning Act, as amended by the National Forest Management Act (NFMA) requires the Forest Service to develop land management plans for units of the National Forest System (NFS). The Act also requires the adoption of implementing regulations to establish a process for developing and revising those plans and to carry out the NFMA's substantive requirements for them (16 USC 1604(a) and (g)). The NFMA implementing regulations are found in Title 36, Code of Federal Regulations, part 219. The regulations establish requirements for planning: assessment; developing, revising, and amending plans and monitoring. The regulations also establish a predecisional objection process for plans, revised plans, and amendments. Further planning direction is set forth in FSM 1920. The full text of the 2012 Planning Rule is included as an exhibit in section 08 of this chapter.

03 – POLICY

Compliance with the Paperwork Reduction Act (PRA) is required for the collection of information of ten or more persons, whether such collection of information is mandatory, voluntary, or required to obtain or retain a benefit. The term information is defined in section 05 of this chapter. The Responsible Official shall review the PRA (5 CFR 1320) requirements to ensure that methods for obtaining information to meet the requirements of 36 CFR 219.6 and this Handbook are consistent with the Act (see, in particular, 5 CFR 1320.3(h)).

The Responsible Official shall not use any method of obtaining information that is prohibited (absent approval) by the Act. The Office of Management and Budget has approved a generic clearance to collect feedback related to land management planning and the assigned control number is #0596-0234.

04 – RESPONSIBILITY

The Forest Supervisor is responsible for developing, amending, or revising plans, except when the Regional Forester; the Chief; the Under Secretary, Natural Resources and Environment; or the Secretary acts as the Responsible Official under Title 36, Code of Federal Regulations, section 219.2(b)(3) (36 CFR 219.2(b)(3)). See FSM 1920 for a broad description of Line Officer responsibilities.

05 – DEFINITIONS

Adaptation. Adjustment in natural or human systems to a new or changing environment. Adaptation includes, but is not limited to, maintaining primary productivity and basic ecological functions such as energy flow; nutrient cycling and retention; soil development and retention; predation and herbivory; and natural disturbances. Adaptation occurs primarily by organisms altering their interactions with the physical environment and other organisms.

Adaptive capacity. The ability of ecosystems to respond, cope, or adapt to disturbances and stressors, including environmental change, to maintain options for future generations. As applied to ecological systems, adaptive capacity is determined by:

1. Genetic diversity within species in ecosystems, allowing for selection of individuals with traits adapted to changing environmental conditions.

2. Biodiversity within the ecosystem, both in terms of species richness and relative abundance, which contributes to functional redundancies.

3. The heterogeneity and integrity of ecosystems occurring as mosaics within broader-scaled landscapes or biomes, making it more likely that some areas will escape disturbance and serve as source areas for re-colonization.

Adaptive Management. Adaptive management is the general framework encompassing the three phases of planning: assessment, plan development, and monitoring (36 CFR 219.5). This framework supports decision-making that meets management objectives while simultaneously accruing information to improve future management by adjusting the plan or plan implementation. Adaptive management is a structured, cyclical process for planning and decision-making in the face of uncertainty and changing conditions with feedback from monitoring, which includes using the planning process to actively test assumptions, track relevant conditions over time, and measure management effectiveness.

Address. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook, an individual's or entity's current address used for U.S. Postal Service or other delivery services; an email address does not meet this definition.

Airshed. A geographic area that, because of topography, meteorology, and/or climate is frequently affected by the same air mass.

Alaska Native Corporation. One of the regional, urban, and village native corporations formed under the Alaska Native Claims Settlement Act of 1971 (36 CFR 219.19).

Area of influence. An area influenced by the management of the plan area that is used during the land management planning process to evaluate social, cultural, and economic conditions. The area is usually a grouping of counties.

Assessment. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook, an assessment is the identification and evaluation of existing information to support land management planning. Assessments are not decision-making documents, but provide current information on select topics relevant to the plan area, in the context of the broader landscape (36 CFR 219.19).

At-risk species. A term used in land management planning and this Handbook to refer to, collectively, the federally recognized threatened, endangered, proposed, and candidate species and species of conservation concern within a plan area.

Best management practices for water quality (BMPs). Methods, measures, or practices selected by an agency to meet its nonpoint source control needs. BMPs include but are not limited to structural and nonstructural controls and operation and maintenance procedures. BMPs can be applied before, during, and after pollution-producing activities to reduce or eliminate the introduction of pollutants into receiving waters (36 CFR 219.19).

Broader Landscape. For land management planning pursuant to 36 CFR part 219 and this Handbook, the plan area and the lands surrounding the plan area. The spatial scale of the broader landscape varies depending upon the social, economic, and ecological issues under consideration.

Candidate species (36 CFR 219.19).

1. For species under the purview of the U.S. Fish and Wildlife Service (USFWS), a species for which the USFWS possesses sufficient information on vulnerability and threats to support a proposal to list as endangered or threatened, but for which no proposed rule has yet been published by the USFWS.

2. For species under the purview of the National Marine Fisheries Service (NMFS), a species that is:

a. The subject of a petition to list as a threatened or endangered species and for which the (NMFS) has determined that listing may be warranted, pursuant to section 4(b)(3)(A) of the Endangered Species Act (16 U.S.C. 1533(b)(3)(A)), or

b. Not the subject of a petition but for which the (NMFS) has announced in the Federal Register the initiation of a status review.

Carbon pool. Any natural region or zone, or any artificial holding area, containing an accumulation of carbon or carbon-bearing compounds or having the potential to accumulate such substances. Carbon pools may include live and dead above ground carbon, soil carbon including coarse roots, and harvested wood products.

Carbon stocks. The amount or quantity of carbon contained in a carbon pool. For purposes of carbon stock assessment for National Forest System (NFS) land management planning, carbon pools do not include carbon in fossil fuel resources, lakes or rivers, emissions from agency operations, or public use of NFS lands (such as emissions from vehicles and facilities).

Climate change adaptation. Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. This adaption includes initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Adaptation strategies include the following:

1. Building resistance to climate-related stressors.

2. Increasing ecosystem resilience by minimizing the severity of climate change impacts, reducing the vulnerability, and/or increasing the adaptive capacity of ecosystem elements.

3. Facilitating ecological transitions in response to changing environmental conditions.

Collaboration or collaborative process. A structured manner in which a collection of people with diverse interests share knowledge, ideas, and resources, while working together in an inclusive and cooperative manner toward a common purpose. Collaboration, in the context of the land management planning regulation at 36 CFR part 219 and this Handbook, falls within the full spectrum of public engagement described in the Council on Environmental Quality's publication of October, 2007: Collaboration in NEPA— A Handbook for NEPA Practitioners (36 CFR 219.19).

Connectivity. Ecological conditions that exist at several spatial and temporal scales that provide landscape linkages that permit the exchange of flow, sediments, and nutrients; the daily and seasonal movements of animals within home ranges; the dispersal and genetic interchange between populations; and the long distance range shifts of species, such as in response to climate change (36 CFR 219.19).

Conservation. The protection, preservation, management, or restoration of natural environments, ecological communities, and species (36 CFR 219.19).

Conserve. For the purpose of meeting the requirements of 36 CFR 219.9 and this Handbook, to protect, preserve, manage, or restore natural environments and ecological communities to potentially avoid federally listing of proposed and candidate species (36 CFR 219.19).

Consultation (in relation to the Endangered Species Act). See Formal Consultation and Informal Consultation.

Critical habitat. For a threatened or endangered species, (1) the specific areas within the geographical area occupied by the species, at the time it is listed in accordance with the provisions of section 4 of the Endangered Species Act (ESA) (16 USC 1533), on which are found those physical or biological features (a) essential to the conservation of the species, and (b) which may require special management considerations or protection; and (2) specific areas outside the geographical area occupied by the species at the time it is listed in accordance with the provisions of section 4 of the ESA (16 USC 1533), upon a determination by the Secretary that such areas are essential for the conservation of the species. ESA, sec. 3 (5)(A), (16 USC 1532 (3)(5)(A)). Critical habitat is designated through rulemaking by the Secretary of the Interior or Commerce. ESA, sec. 4 (a)(3) and (b)(2) (16 USC 1533 (a)(3) and (b)(2)).

Critical load. The concentration of air pollution or total deposition of pollutants above which specific deleterious effects may occur.

Designated area. An area or feature identified and managed to maintain its unique special character or purpose. Some categories of designated areas may be designated only by statute and some categories may be established administratively in the land management planning process or by other administrative processes of the Federal executive branch. Examples of statutorily designated areas are national heritage areas, national recreational areas, national scenic trails, wild and scenic rivers, wilderness areas, and wilderness study areas. Examples of administratively designated areas are experimental forests, research natural areas, scenic byways, botanical areas, and significant caves (36 CFR 219.19).

Decision document. A record of decision, decision notice, or decision memo (36 CFR 220.3).

Decision memo. A concise written record of the Responsible Official's decision to implement an action that is categorically excluded from further analysis and documentation in an environmental impact statement (EIS) or environmental assessment (EA), where the action is one of a category of actions which do not individually or cumulatively have a significant effect on the human environment, and does not give rise to extraordinary circumstances in which a normally excluded action may have a significant environmental effect (36 CFR 219.62).

Decision Notice. A concise written record of the Responsible Official's decision when an EA and finding of no significant impact (FONSI) have been prepared (36 CFR 220.3).

Desired conditions. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook, a description of specific social, economic, and/or ecological characteristics of the plan area, or a portion of the plan area, toward which management of the land and resources should be directed. Desired conditions must be described in terms that are specific enough to allow progress toward their achievement to be determined, but do not include completion dates (36 CFR 219.7(e)(1)(i)). Desired conditions are achievable, and may reflect social, economic, or ecological attributes, including ecosystem processes and functions.

Disturbance. Any relatively discrete event in time that disrupts ecosystem, watershed, community, or species population structure and/or function and changes resources, substrate availability, or the physical environment (36 CFR 219.19).

Disturbance regime. A description of the characteristic types of disturbance on a given landscape; the frequency, severity, and size distribution of these characteristic disturbance types; and their interactions (36 CFR 219.19).

Ecological conditions. The biological and physical environment that can affect the diversity of plant and animal communities, the persistence of native species, and the productive capacity of ecological systems. Ecological conditions include habitat and other influences on species and the environment. Examples of ecological conditions include the abundance and distribution of aquatic and terrestrial habitats, connectivity, roads and other structural developments, human uses, and invasive species (36 CFR 219.19).

Ecological integrity. The quality or condition of an ecosystem when its dominant ecological characteristics (for example, composition, structure, function, connectivity, and species composition and diversity) occur within the natural range of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human influence (36 CFR 219.19).

Ecological sustainability. See sustainability.

Ecological system. See ecosystem.

Economic sustainability. See sustainability.

Ecosystem. (36 CFR 219.19) A spatially explicit, relatively homogeneous unit of the Earth that includes all interacting organisms and elements of the abiotic environment within its boundaries. An ecosystem is commonly described in terms of its:

1. Composition. The biological elements within the different levels of biological organization, from genes and species to communities and ecosystems.

2. Structure. The organization and physical arrangement of biological elements such as, snags and down woody debris, vertical and horizontal distribution of vegetation, stream habitat complexity, landscape pattern, and connectivity.

3. Function. Ecological processes that sustain composition and structure, such as energy flow, nutrient cycling and retention, soil development and retention, predation and herbivory, and natural disturbances such as wind, fire, and floods.

4. Connectivity. See connectivity above.

Ecosystem diversity. The variety and relative extent of ecosystems (36 CFR 219.19).

Ecosystem integrity. See ecological integrity.

Ecosystem services. Benefits people obtain from ecosystems, including:

1. Provisioning services, such as clean air and fresh water, energy, food, fuel, forage, wood products or fiber, and minerals;

2. Regulating services, such as long-term storage of carbon; climate regulation; water filtration, purification, and storage; soil stabilization; flood and drought control; and disease regulation;

3. Supporting services, such as pollination, seed dispersal, soil formation, and nutrient cycling; and

4. Cultural services, such as educational, aesthetic, spiritual, and cultural heritage values, recreational experiences, and tourism opportunities.

Endangered Species. Any species that the Secretary of the Interior or the Secretary of Commerce has determined is in danger of extinction throughout all or a significant portion of its range. Endangered species are listed at 50 CFR sections 17.11, 17.12, and 224.101.

Environmental assessment (EA). A public document that provides sufficient evidence and analysis for determining whether to prepare an EIS or a finding of no significant impact, aids an agency's compliance with the NEPA when no EIS is necessary, and facilitates preparation of a statement when one is necessary (40 CFR 1508.9; FSH 1909.15, ch. 40) (36 CFR 219.62).

Environmental document. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook: an environmental assessment, environmental impact statement, finding of no significant impact, categorical exclusion, and notice of intent to prepare an environmental impact statement (36 CFR 219.19).

Environmental impact statement (EIS). A detailed written statement as required by section 102(2)(C) of the National Environmental Policy Act (NEPA) of 1969 (40 CFR 1508.11; 36 CFR 220) (36 CFR 219.62).

Ephemeral stream. A stream that flows only in direct response to precipitation in the immediate locality (watershed or catchment basin), and whose channel is at all other times above the zone of saturation.

Essential Fish Habitat (EFH). Those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity for species managed in Fishery Management Plans under the Magnuson-Stevens Fishery Conservation and Management Act. In this definition, "waters" include aquatic areas and their associated physical, chemical, and biological properties that are used by fish and may include aquatic areas historically used by fish where appropriate; "substrate" includes sediment, hard bottom, structures underlying the waters, and associated biological communities; "necessary" means the habitat required to support a sustainable fishery and the managed species' contribution to a healthy ecosystem; and "spawning, breeding, feeding growth to maturity" covers a species' full life cycle.

Even-aged stand. A stand of trees composed of a single age class (36 CFR 219.19).

Federally recognized Indian Tribe. An Indian Tribe or Alaska Native Corporation, band, nation, pueblo, village, or community that the Secretary of the Interior acknowledges to exist as an Indian Tribe under the Federally Recognized Indian Tribe List Act of 1994, 25 U.S.C. 479a (36 CFR 219.19).

Focal species. A small subset of species whose status permits inference to the integrity of the larger ecological system to which it belongs and provides meaningful information regarding the effectiveness of the plan in maintaining or restoring the ecological conditions to maintain the diversity of plant and animal communities in the plan area. Focal species would be commonly selected on the basis of their functional role in ecosystems (36 CFR 219.19).

Forest land. Land at least 10 percent occupied by forest trees of any size or formerly having had such tree cover and not currently developed for non-forest uses. Lands developed for non-forest use include areas for crops, improved pasture, residential or administrative areas, improved roads of any width and adjoining road clearing, and power line clearings of any width (36 CFR 219.19).

Formal comments. See substantive formal comments (36 CFR 219.62).

Formal Consultation. A process between the USFWS and/or NMFS and a Federal agency proposing an action that 1) determines whether the proposed Federal action is likely to jeopardize the continued existence of listed species or destroy or adversely modify designated critical habitat; 2) begins with a Federal agency's written request and submittal of a complete initiation package; and 3) concludes with the issuance of a biological opinion by USFWS and/or NMFS, that may include an incidental take statement by the USFWS or NMFS. If a proposed Federal action may affect a listed species or designated critical habitat, formal consultation is required, except when the USFWS or NMFS concurs, in writing, that a proposed action "is not likely to adversely affect" listed species or designated critical habitat (50 CFR sections 402.02 and 402.14).

Geographic area. A spatially contiguous land area identified within the planning area. A geographic area may overlap with a management area (36 CFR 219.19).

Goals. An optional plan component that are broad statements of intent, other than desired conditions, usually related to process or interaction with the public. Goals are expressed in broad, general terms, but do not include completion dates (36 CFR part 219.7(e)(2)).

Groundwater-dependent ecosystem**.** Community of plants, animals, and other organisms whose extent and life processes depend on groundwater. Examples include many wetlands, groundwater-fed lakes and streams, cave and karst systems, aquifer systems, springs, and seeps.

Guideline. A constraint on project and activity decision-making that allows for departure from its terms, so long as the purpose of the guideline is met (36 CFR section 219.15(d)(3)). Guidelines are established to help achieve or maintain a desired condition or conditions, to avoid or mitigate undesirable effects, or to meet applicable legal requirements.

Habitat type. A land or aquatic unit, consisting of an aggregation of habitats having equivalent structure, function, and responses to disturbance.

Informal Consultation. An optional consultation process that includes all discussions, correspondence, and so forth between the FWS/NMFS and a Federal action agency or designated non-Federal representative prior to formal consultation, if required (50 CFR sections 402.02 and 402.14).

Information. For information collection from the public pursuant to 5 CFR part 1320, any statement or estimate of fact or opinion, regardless of form or format, whether in numerical, graphic, or narrative form, and whether oral or maintained on paper, electronic or other media. "Information" does not generally include items in the following categories; however, OMB may determine that any specific item constitutes "information":

(1) Affidavits, oaths, affirmations, certifications, receipts, changes of address, consents, or acknowledgments; provided that they entail no burden other than that necessary to identify the respondent, the date, the respondent's address, and the nature

of the instrument (by contrast, a certification would likely involve the collection of "information" if an agency conducted or sponsored it as a substitute for a collection of information to collect evidence of, or to monitor, compliance with regulatory standards, because such a certification would generally entail burden in addition to that necessary to identify the respondent, the date, the respondent's address, and the nature of the instrument);

(2) Samples of products or of any other physical objects;

(3) Facts or opinions obtained through direct observation by an employee or agent of the sponsoring agency or through nonstandardized oral communication in connection with such direct observations;

(4) Facts or opinions submitted in response to general solicitations of comments from the public, published in the Federal Register or other publications, regardless of the form or format thereof, provided that no person is required to supply specific information pertaining to the commenter, other than that necessary for self-identification, as a condition of the agency's full consideration of the comment;

(5) Facts or opinions obtained initially or in follow-on requests, from individuals (including individuals in control groups) under treatment or clinical examination in connection with research on or prophylaxis to prevent a clinical disorder, direct treatment of that disorder, or the interpretation of biological analyses of body fluids, tissues, or other specimens, or the identification or classification of such specimens;

(6) A request for facts or opinions addressed to a single person;

(7) Examinations designed to test the aptitude, abilities, or knowledge of the persons tested and the collection of information for identification or classification in connection with such examinations;

(8) Facts or opinions obtained or solicited at or in connection with public hearings or meetings;

(9) Facts or opinions obtained or solicited through nonstandardized follow-up questions designed to clarify responses to approved collections of information; and

(10) Like items so designated by OMB (5 CFR 1320.3(h)).

<u>Inherent capability of the plan area</u>. The ecological capacity or ecological potential of an area characterized by the interrelationship of its physical elements, its climatic regime, and natural disturbances (36 CFR 219.19).

Integrated resource management. Multiple use management that recognizes the interdependence of ecological resources and is based on the need for integrated consideration of ecological, social, and economic factors (36 CFR 219.19).

Intermittent stream. A stream or reach of stream channel that flows, in its natural condition, only during certain times of the year or in several years, and is characterized by interspersed, permanent surface water areas containing aquatic flora and fauna adapted to the relatively harsh environmental conditions found in these types of environments. Intermittent streams are identified as dashed blue lines on USGS 7 1/2-inch quadrangle maps.

Invasive Species. An alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health. A species that causes, or is likely to cause, harm and that is exotic to the ecosystem it has infested. Invasive species infest both aquatic and terrestrial areas and can be identified within any of the following four taxonomic categories: Plants, Vertebrates, Invertebrates, and Pathogens (Executive Order 13112).

Key ecosystem services. Ecosystem services provided by the plan area that are important in the broader landscape outside the plan area and are likely to be influenced by the land management plan.

Landscape. A defined area irrespective of ownership or other artificial boundaries, such as a spatial mosaic of terrestrial and aquatic ecosystems, landforms, and plant communities, repeated in similar form throughout such a defined area (36 CFR 219.19).

Lead objector. For an objection submitted with multiple individuals, multiple entities, or combination of individuals and entities listed, the individual or entity identified to represent all other objectors for the purposes of communication, written or otherwise, regarding the objection (36 CFR 219.62).

Line Officer. A Forest Service official who serves in a direct line of command from the Chief (36 CFR 219.62).

Maintain. In reference to an ecological condition: To keep in existence or continuance of the desired ecological condition in terms of its desired composition, structure, and processes. Depending upon the circumstance, ecological conditions may be maintained by active or passive management or both (36 CFR 219.19).

Management area. A land area identified within the planning area that has the same set of applicable plan components. A management area does not have to be spatially contiguous (36 CFR 219.19).

Management system. For the purposes of the land management planning regulation at 36 CFR Part 219 and this Handbook, a timber management system including even aged management and uneven-aged management (36 CFR 219.19).

Mitigate. To avoid, minimize, rectify, reduce, or compensate the adverse environmental impacts associated with an action.

Monitoring. A systematic process of collecting information to evaluate effects of actions or changes in conditions or relationships (36 CFR 219.19).

Multiple use. The management of all the various renewable surface resources of the NFS so that they are utilized in the combination that will best meet the needs of the American people; making the most judicious use of the land for some or all of these resources or related services over areas large enough to provide sufficient latitude for periodic adjustments in use to conform to changing needs and conditions; that some land will be used for less than all of the resources; and harmonious and coordinated management of the various resources, each with the other, without impairment of the productivity of the land, with consideration being given to the relative values of the various resources, and not necessarily the combination of uses that will give the greatest dollar return or the greatest unit output, consistent with the Multiple-Use Sustained-Yield Act of 1960 (16 U.S.C. 528–531) (36 CFR 219.19).

Name. The first and last name of an individual or the name of an entity. An electronic username is insufficient for identification of an individual or entity (36 CFR 219.62).

National Forest System. Includes National Forests, National Grasslands, and the National Tallgrass Prairie (36 CFR 219.62).

Native knowledge. A way of knowing or understanding the world, including traditiona,l ecological, and social knowledge of the environment derived from multiple generations of indigenous peoples' interactions, observations, and experiences with their ecological systems. Native knowledge is place-based and culture-based knowledge in which people learn to live in and adapt to their own environment through interactions, observations, and experiences with their ecological system. This knowledge is generally not solely gained, developed by, or retained by individuals, but is rather accumulated over successive generations and is expressed through oral traditions, ceremonies, stories, dances, songs, art, and other means within a cultural context (36 CFR 219.19).

Native species. An organism that was historically or is present in a particular ecosystem as a result of natural migratory or evolutionary processes and not as a result of an accidental or deliberate introduction into that ecosystem. An organism's presence and evolution (adaptation) in an area are determined by climate, soil, and other biotic and abiotic factors (36 CFR 219.19).

Natural range of variation (NRV). The variation of ecological characteristics and processes over scales of time and space that are appropriate for a given management application. In contrast to the generality of historical ecology, the NRV concept focuses on a distilled subset of past ecological knowledge developed for use by resource managers; it represents an explicit effort to incorporate a past perspective into management and conservation decisions (adapted from Weins, J.A. et al., 2012). The pre-European influenced reference period considered should be sufficiently long, often several centuries, to include the full range of variation produced by dominant natural disturbance regimes such as fire and flooding and should also include short-term variation and cycles in climate. The NRV is a tool for assessing the ecological integrity and does not necessarily constitute a management target or desired condition. The NRV can help identify key structural, functional, compositional, and connectivity characteristics, for which plan components may be important for either maintenance or restoration of such ecological conditions.

Newspaper(s) of record. The newspaper(s) of record is (are) the principal newspaper(s) of general circulation annually identified and published in the Federal Register by each Regional Forester to be used for publishing notices as required by 36 CFR 215.5. The newspaper(s) of record for projects in a plan area is (are) the newspaper(s) of record for notices related to planning (36 CFR 219.62).

Objection. The written document filed with a Reviewing Officer by an individual or entity seeking pre-decisional administrative review of a plan, plan amendment, or plan revision (36 CFR 219.62).

Objection period. The allotted filing period following publication of a public notice in the applicable newspaper of record (or the Federal Register, if the Responsible Official is the Chief) of the availability of the appropriate environmental documents and draft decision document, including a plan, plan amendment, or plan revision during which an objection may be filed with the reviewing officer (36 CFR 219.62).

Objection process. Those procedures established for pre-decisional administrative review of a plan, plan amendment, or plan revision (36 CFR 219.62).

Objective. A concise, measurable, and time-specific statement of a desired rate of progress toward a desired condition or conditions. Objectives should be based on reasonably foreseeable budgets.

Objector. An individual or entity who meets the requirements of section 219.53, and files an objection that meets the requirements of sections 219.54 and 219.56 (36 CFR 219.62).

Online. Refers to the appropriate Forest Service website or future electronic equivalent (36 CFR 219.62).

Participation. Activities that include a wide range of public involvement tools and processes, such as collaboration, public meetings, open houses, workshops, and comment periods (36 CFR 219.19).

Perennial stream. A stream or reach of a channel that flows continuously or nearly so throughout the year and whose upper surface is generally lower than the top of the zone of saturation in areas adjacent to the stream. These streams are identified as solid blue on the USGS 7 1/2-inch quadrangle maps.

Persistence. Continued existence (36 CFR 219.19).

Plan or land management plan. A document or set of documents that provide management direction for an administrative unit of the NFS developed under the requirements of the land management planning regulation at 36 CFR part 219 or a prior planning rule (36 CFR 219.19).

Plan area. The NFS lands covered by a plan (36 CFR 219.19).

Plan components. The parts of a land management plan that guide future project and activity decision-making. Specific plan components may apply to the entire plan area, to specific management areas or geographic areas, or to other areas as identified in the plan. Every plan must include the following plan components: Desired conditions; Objectives; Standards; Guidelines; Suitability of Lands. A plan may also include Goals as an optional component.

Plan monitoring program. An essential part of the land management plan that sets out the plan monitoring questions and associated indicators, based on plan components. The plan monitoring program informs management of resources on the plan area and enables the Responsible Official to determine if a change in plan components or other plan content that guide management of resources on the plan area may be needed.

Planning record. The documents and materials considered in the making of a forest plan, plan revision, or plan amendment.

Plant and animal community. A naturally occurring assemblage of plant and animal species living within a defined area or habitat (36 CFR 219.19).

Productivity. The capacity of NFS lands and their ecological systems to provide the various renewable resources in certain amounts in perpetuity. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook, productivity is an ecological term, not an economic term (36 CFR 219.19).

Project. An organized effort to achieve an outcome on NFS lands identified by location, tasks, outputs, effects, times, and responsibilities for execution (36 CFR 219.19).

Proposed Species. Any species of fish, wildlife, or plant that is proposed by the U. S. Fish and Wildlife Service or the National Marine Fisheries Service in the Federal Register to be listed under Section 4 of the Endangered Species Act. (36 CFR 219.19)

Public and governmental participation. Phrase used in this Handbook as shorthand for participation by all Tribes and Alaska Native Corporations, other Federal agencies, State and local governments, public and private organizations, and interested individuals. This can include people and government and non-governmental entities in other countries, for example, where plan areas are adjacent or proximate to international borders.

Recovery. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook and with respect to threatened or endangered species: The improvement in the status of a listed species to the point at which listing as federally endangered or threatened is no longer appropriate (36 CFR 219.19).

Recreation opportunity. An opportunity to participate in a specific recreation activity in a particular recreation setting to enjoy desired recreation experiences and other benefits that accrue. Recreation opportunities include non-motorized, motorized, developed, and dispersed recreation on land, water, and in the air (36 CFR 219.19).

Recreation setting. The social, managerial, and physical attributes of a place that, when combined, provides a distinct set of recreation opportunities. The Forest Service uses the recreation opportunity spectrum to define recreation settings and categorize them into six distinct classes: primitive, semi-primitive non-motorized, semi-primitive motorized, roaded natural, rural, and urban (36 CFR 219.19).

Redundancy. The presence of multiple occurrences of ecological conditions such that not all occurrences may be eliminated by a catastrophic event.

Representativeness. The presence of a full array of ecosystem types and successional states, based on the physical environment and characteristic disturbance processes.

Resilience. The ability of an ecosystem and its component parts to absorb, or recover from the effects of disturbances through preservation, restoration, or improvement of its essential structures and functions and redundancy of ecological patterns across the landscape.

Responsible Official. The official with the authority and responsibility to oversee the planning process and to approve a plan, plan amendment, and plan revision (36 CFR 219.62).

Restoration, ecological. The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. Ecological restoration focuses on reestablishing the composition, structure, pattern, and ecological processes necessary to facilitate terrestrial and aquatic ecosystems sustainability, resilience, and health under current and future conditions (36 CFR 219.19).

Restoration, functional. Restoration of abiotic and biotic processes in degraded ecosystems. Functional restoration focuses on the underlying processes that may be degraded, regardless of the structural condition of the ecosystem. Functionally restored ecosystem may have a different structure and composition than the historical reference condition. As contrasted with ecological restoration that tends to seek historical reference condition, the functional restoration focuses on the dynamic processes that drive structural and compositional patterns. Functional restoration is the manipulation of interactions among process, structure, and composition in a degraded ecosystem to improve its operations. Functional restoration aims to restore functions and improve structures with a long-term goal of restoring interactions between function and structure. It may be, however, that a functionally restored system will look quite different than the reference condition in terms of structure and composition and these disparities cannot be easily corrected because some threshold of degradation has been crossed or the environmental drivers, such as climate, that influenced structural and (especially) compositional development have changed.

Restore. To renew by the process of restoration. See restoration (36 CFR 219.19).

Reviewing Officer. The USDA or Forest Service official having the delegated authority and responsibility to review an objection filed under the planning rule at 36 CFR part 219, subpart B. (36 CFR 219.62).

Riparian Areas. Three-dimensional ecotones [the transitio17.n zone between two adjoining communities] of interaction that include terrestrial and aquatic ecosystems that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near-slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at variable widths (36 CFR 219.19).

Riparian management zone. Portions of a watershed where riparian-dependent resources receive primary emphasis, and for which plans include plan components to maintain or restore riparian functions and ecological functions (36 CFR 219.19).

Risk. A combination of the likelihood that a negative outcome will occur and the severity of the subsequent negative consequences (36 CFR 219.19).

Scenic character. A combination of the physical, biological, and cultural images that gives an area its scenic identity and contributes to its sense of place. Scenic character provides a frame of reference from which to determine scenic attractiveness and to measure scenic integrity (36 CFR 219.19).

Social sustainability. See sustainability.

Sole source aquifer. Underground water supply designated by the Environmental Protection Agency (EPA) as the ‘‘sole or principle’’ source of drinking water for an area as established under section 1424(e) of the Safe Drinking Water Act (42 U.S.C. 300h–3(e)) (36 CFR 219.19).

Source water protection areas. The area delineated by a State or Tribe for a public water system (PWS) or including numerous PWSs, whether the source is ground water or surface water or both, as part of a State or tribal source water assessment and protection program (SWAP) approved by the Environmental Protection Agency under section 1453 of the Safe Drinking Water Act (42 U.S.C. 300h–3(e)) (36 CFR 219.19).

Species of conservation concern. A species, other than federally recognized threatened, endangered, proposed, or candidate species, that is known to occur in the plan area and for which the Regional Forester has determined that the best available scientific information indicates substantial concern about the species' capability to persist over the long-term in the plan area (36 CFR 219.9(c)).

Standard. A mandatory constraint on project and activity decision-making, established to help achieve or maintain the desired condition or conditions, to avoid or mitigate undesirable effects, or to meet applicable legal requirements.

Stressors. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook, factors that may directly or indirectly degrade or impair ecosystem composition, structure, or ecological process in a manner that may impair its ecological integrity, such as an invasive species, loss of connectivity, or the disruption of a natural disturbance regime (36 CFR 219.19).

Substantive formal comments. Written comments submitted to, or oral comments recorded by, the Responsible Official or designee during an opportunity for public participation provided during the planning process (sections 219.4 and 219.16), and attributed to the individual or entity providing them. Comments are considered substantive when they are within the scope of the proposal, are specific to the proposal, have a direct relationship to the proposal, and include supporting reasons for the Responsible Official to consider (36 CFR 219.62).

Suitability of lands. A determination that specific lands within a plan area may be used, or not, for various multiple uses or activities, based on the desired conditions applicable to those lands. The suitability of lands determinations need not be made for every use or activity, but every plan must identify those lands that are not suitable for timber production.

Sustainability. The capability to meet the needs of the present generation without compromising the ability of future generations to meet their needs. For the purposes of the land management planning regulation at 36 CFR part 219 and this Handbook ‘‘ecological sustainability’’ refers to the capability of ecosystems to maintain ecological integrity; ‘‘economic sustainability’’ refers to the capability of society to produce and consume or otherwise benefit from goods and services including contributions to jobs and market and nonmarket benefits; and ‘‘social sustainability’’ refers to the capability of society to support the network of relationships, traditions, culture, and activities that connect people to the land and to one another, and support vibrant communities (36 CFR 219.19).

Sustainable recreation. The set of recreation settings and opportunities on the National Forest System that is ecologically, economically, and socially sustainable for present and future generations (36 CFR 219.19).

Timber harvest. The removal of trees for wood fiber use and other multiple use purposes (36 CFR 219.19).

Threatened Species. Any species that the Secretary of the Interior or the Secretary of Commerce has determined is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range. Threatened species are listed at 50 CFR sections 17.11, 17.12, and 223.102.

Timber production. The purposeful growing, tending, harvesting, and regeneration of regulated crops of trees to be cut into logs, bolts, or other round sections for industrial or consumer use (36 CFR 219.19).

Traditional Ecological Knowledge. See Native Knowledge.

Tribal consultation. A formal government-to-government process that enables Indian Tribes and Alaska Native Corporations to provide meaningful timely input and, as appropriate, exchange views, information, and recommendations on Forest Service proposed policies or actions that may affect their rights or interests prior to a decision. Consultation is a unique form of communication characterized by trust and respect (FSM 1509.05).

Viable population. A population of a species that continues to persist over the long term with sufficient distribution to be resilient and adaptable to stressors and likely future environments (36 CFR 219.19).

Watershed. A region or land area drained by a single stream, river, or drainage network; a drainage basin (36 CFR 219.19).

Watershed condition. The state of a watershed based on physical and biogeochemical characteristics and processes (36 CFR 219.19).

Wild and Scenic River. A river designated by Congress as part of the National Wild and Scenic Rivers System that was established in the Wild and Scenic Rivers Act of 1968 (16 U.S.C. 1271 (note), 1271–1287) (36 CFR 219.19).

Wilderness. Any area of land designated by Congress as part of the National Wilderness Preservation System that was established in the Wilderness Act of 1964 (16 U.S.C. 1131–1136) (36 CFR 219.19).

05.1 – Degree of Compliance or Restriction in this Handbook

Based on FSM 1110.8, the following exhibit 01 explains the degree of compliance as conveyed by the helping verbs, imperative mood, and introductory phrases used in this Handbook.

05.1 - Exhibit 01

Degree of Compliance or Restriction in this Handbook

Helping Verbs	Degree of Compliance or Restriction
must, shall	Action is mandatory and full compliance is required, unless specifically waived in accordance with FSM 1103.
should, ought	Action is mandatory, unless a justifiable reason exists for not taking action. Employees must fully consider, but may depart from based on a written finding as applied to specific circumstances that the deviation will enhance program management efficiency or better achieve desired results or other objectives.
may not	Action is prohibited.
may only	Action is permitted only in the circumstance(s) described.
may	Action is optional.
will	This verb does not convey a degree of restriction or mandate action.
can or could	This verb is not directive; it expresses inherent capability.

Mood of Verb	Degree of Compliance or Restriction
imperative	Direction written with a verb in the imperative mood is also mandatory. For example: “Ensure cost-efficient delivery of services.” In this sentence, the missing subject is understood to be “you” and the direction (“ensure cost-efficient delivery of services”) is a direct command meaning “you shall ensure.” The verb “ensure” is in the imperative mood.

05.1 - Exhibit 01—Continued

Degree of Compliance or Restriction in this Handbook

Introductory phases to lists of items in this handbook	**Degree of Compliance or Restriction**
The task should include:	The following listed items must be done unless a written finding supports another way that enhances efficiency or better achieves desired objectives.
Should consider—	Thinking about a list of considerations is mandatory unless a justifiable reason exists for not taking action.
When doing task A, you may consider— This task A may include information such as— Doing task A, you may consider conditions such as—	Task A is mandatory. You may think about the list or you may consider other items, information, or conditions when doing task A. You may use part of the list, or none of the list.
When there is available information, the responsible official should—	If you have the information, the direction is mandatory unless deviation based on a written finding will enhance efficiency or better achieve desired objectives. If there is no existing information, no action is required.
You should do task A, such as—	Mandatory task, unless deviation based on a written finding will enhance efficiency or better achieve desired objectives. The listed items are optional ways of doing the task. You may select one of the ways or you may do it another way.
Should identify and evaluate relevant information about resource A, such as—	Mandatory to identify and evaluate information about resource, unless deviation based on a written finding will enhance efficiency or better achieve desired objectives. The list provides only examples. You may evaluate other information.

06 – ADAPTIVE MANAGEMENT

The three phases of planning (assessment, planning, and monitoring) in Title 36, Code of Federal Regulations, part 219 (36 CFR 219) are a framework for adaptive management that will facilitate learning and continuous improvement in plans and Agency decision-making. Adaptive management is a structured, cyclical process for planning and decision-making in the face of uncertainty and changing conditions with feedback from monitoring, which includes using the planning process to actively test assumptions, track relevant conditions over time, and measure management effectiveness.

This approach supports decision-making that meets resource management objectives while simultaneously accruing information to improve future management.

06.1 – Features of Adaptive Management

Features of adaptive management include:

1. Explicitly characterizing uncertainty and assumptions.

2. Testing assumptions and collecting data using data collection protocols at appropriate temporal and spatial scales.

3. Analyzing new information obtained through monitoring and project experience.

4. Learning from feedback from monitoring results and new information.

5. Adapting assumptions and strategies to design better plans and management direction.

6. Adjusting actions and making decisions on the basis of what has been learned.

7. Creating an open and transparent process that shares learning internally and with the public.

06.2 – Adaptive Management Questions

The intent of adaptive management in land management planning is to structure the assessment, plan components, and monitoring program in a way that will provide feedback to inform decision-making. Over time, this feedback can provide information about questions such as:

1. Are assumptions being validated, or is there new information that may suggest a need to change assumptions?

2. Are areas of uncertainty being reduced?

3. Are basic conditions that influence the outcome staying the same, or are they changing?

4. Are the actions being taken having the desired effect? Are conditions moving in the desired direction? Is there progress towards achieving desired conditions?

5. How can management be improved so that it is more effective? How can the information be used to change or improve the plan?

6. Does the information indicate other questions or sources of data that could provide further feedback to support improved decision-making?

7. Is the monitoring design effective and are the correct variables being measured at the appropriate spatial and temporal scales?

06.3 – Adaptive Management in the Phases of Planning

Responsible Officials should focus on the purpose of adaptive management during each of the three phases:

1. Assessment phase. Gather and evaluate existing information to form a base of information and context for plan decision-making, and identify important assumptions, areas of uncertainty, and risks.

2. Planning phase. Be responsive to information that is already available, and structure plan components in a way that will allow for monitoring to test the effectiveness of those plan components. Design a monitoring program in the plan to test assumptions, evaluate risks, reduce uncertainties, and measure management effectiveness.

3. Monitoring phase. After the plan has been developed or revised:

   a. Design management activities in a way that will yield specific information and support learning.

   b. Analyze monitoring results in the biennial monitoring report to evaluate progress toward achieving desired conditions and objectives of the plan and to validate the assumptions used in developing the plan. Well-designed monitoring programs using scientific methods and protocols for collecting information contribute to better scientific analysis of these results.

   c. Learn from the results of the evaluation and share with land managers and the public how the results either confirm or modify the existing assumptions or provide feedback on management effectiveness.

d. Use the biennial monitoring report to determine what changes may be needed to the plan, management activities, or to the monitoring program. Adapt planning and management activities based on learning from the evaluation. Adaptation may include modifying assumptions, models, data, and understanding of the system. This knowledge is then used to inform the planning process that leads to adjusting plans and projects.

Based on learning in the monitoring phase, determine if an assessment and/or plan amendment or revision is warranted. A new assessment restarts the basic adaptive management cycle.

07 – USE OF BEST AVAILABLE SCIENTIFIC INFORMATION TO INFORM THE LAND MANAGEMENT PLANNING PROCESS

07.1 – Use of Best Available Scientific Information

The responsible official shall use the best available scientific information to inform the planning process required by this subpart. **(**36 CFR 219.3)

The Responsible Official shall identify and use the best available scientific information (BASI) to inform the planning process and document how BASI was determined to be accurate, reliable, and relevant to issues being considered. The BASI includes relevant ecological, social, and economic scientific information. Use of BASI must be documented for the assessment, the plan decision, and the monitoring program.

While the BASI informs the planning process, plan components, and other plan content, it does not dictate what the decisions must be. There may be competing scientific perspectives and uncertainty in the available science. Plan decisions also reflect other relevant factors such as budget, legal authorities, traditional ecological knowledge, agency policies, public input, and the experience of land managers.

The rule does not require that planning develop additional scientific information, but that planning should be based on scientific information that is already available. New studies or the development of new information is not required for planning unless required by other laws or regulation. In the context of the BASI, "available" means that the information currently exists in a form useful for the planning process without further data collection, modification, or validation. Analysis or interpretation of the BASI may be needed to place it in the appropriate context for planning.

When evaluating the information, the Responsible Official shall be guided by the Forest Service's policies for implementation of the Data Quality Act (Public Law 106-554).
The Responsible Official may choose to subject certain issues to reviews by the scientific community to confirm that the BASI appropriately informed the planning process.

07.11 – Integration of the BASI in the Planning Process

Best available scientific information (BASI) is integrated differently in each phase in the planning process. Sections 07.11a through 07.11c discuss the role of BASI in each phase.

07.11a – Assessment Phase

The assessment phase identifies and evaluates information relevant to the issues that will be considered later in the development of plan components and other plan content. During the assessment, the Responsible Official shall identify and evaluate information, including the conditions and trends about the 15 assessment topics listed in 36 CFR 219.6(b) and the sustainability of social, economic, and ecological systems (36 CFR 219.5(a)(1)). For the assessment, the issues under consideration are those related to the 15 topics and sustainability that form a basis for plan decision-making. This identification and evaluation uses information determined to be the BASI (sec. 07.12 of this Handbook) as well as other information.

Early in the assessment phase the Responsible Official shall provide opportunities for public and governmental participation, inviting submission of information, including scientific information that may be relevant to the planning process. The Responsible Official also provides opportunity for public and governmental participation to develop a shared understanding of the BASI and to make clear how the BASI was identified for the assessment process.

07.11b – Planning Phase

The planning phase begins by making a preliminary identification of the need to change the plan as informed by the assessment. The issues for consideration in the planning phase are identified in the NEPA scoping process and the BASI for these issues is used to inform the development of the plan components and other plan content.

The Responsible Official continues to engage governments and the public on the determination and use of the BASI, as part of the public and governmental participation opportunities provided in the early stages of the planning process. Governments and the public may submit any additional or new scientific information for consideration in the planning process, and the Responsible Official shall determine whether any such information is the BASI.

BASI informs the development of plan components and the evaluation of environmental effects in National Environmental Policy Act (NEPA) documentation. Information identified in BASI, such as uncertainties, risks, opportunities, strategies, or methodologies should be recognized in the planning process to develop management approaches and plan components. The BASI may lead the Responsible Official to consider specific plan components, or a range of potential plan components in the development of the plan.

07.11c – Monitoring

Best available scientific information must be used to inform the development of the monitoring program. The Responsible Official must design the monitoring program to test assumptions used in developing plan components and to evaluate relevant changes and management effectiveness of the plan components.

The issues being considered in the monitoring program are those related to the selection of monitoring questions and indicators in the monitoring program. Typically, monitoring questions seek additional information to increase knowledge and understanding of changing conditions, uncertainties, and risks identified in the BASI as part of an adaptive management framework. BASI can identify indicators that address associated monitoring questions. The BASI is also important in the further development of the monitoring program as it may help identify protocols and specific methods for the collection and evaluation of monitoring information.

07.12 – Determining Best Available Scientific Information

> **. . ., the responsible official shall determine what information is the most accurate, reliable, and relevant to the issues being considered. . .** (36 CFR 219.3)

The Preamble of the planning rule makes clear that there is range of information that can be considered to be the best available scientific information (BASI):

> "In some circumstances, the BASI would be that which is developed using the scientific method, which includes clearly stated questions, well-designed investigations and logically analyzed results, documented clearly and subjected to peer review. However, in other circumstances the BASI for the matter under consideration may be information from analyses of data obtained from a local area, or studies to address a specific question in one area. In other circumstances, the BASI also could be the result of expert opinion, panel consensus, or observations, as long as the responsible official has a reasonable basis for relying on that scientific information as the best available."
> (77 FR 21192 (April 9, 2012))

However, not all information used in the planning process should be considered to be scientific information. Of the scientific information there is a subset that is the BASI. The Responsible Official shall determine the BASI based on the following three criteria:

1. Accurate. To be accurate, the scientific information must estimate, identify, or describe the true condition of its subject matter. This description of the true conditions may be a measurement of specific conditions, a description of operating behaviors (physical, biological, social, or economic), or an estimation of trends. Statistically accurate information is near to the true value of its subject, quantitatively unbiased, and free of error in its methods.

The extent to which scientific information is accurate depends on the relationship of the scientific findings to supportable evidence that identifies the relative accuracy or uncertainty of those findings. The accuracy of scientific information can be more easily evaluated if reliable statistical or other scientific methods have been used to establish the accuracy or uncertainty of any findings relevant to the planning process.

2. Reliable. Reliability reflects how appropriately the scientific methods have been applied and how consistent the resulting information is with established scientific principles. The scientific information is more reliable if it was resulted from an appropriate study design and well-developed scientific methods that are clearly described. The assumptions, analytical techniques, and conclusions are well referenced with citations to relevant, credible literature, and other pertinent existing information. The conclusions presented are based on reasonable assumptions supported by other studies and consistent with the general theory underlying those assumptions or are logically and reasonably derived from the data presented. Any gaps in information and inconsistencies with other pertinent scientific information are adequately explained.

Scientific information that describes statistical or other scientific methods used to determine both its accuracy and uncertainty can be considered to be more reliable. The use of quantitative analysis that has known (and quantifiable) rates of errors and results improves this reliability. An accuracy assessment of the data supports the reliability of the quantitative analysis.

The application of quality control to the scientific information also improves the reliability of the information. One form of quality control is peer review when scientific information has been critically reviewed by qualified scientific experts in that discipline and the criticism provided by the experts has been addressed by the proponents of the information. Publication in a refereed scientific journal usually indicates that the information has been appropriately peer reviewed.

3. Relevant. The information must pertain to the issues under consideration at spatial and temporal scales appropriate to the plan area and to a land management plan. Relevance in the assessment phase is scientific information that is relevant to providing information, including conditions and trends, about the 15 topics in 36 CFR 219(b) or to the sustainability of social, economic, or ecological systems (36 CFR 36 219.5(a)(1)). Relevance in the planning phase is scientific information pertinent to the plan area or issues being considered for the development of plan components or other plan content.

For any particular scientific subject relevant to the planning process, the Responsible Official shall evaluate the scientific information based on the three criteria described. To the extent that a scientific consensus exists, it may be easy to identify the BASI. In other cases, the Responsible

Official may recognize multiple sources and possibly conflicting scientific information as BASI where a clear scientific consensus does not exist. The Responsible Official does not have to identify a single source of scientific information that is "best" as BASI for a specific subject.

07.13 – Sources of Scientific Information

Scientific information that may be considered the BASI includes:

1. Peer reviewed articles.

2. Scientific assessments.

3. Other scientific information, including, expert opinion, panel consensus, inventories, or observational data.

4. Data prepared and managed by the Forest Service or other Federal agencies. This information may include monitoring results, information in spatially referenced databases, data about the lands and resources of the planning unit, and various types of statistical or observational data.

5. Scientific information prepared by universities, national research networks, and other reputable scientific organizations.

6. Data or information from public and governmental participation.

07.14 – Data Quality

The U. S. Department of Agriculture (USDA) and the Forest Service have data quality standards that apply to the use and dissemination of information in the planning process. The USDA information quality guidelines) (*http://www.ocio.usda.gov/policy-directives-records-forms/information-quality-activities*) require USDA agencies to strive to ensure and maximize the quality, objectivity, and integrity of information disseminated to the public. This also includes transparency and documentation to ensure that information used to influence policy meets a basic standard of quality in terms of objectivity, utility, and integrity.

If the scientific information used in the planning process is considered "influential," the Responsible Official shall decide if the material should be, or should have been, peer reviewed. OMB guidelines define "influential" information as information that the agency reasonably can determine will have or does have a clear and substantial impact on important public policies or important private sector decisions. Guidance for determining whether information is "influential" can be found at *http://www.ocio.usda.gov/policy-directives-records-forms/guidelines-quality-information/background*. To determine if there is a need for peer review, the Responsible Official should consider the breadth and intensity of the potential impact, or whether the information affects a broad range of parties and may have a costly or crucial impact. The Forest Service provides guidance for the peer review process at: *http://www.fs.fed.us/qoi/peerreview.shtml*.

07.15 – Documenting Best Available Scientific Information in the Planning Process

> **. . . The responsible official shall document how the best available scientific information was used to inform the assessment, the plan decision and the monitoring program as required in 219.6(a)(3) and 219.14(a)(4). Such documentation must: Identify what information was determined to be the best available scientific information, explain the basis for that determination, and explain how the information was applied to the issues considered.** (36 CFR 219.3)
>
> *****
>
> **(3) . . . Document in the [assessment] report how the best available scientific information was used to inform the assessment (§219.3). . . .** (36 CFR 219.6(a))
>
> *****
>
> **(a) *Decision document.* The responsible official shall record approval of a new plan, plan amendment, or revision in a decision document prepared according to Forest Service NEPA procedures (36 CFR 220). The decision document must include**
>
> ***
>
> **(4) The documentation of how the best available scientific information was used to inform planning, the plan components, and other plan content including the plan monitoring program (§219.3). . .** (36 CFR 219.14)

The Responsible Official shall document how the best available scientific information (BASI) informed the assessment, the plan decision, and the monitoring program as required by the planning rule. The documentation in the assessment report and the decision document should summarize how the BASI information was applied to the issues considered. The assessment report and the decision documents are not intended to be research papers or a comprehensive survey of the science used in the planning process. Instead, these documents are intended to provide a summary sufficient to provide the reader with an understanding of what was determined to be the BASI, how it was determined to the BASI, and how it was used to inform the assessment, planning process, plan components, and other plan content including the monitoring program. Documentation of the BASI should occur throughout the planning process in the planning record.

The amount of detail to include in the summary depends upon a number of factors, such as the controversy over the issue or the amount of controversy about the scientific information itself (how much disagreement there is by scientists and/or others as to whether the information is the BASI). For some topics, the discussion of BASI could be very brief but in others it would be a more detailed documentation.

Documents associated with the planning process should use standard citations to link findings or information to the BASI. The use of such citation in the documents should provide evidence of how the BASI was used to inform consideration of the issues. The assessment report, environmental documents, and the decision document should use citations as one of the principal methods to show how the BASI was applied to the issues being considered and provide additional explanation if needed.

07.15a – Documentation of Best Available Scientific Information in the Assessment Report

Documentation of BASI is used to inform the assessment should focus on how the BASI informed the evaluation of conditions and trends for the 15 topics of the assessment (36 CFR 219.6(b)), the sustainability of social, economic, and ecological systems (36 CFR 219.5(a)(1)), and any other topic identified by the responsible official for the assessment. In doing so, the Responsible Official shall:

1. Identify the scientific information determined to be the BASI based on what is most accurate, reliable, and relevant to the issues of the assessment. This may be done through reference to a list of the BASI or other methodology as determined by the Responsible Official. Explain the basis for this determination.

2. Describe how the BASI was used to inform the assessment for the issues being considered. This can be done through a brief explanation and citation of the BASI. Contradictory BASI should also be briefly described.

07.15b – Documenting Best Available Scientific Information in the Plan Decision Document

Documentation of the BASI in the decision document should focus on how it was used to inform the development of plan components and other plan content, including the plan monitoring program. In doing so, the Responsible Official shall:

1. Identify the information determined to be the BASI, based on the determination of what is most accurate, reliable, and relevant for the issues being considered (sec. 07.12 of this Handbook). This may be done through reference to a list of the BASI or other methodology as determined by the Responsible Official. Explain the basis for this determination.

2. Describe how the BASI was used to inform the development of plan components, or sets of plan components, and other plan content, including the plan monitoring program. This can be done through a brief explanation and citation of the BASI. Contradictory BASI should also be briefly described.

The Responsible Official should also summarize the general process of how the BASI was identified, evaluated, and used throughout the planning process. This summary should describe outreach to gather scientific information, the evaluation process, models and methods used, evaluation of risks, uncertainties or assumptions, and any science reviews conducted (sec. 07.2 of this Handbook).

07.2 – Optional Science Reviews in the Land Management Planning Process

The Responsible Official, Project Manager, or Interdisciplinary Team Leader, may choose to initiate a science review of the identification and use of BASI to inform the assessment or planning process. Science reviews may cover one or more specific scientific questions or the overall use of scientific information in the assessment or planning process. Science reviews can occur on a continuum from less formal reviews to validate how specific BASI is identified and used to inform the planning process to a more formal review of the use of BASI in plan documents (sec. 07.21 of this Handbook). Science reviews are discretionary.

The purpose of science reviews is to support the quality and credibility of planning and to review whether the BASI adequately informed the planning process. The review may focus on a specific aspect of the scientific information under consideration or evaluate how scientific information was used throughout the planning process. Reviews should be conducted in a timely and expeditious manner to provide useful feedback that is within the defined scope of the planning process.

1. A science review may be considered when:

   a. There is substantial controversy regarding a specific science issue.

   b. There is perceived to be substantial risk to important resources in the plan area or the broader landscape.

   c. There is a lack of scientific consensus or a high degree of uncertainty around a science question.

   d. The Responsible Official or interdisciplinary Team Leader wants broader confirmation that the scientific information considered is credible or that its interpretation is correct.

2. A science review may address central questions, including:

   a. Has applicable and available scientific information been considered and interpreted appropriately?

   b Has the Responsible Official appropriately determined the BASI?

   c. Have the uncertainties, risks, and assumptions associated with the scientific information been accurately acknowledged and documented?

07.21 – Levels of Science Reviews

Each science review is unique, but the range of science reviews can be represented with different levels varying in intensity from less formal to more formal. For less formal or lower-level review, the Interdisciplinary Team Leader may initiate or manage the review. Only the Responsible Official may initiate a more formal or higher-level review. Exhibit 01 displays factors to consider when determining what level of review is appropriate.

07.21 - Exhibit 01

Level of Review Factors

Factors	Lower Level of Review	Higher Level of Review
State of the Knowledge	Well-developed routine analysis. Professionally recognized science findings.	Emerging science and technology. Inconsistent findings and interpretations.
Data Availability	Well-developed data. Well-accepted techniques.	Data gaps. Highly insufficient data or collection techniques.
Controversy	Generally accepted.	Highly disputed.
Risk	Risk to elements of sustainability is low.	Risk to elements of sustainability is high.

A lower-level review focuses on basic consideration and evaluation of specific scientific information and how to use such information in the planning process. These reviews would normally occur early in the process as a review of work in progress before publication of documents. Such a review can be a check that the scientific information is being correctly interpreted and applied. Lower-level reviews may be informal and use reviewers who primarily work for the Forest Service. Some draft material may also be reviewed for feedback that the scientific information is being correctly interpreted and applied. The interdisciplinary team may adjust the work in progress as a result of these reviews.

The purpose of higher-level review is a more comprehensive check on the interpretation and application of the scientific information in draft documents such as the draft assessment or draft environmental document. Such review would not be used to evaluate the merit of plan components. Higher-level review normally occurs later in the process when draft documents have been developed. Higher-level review may involve reviewers outside the Forest Service who submit written comments. Higher-level reviews need careful focus in forming questions for the review and overall management to ensure response is timely in the planning process. Response by the Responsible Official may lead to adjustments in the documents reviewed.

08 – REFERENCES

This section displays major statutes, regulations, and guidelines needed to carry out the procedures in this Handbook.

08.1 – Planning

1. Text of the Forest and Rangeland Renewable Resources Planning Act of 1974, as amended by the National Forest Management Act of October 22, 1976 (collectively referred to as NFMA) (16 USC at 1600-1614) available at: *http://www.fs.fed.us/emc/nfma/includes/RPA_amended_by_NFMA_USCver.pdf.*

2. Text of 36 CFR 219 governing land and resource management planning as amended through April 19, 2013, available at: *http://www.gpo.gov/fdsys/pkg/CFR-2013-title36-vol2/pdf/CFR-2013-title36-vol2-part219.pdf.*

3. Text of 2000 planning rule (36 CFR 219 (2011)) (available at: *http://www.gpo.gov/fdsys/pkg/CFR-2011-title36-vol2/pdf/CFR-2011-title36-vol2-part219-subpartA.pdf.*

4. Text of the 1982 planning rule procedures (36 CFR 219 (2000)), available at: *http://www.fs.fed.us/emc/nfma/includes/nfmareg.html.*

5. Text of the Wilderness Act of September 3, 1964 (16 USC 1131-1136) is available at: *http://www.gpo.gov/fdsys/pkg/USCODE-2012-title16/pdf/USCODE-2012-title16-chap23.pdf.*

6. Text of the Eastern Wilderness Act of January 3, 1975 (Public Law 93- 622; 16 USC 1132 (note)) is available at: *http://www.wilderness.net/NWPS/documents/publicLaws/PDF/93-622.pdf.*

7. Selected text of the Wild and Scenic Rivers Act of October 2, 1968 (Public Law 90-572; 16 USC 1271-1287), as amended, is available at: *http://www.rivers.gov/documents/wsr-act.pdf.*

8. Text of the Departments of the Interior and Agriculture Guidelines for Eligibility, Classification, and Management of River Areas (47 FR 39454, September 7, 1982) is available at: *http://www.rivers.gov/documents/guidelines.pdf.*

FOREST SERVICE MANUAL
NATIONAL HEADQUARTERS (WO)
WASHINGTON, DC

FSM 2000 – NATIONAL FOREST RESOURCE MANAGEMENT

CHAPTER 2020 – ECOSYSTEM RESTORATION

Amendment No.: 2000-2016-1

Effective Date: May 27, 2016

Duration: This amendment is effective until superseded or removed.

Approved: GREGORY SMITH
Acting Associate Deputy Chief

Date Approved: 09/04/2014

Posting Instructions: Amendments are numbered consecutively by title and calendar year. Post by document; remove the entire document and replace it with this amendment. Retain this transmittal as the first page(s) of this document. The last amendment to this title was 2000-2013-1 to FSM 2060.

New Document	2020	9 Pages
Superseded Document(s) by Issuance Number and Effective Date	id_2020-2015-1, 10/15/2015	12 Pages

Digest:

2020 - Incorporates id_2020-2015-1 in its entirety.

2020.5 - Revises terminology in several definitions: (1) for consistency with definitions used by the Intergovernmental Panel on Climate Change (IPCC) in the IPCC Fourth Assessment Report, Climate Change 2007, Synthesis Report, Annex II Glossary; and (2) in response to public comment received on the proposed planning rule Title 36, Code of Federal Regulations, Part 219—Planning, Subpart A--National Forest System Land Management Planning (36 CFR part 219, subpart A).

Table of Contents

FSM 2020 provides policy for reestablishing and retaining ecological resilience of National Forest System lands and resources to achieve sustainable multiple use management and provide a broad range of ecosystem services. Resilient ecosystems have greater capacity to survive disturbances and large-scale threats, especially under changing and uncertain future environmental conditions, such as those driven by climate change and human uses. The directive reaches across all program areas and activities applicable to management of National Forest System lands and resources so as to ensure integration and coordination at all levels and organizational units. It does not directly affect land management plans or the occupancy and use of National Forest System lands, leaving to responsible officials the discretion to decide when and how to authorize restoration projects and activities. When applying or implementing this policy, the Forest Service must comply with applicable laws and regulations, including the National Forest Management Act (NFMA), Multiple-Use Sustained-Yield Act (MUSYA), and the principal statutes in section FSM 2020.11.

2020.1 – Authority

The authority for sustainably managing the National Forest System derives from laws enacted by Congress that set out the purpose for which it has been established and is to be administered. These laws are cited throughout the Forest Service Manual and Handbooks. FSM 1010 lists the most significant laws and provides guidance on where to obtain copies of them.

The history of federal policies, treaties, statutes, court decisions, and Presidential direction regarding Indian Tribes and tribal rights and interests is extensive. FSM 1563.01a through FSM 1563.01i set out the legal authorities relevant to Forest Service relationships with Tribes.

The President issued direction through several Executive Orders relevant to protection of resources or restoration of ecosystem processes and functions (FSM 2020.12). Also, numerous regulations governing the sustainable management and restoration of National Forest System lands are found in the Code of Federal Regulations under Title 36, Chapter II, parts 200-299.

2020.11 – Laws

The principal statutes governing the reestablishing and retaining ecological resilience of National Forest System lands and resources to achieve sustainable multiple use management and provide a broad range of ecosystem services, include but are not limited to, the following statutes, which are listed in alphabetical order. Except where specifically stated, these statutes apply to all National Forest System lands and resources.

1. <u>Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974, as amended by National Forest Management Act (NFMA) of 1976 (16 U.S.C. 1600-1614, 472a)</u>. This Act states that the development and administration of the renewable resources of the National Forest System are to be in full accord with the concepts for multiple use and sustained yield of products and services as set forth in the Multiple-Use Sustained-Yield

Act of 1960. The Act establishes the policy of the Congress that all forested lands in the National Forest System be maintained in appropriate forest cover with species of trees, degree of stocking, rate of growth, and stand conditions designed to secure the maximum benefits of multiple use sustained yield management in accordance with land management plans. It sets forth the requirements for land and resource management plans for units of the National Forest System, including requiring guidelines to provide for the diversity of plant and animal communities based on the suitability and capability of the specific land area and within multiple use objectives.

2. <u>Healthy Forests Restoration Act (HFRA) of 2003 (16 U.S.C. 6501-6591)</u>. This Act provides processes for developing and implementing hazardous fuel reduction projects on certain types of "at-risk" National Forest System and Bureau of Land Management (BLM) lands, and also provides other authorities and direction to help reduce hazardous fuels and protect, restore, and enhance healthy forest and rangeland ecosystems.

3. <u>Multiple-Use Sustained-Yield Act of 1960 (16 U.S.C. 528-531)</u>. This Act states that the National Forests are to be administered for outdoor recreation, range, timber, watershed, and wildlife and fish purposes, and adds that the establishment and maintenance of wilderness areas are consistent with this Act. This Act directs the Secretary to manage renewable surface resources of the National Forests for multiple use and sustained yield of the several products and services obtained therefrom. Multiple use means the management of all the various renewable surface resources of the National Forests in the combination that will best meet the needs of the American people; providing for periodic adjustments in use to conform to changing needs and conditions; and harmonious and coordinated management of the resources without impairment of the productivity of the land. Sustained yield of the several products and services means achieving and maintaining in perpetuity a high-level annual or regular periodic output of renewable resources without impairment of the productivity of the land.

4. <u>Organic Administration Act (at 16 U.S.C. 475, 551)</u>. This Act states the purpose of the National Forests, and directs their control and administration to be in accord with such purpose, that is, "[n]o national forest shall be established, except to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States." Authorizes the Secretary of Agriculture to "make such rules and regulations . . . to preserve the [national] forests from destruction."

Other statutes, regulations, and Executive Orders related to the policies in the restoration policy are referenced in FSM 2020.6.

2020.2 – Objective

Ecosystems ecologically or functionally restored, so that over the long term they are resilient and can be managed for multiple use and provide ecosystem services, including but not limited to carbon storage and sequestration.

2020.3 – Policy

1. The Forest Service will emphasize ecosystem restoration across the National Forest System and within its multiple use mandate.

2. The Forest Service land and resource management plans, project plans, and other Forest Service activities may include goals or objectives for restoration. The goals or objectives for ecosystem restoration must be consistent to all applicable laws and regulations. In development of restoration goals or objectives, the Forest Service should consider:

a. factors such as the following:

(1) public values and desires;

(2) the natural range of variation (NRV);

(3) ecological integrity;

(4) current and likely future ecological capabilities;

(5) a range of climate and other environmental change projections;

(6) the best available scientific information; and,

(7) detrimental human uses.

b. technical and economic feasibility to achieve desired future conditions.

c. ecological, social, and economic sustainability.

d. the recovery, maintenance, and enhancement of carbon stocks.

e. opporunities to incorporate restoration objectives into resource management projects to achieve complementary or synergistic results.

f. the concept that an ecological system is dynamic and follows an ecological trajectory

g. the social, economic and ecological influences of restoration activities at multiple scales.

3. The Forest Service may reestablish, maintain, or modify the composition, structure, function, and connectivity of aquatic and terrestrial ecosystems in order to sustain their resilience and adaptive capacity.

4. Activities with localized, short-term adverse effects may be acceptable in order to achieve long-term restoration objectives.

5. The definitions for following terms in this policy are identical to the definitions for the same terms in the National Forest System, Land Management Planning Directive: adaptation, adaptive capacity, adaptive management, disturbance, disturbance regime, ecological integrity, ecosystem, ecosystem services, landscape, natural range of variation (NRV), resilience, restoration–ecological, restoration–functional, stressors, and sustainability. (FSH 1909.12, zero code, section 05).

6. When ecosystems have been altered to such an extent that reestablishing key ecosystem characteristics within the NRV may not be ecologically or economically possible, the restoration focus should be to create functioning ecosystems.

7. Resource managers should consider ecological conditions across ownerships and jurisdictions to develop and achieve landscape restoration objectives by engaging the public, State and local governments, and consultation with Indian Tribes.

8. Not all natural resource management activities are required to include restoration, and not all National Forest System lands require restoration.

2020.4 – Responsibility

The responsible officials to carry out the Ecosystem Restoration Policy are the Agency employees who have the delegated authority to approve land and resource management plans, project plans, or other Forest Service activities.

2020.5 – Definitions

The definitions at the Land Management Planning Handbook, FSH 1909.12, zero code chapter, section 05 at *http://www.fs.fed.us/im/directives/fsh/1909.12/wo_1909.12_zero_code.docx* apply for the following terms in this policy: adaptation, adaptive capacity, adaptive management, carbon pool, carbon stocks, disturbance, disturbance regime, ecological integrity, ecosystem, ecosystem services, landscape, natural range of variation (NRV), resilience, restoration–ecological, restoration–functional, stressors, and sustainability.

2020.6 – References

This section displays references to statutes, regulations, and Executive Orders related to the policies in FSM 2020.

2020.61 – References to Statutes

1. Text of the Agricultural Act of 2014 (16 U.S.C. 6591c and 16 U.S.C. 2113a) Title VIII, Sections 8205 & 8206 is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2014-title16/pdf/USCODE-2014-title16-chap84-subchapVI-sec6591c.pdf* and *https://www.gpo.gov/fdsys/pkg/USCODE-2014-title16/pdf/USCODE-2014-title16-chap41-sec2113a.pdf*.

2. Text of the Anderson-Mansfield Reforestation and Revegetation Joint Resolution Act of 1949 (at 16 U.S.C. 581j and 581j (note)) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap3-subchapII-sec581j.pdf*.

3. Text about visibility protection for Federal class I areas (43 U.S.C. 7491) and text about Control of air pollution from Federal facilities under the Clean Air Act (42 U.S.C. 7401, 7418, 7470. 7472, 7474, 7475, 7491, 7506, 7602) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2014-title42/pdf/USCODE-2014-title42-chap85-subchapI-partC-subpartii-sec7491.pdf* and *https://www.gpo.gov/fdsys/pkg/USCODE-2014-title42/pdf/USCODE-2014-title42-chap85-subchapI-partA-sec7418.pdf*.

4. Text about Federal facilities water pollution control responsibilities (33 U.S.C. 1323) under the Clean Water Act (33 U.S.C. 1251, 1254, 1323, 1324, 1329, 1342, 1344) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2014-title33/pdf/USCODE-2014-title33-chap26-subchapIII-sec1323.pdf*.

5. Text of the Endangered Species Act of 1973 (16 U.S.C. 1531-1544, as amended) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap35.pdf*.

6. Text of the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974, as amended by National Forest Management Act (NFMA) of 1976 (16 U.S.C. 1600-1614, 472a) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2010-title16/html/USCODE-2010-title16-chap5C.htm*.

7. Text of the Granger-Thye Act (16 U.S.C. at 580g-h) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap3-subchapI-sec580g.pdf* and *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap3-subchapI-sec580h.pdf*.

8. Text of the Healthy Forests Restoration Act (HFRA) of 2003 (16 U.S.C. 6501-6591) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap84.pdf*.

9. Text of the Knutson-Vandenberg Act (16 U.S.C. at 576b) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap3-subchapI-sec576b.pdf*.

10. Text of the Magnuson-Stevens Fishery Conservation and Management Act of 2006 (16 U.S.C. 1855, as amended) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap38-subchapIV-sec1855.pdf*.

11. Text of the Multiple-Use Sustained-Yield Act of 1960 (16 U.S.C. 528-531) is available at: *http://www.fs.fed.us/emc/nfma/includes/musya60.pdf*.

12. Text of the National Environmental Policy Act of 1969 (NEPA) (42 U.S.C. 4321 et seq.) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title42/pdf/USCODE-2011-title42-chap55.pdf*.

13. Text of the North American Wetland Conservation Act (16 U.S.C. 4401 (note), 4401-4413, 16 U.S.C. 669b (note)). Section 9 (U.S.C. 4408) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap64-sec4408.pdf*.

14. Text of the Organic Administration Act (at 16 U.S.C. 475, 551) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap2-subchapI-sec475.pdf* and *https://www.gpo.gov/fdsys/pkg/USCODE-2011-title16/pdf/USCODE-2011-title16-chap3-subchapI-sec551.pdf*.

15. Text of the Sikes Act (16 U.S.C. at 670g) is available at: *https://www.gpo.gov/fdsys/pkg/USCODE-2010-title16/html/USCODE-2010-title16-chap5C.htm*.

16. Text of the Tribal Forest Protection Act of 2004 (25 U.S.C. 3115a) is available at: *http://www.fs.fed.us/restoration/documents/stewardship/tfpa/TribalForestProtectionAct2004.pdf*.

17. Text of the Weeks Act, as amended (at 16 U.S.C. 515, 552) is available at: http://www.fs.fed.us/land/staff/Documents/Weeks%20Law.pdf.

18. Text of the Wilderness Act of September 3, 1964 (16 U.S.C. 1131-1136) is available at: http://www.gpo.gov/fdsys/pkg/USCODE-2012-title16/pdf/USCODE-2012-title16-chap23.pdf.

19. Selected text of the Wild and Scenic Rivers Act of October 2, 1968 (Public Law 90-572; 16 U.S.C. 1271-1287), as amended, is available at: http://www.rivers.gov/documents/wsr-act.pdf.

2020.62 – References to Federal Regulations

Text of 36 CFR 219 governing land and resource management planning as amended through April 19, 2013 is available at: http://www.gpo.gov/fdsys/pkg/CFR-2013-title36-vol2/pdf/CFR-2013-title36-vol2-part219.pdf.

2020.63 – References to Executive Orders

1. Text of Executive Order 11514 issued March 5, 1970, as amended by E.O. 11991, issued May 24, 1977. Protection and enhancement of environmental quality (35 FR 4247, March 7, 1970; 42 FR 26967, May 25, 1977) is available at: *http://www.archives.gov/federal-register/codification/executive-order/11514.html*.

2. Text of the *Executive Order 11644* issued February 8, 1972. Use of off-road vehicles on the public lands. (37 FR 2877, February 9, 1972). Amended by E.O. 11989 issued May 24, 1977 and E.O. 12608 issued September 9, 1987 is available at: *http://www.archives.gov/federal-register/codification/executive-order/11644.html*.

3. Text of the *Executive Order 11988* issued May 24, 1977. Floodplain management (42 FR 26951 (May 25, 1977)) is available at: *http://www.archives.gov/federal-register/codification/executive-order/11988.html.*

4. Text of the Executive Order 11990 issued May 24, 1977. Protection of wetlands. (42 FR 26961, May 25, 1977) is available at: *http://www.archives.gov/federal-register/codification/executive-order/11990.html*.

5. Text of the *Executive Order 13112* issued February 3, 1999. Invasive Species. (64 FR 6183 (February 8, 1999)) is available at: *https://www.gpo.gov/fdsys/pkg/FR-1999-02-08/pdf/99-3184.pdf*.

6. Text of the *Executive Order 13653* issued November 1, 2013. Preparing the United States for the Impacts of Climate Change. (78 FR 66819 (November 6, 2013)) is available at: *https://www.gpo.gov/fdsys/pkg/FR-2013-11-06/pdf/2013-26785.pdf*.

Estimating Regional Wood Supply Based on Stakeholder Consensus for Forest Restoration in Northern Arizona

Haydee M. Hampton, Steven E. Sesnie, John D. Bailey, and Gary B. Snider

ABSTRACT

Thinning treatments focused on small-diameter trees have been designed to restore fire-adapted ponderosa pine ecosystems. Estimating the volume of wood byproducts derived from treatments can assist with agency planning of multiyear thinning contracts that sustain existing and attract new wood product businesses. Agency, local government, industry, and environmental representatives were engaged to assess the level of agreement on restoration treatments in northern Arizona. Participants unanimously agreed on appropriate management across two-thirds of the 2.4 million ac analysis area and defined desired posttreatment conditions using forest structure information derived from remotely sensed data. Results indicate that an estimated 850 million ft^3 of stem volume and 8.0 million green tn of tree crown biomass could be generated from tree thinning to reestablish fire-adapted conditions and stimulate new economic opportunities while meeting social and environmental criteria. Wood supply defined by stakeholders exceeded current utilization levels by 88% when extrapolated over the next 10 years.

Keywords: restoration treatments, wood supply, stakeholder agreement, ponderosa pine

Agreement exists among stakeholders that ponderosa pine (*Pinus ponderosa*) forest ecosystems in the southwestern United States are in urgent need of restoration to conditions supporting frequent and low-intensity fire regimes (Allen et al. 2002). Forest structural changes in these systems, such as increased surface fuel loading, crown contiguity, and ladder fuels known to bolster the size and intensity of crown fires, have been attributed to over 100 years of fire suppression, livestock grazing, human development, selective harvesting of large trees, predator control, and other human activities (Covington and Moore 1994, Mast et al. 1999, Swetnam et al. 1999). A subsequent increase in small-diameter trees and hazardous fuels conditions has precipitated severe fire behavior at an unprecedented scale, such as the 2002 Rodeo-Chediski fire, Arizona's largest wildfire in recorded history (467,066 ac). This and other recent severe wildfire events, which compromise watershed, wildlife, and aesthetic values, have galvanized public support for active and broad-scale forest restoration activities. Reductions in overall forest structural heterogeneity and understory species composition are also of concern in terms of diminished biodiversity levels (Allen et al. 2002, Chambers and Germaine 2003).

Mechanical tree thinning and prescribed burning are recommended to aid in restoring ponderosa pine forests throughout the Southwest (Fulé et al. 2001a, Pollet and Omi 2002, Graham et al. 2004, Schoenna-

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Table 1. List of wood supply working group members and affiliations.

Name	Position	Affiliation
Ethan Aumack	Director of Restoration Programs	Grand Canyon Trust
Pascal Berlioux	President and Chief Executive Officer	Arizona Forest Restoration Products Inc.
Kim Newbauer	Timber Sales Contracting Officer	Coconino National Forest
Rob Davis	**President/Owner**	**Forest Energy/Future Forests**
Paul DeClay Jr.[a]	Tribal Forest Manager	White Mountain Apache Tribal Forestry
Jerry Drury	Timber Staff Officer	Kaibab National Forest
Steve Gatewood	**Owner/Consultant**	**WildWood Consulting, LLC, representing Greater Flagstaff Forests Partnership**
Bill Greenwood	City Manager	Town of Eagar
Shaula Hedwall	Senior Fish and Wildlife Biologist	US Fish and Wildlife Service
Scott Higginson	Executive Vice-President	NZ Legacy, LLC/Snowflake White Mountain Power/Renegy, LLC
Herb Hopper[b]	Community-based forest and wood products advocate	Little Colorado Plateau Resource, Conservation and Development
Robert LaCapa	Forest Manager	Fort Apache Agency, Branch of Forestry, Bureau of Indian Affairs, Department of the Interior
Sarah (Lantz) Reif	Urban Wildlife Planner	Arizona Game and Fish Department, Region II, Flagstaff Office
Lisa McNeilly	Northern Arizona Program Director	The Nature Conservancy
Keith Pajkos	Timber Staff Officer	Arizona State Lands Department, Forestry Division
Chuck Peone Jr.	Tribal Forester	Fort Apache Timber Company
Molly Pitts[b]	Community-based forest and wood products advocate/Consulting forester	Northern Arizona Wood Products Association
Todd Schulke	**Forest Programs Director**	**Center for Biological Diversity**
Larry Stephenson	Executive Director	Eastern Arizona Counties/Economic Environmental Counties Organization
Diane Vosick	**Associate Director**	**Ecological Restoration Institute**
Elaine Zieroth[c]	**Forest Supervisor**	**Apache-Sitgreaves National Forests**

Steering committee member information is shown in bold type.
[a] The authors were honored by Paul DeClay Jr.'s presence before his passing in November 2007. They recognize the helpful participation of Mary Stuever, White Mountain Apache Tribe Forestry, who served as an alternate representative for the tribe at project workshops.
[b] Invited to alternate attendance occupying one shared seat to better accommodate their schedules.
[c] Retired in December 2007 and replaced by Robert Taylor, Supervisory Natural Resource Specialist, Apache-Sitgreaves National Forests.

gel et al. 2004). However, broad stakeholder agreement on acceptable treatment levels at the regional scale is needed to improve forest health conditions over extensive areas of the inland West. Because forest restoration has not kept pace with hazardous fuels accumulation (Stephens and Ruth 2005, Hjerpe and Kim 2008), efforts are underway in many western states to develop private wood products businesses that could purchase restoration byproducts. Restoration projects implemented through US Forest Service thinning contracts that guarantee supply over several years will help forest restoration–based industries attract investors and meet lending requirements and provide a cost-effective mechanism to restore fire-adapted conditions over large areas (US Public Law 108-7 2003). By reaching agreement across large areas, stakeholders gain assurance that industry will be "appropriately scaled" (i.e., the need to improve forest health will drive utilization opportunities) and individual project decisions will be designed within a framework of acceptable thinning levels. Significant administrative cost savings will likely stem from this approach, e.g., as increased trust and understanding translates into reductions in controversy over proposed forest management actions on public land.

In northern Arizona, agency representatives and stakeholder groups believe that forest restoration can lead to the creation of new utilization opportunities while existing industries can continue to help achieve landscape-level restoration goals. In 2006, an ad hoc group of forest restoration professionals from agencies, environmental organizations, community forest partnerships, and academia in Arizona and New Mexico convened to determine the steps needed to accomplish these objectives. At a meeting of the ad hoc group, five members volunteered to form a steering committee designed to represent a diversity of backgrounds and stakeholder interests (Table 1) to act as advisors in the collaborative process, public outreach, and other aspects of the project described here. Concurrent with this process, Arizona's governor-appointed Forest Health Council developed a Statewide Strategy for Restoring Arizona's Forests outlining similar recommendations and action items (Governor's Forest Health Councils 2007). The two priority information needs emerging from these efforts were (1) an estimate of restoration treatment levels that could be considered ecologically appropriate and broadly accepted by stakeholders and (2) an estimate of the potential wood volume from large-scale forest restoration treatments that could supply existing and proposed wood utilization facilities. To perform these analyses, an assessment of existing forest structural conditions and potential wood supply derived from forest thinning was needed across multiple land-management jurisdictions and locations where up-to-date forest inventory data is typically lacking.

We present a case study that focused on filling the aforementioned information gaps and advancing Arizona's newly crafted state restoration strategy. Case studies are useful tools to establish innovative and creative problem-solving mechanisms for mediating contemporary land-management issues. To accomplish this, and with substantial guidance from the steering committee, we

• Organized a series of highly focused stakeholder workshops to identify acceptable locations and restoration treatment levels and consequent wood supply.

• Developed new data resources using US Forest Service Forest Inventory and

Designing successful collaborations. The importance of obtaining broad stakeholder acceptance of land-management practices has increased since 1970, when the first US Forest Service land-management decision was overturned in court (Coggins et al. 2001). In a study of over 700 final case outcomes between 1989 and 2002, Keele et al. (2006) found litigants won or obtained settlements in approximately 40% of cases brought against the US Forest Service. In an effort to avoid high litigation costs and adversarial interactions, most state, federal, and regional policies over the last 6 years call for the use of collaboration in land-management decision-making (Vosick et al. 2007). To be truly collaborative, a process needs to involve more than gathering and summarizing input from stakeholders, such as accomplished in open houses, public hearings, and comment periods typical of most NEPA processes. To make informed recommendations, our project steering committee sought a higher level of participation including access to planning and assessment tools. With their guidance, we performed a process encompassing the following major factors correlated with successful collaboration (Cestero 1999; Moote and Lowe 2008):

- Involve recognized authorities having
  - —Broad representation
  - —Formal recognition by government units
  - —Ability and willingness to work together
- Secure adequate resources
- Follow existing regulations
- Provide common factual basis
- Develop and adhere to agreed on and achievable goals while maintaining flexibility
- Maintain a fair, open, and effective process

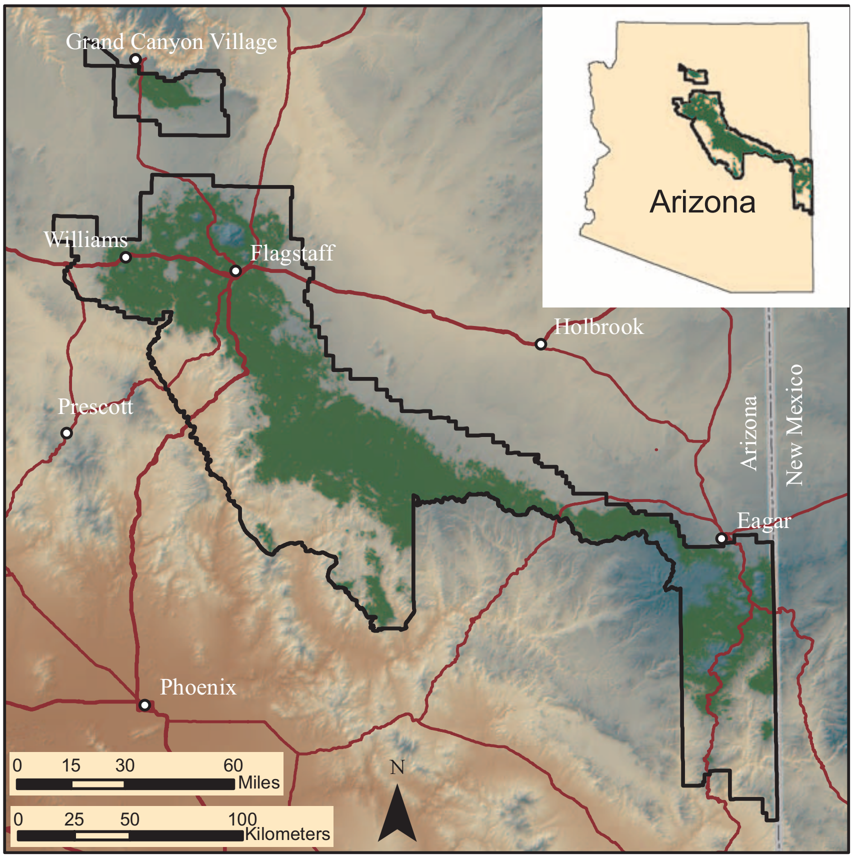


Figure 1. Map detailing the 2.4 million–ac wood supply analysis area in northern Arizona. The study area includes ponderosa pine and pine–oak vegetation (shown in green) south of the Grand Canyon and across the Mogollon Plateau to the border of Arizona and New Mexico within the proclamation boundaries of the Kaibab (South of Grand Canyon), Coconino, and Apache-Sitgreaves National Forests, and the Payson and Pleasant Valley Ranger Districts of the Tonto National Forest (outlined in black).

Analysis (FIA) plot data combined with remote-sensing techniques to estimate existing wood volume and potential supply across Arizona's most contiguous forest type (ponderosa pine).

The principal objective of this study was to determine a socially and environmentally credible region-scale wood supply estimate based on thinning levels and locations required to accomplish forest restoration and improve forest health. Laird (1993) argues that the economic and social implications of technological and environmental issues create a normative requirement that they be subject to democratic scrutiny. This study integrates the idea of "discursive democracy" or public input in decisionmaking intrinsic to the democratic process (Dryzek 1990) and encouraging "participatory science" or public participation in science (Fischer 2000). The stated intent of the US Forest Service was to use the supply estimate as a tool for developing long-term thinning contracts and to inform local planning. The estimate would also serve to foster expanded and appropriately scaled restoration-based wood products businesses.

Analysis Area

The steering committee selected a 2.4 million ac analysis area in northern Arizona (Figure 1). The analysis area was selected because it comprises the largest contiguous ponderosa pine forest in Arizona. Recent wildfire activity has shown to pose an extreme threat to human communities and multiple ecosystem values for this area. The area included the White Mountain Stewardship project designed to thin approximately 150,000 ac of forest in the wildland–urban interface (WUI; Neary and Zieroth 2007, Fleeger 2008). The analysis area did not include extensive ponderosa pine forests on White Mountain Apache tribal lands, which could potentially contribute to regional wood supply. Ninety-five percent of the analysis area includes US Forest Service lands. Decisions on these lands must be consistent with the National Forest Management Act, National Environmental Policy Act (NEPA), and other laws and regulations.

Method for Building Agreement on Selection of Treatment Area Location and Type

To build agreement among stakeholders in the region on the location and type of restoration treatments, we worked with the

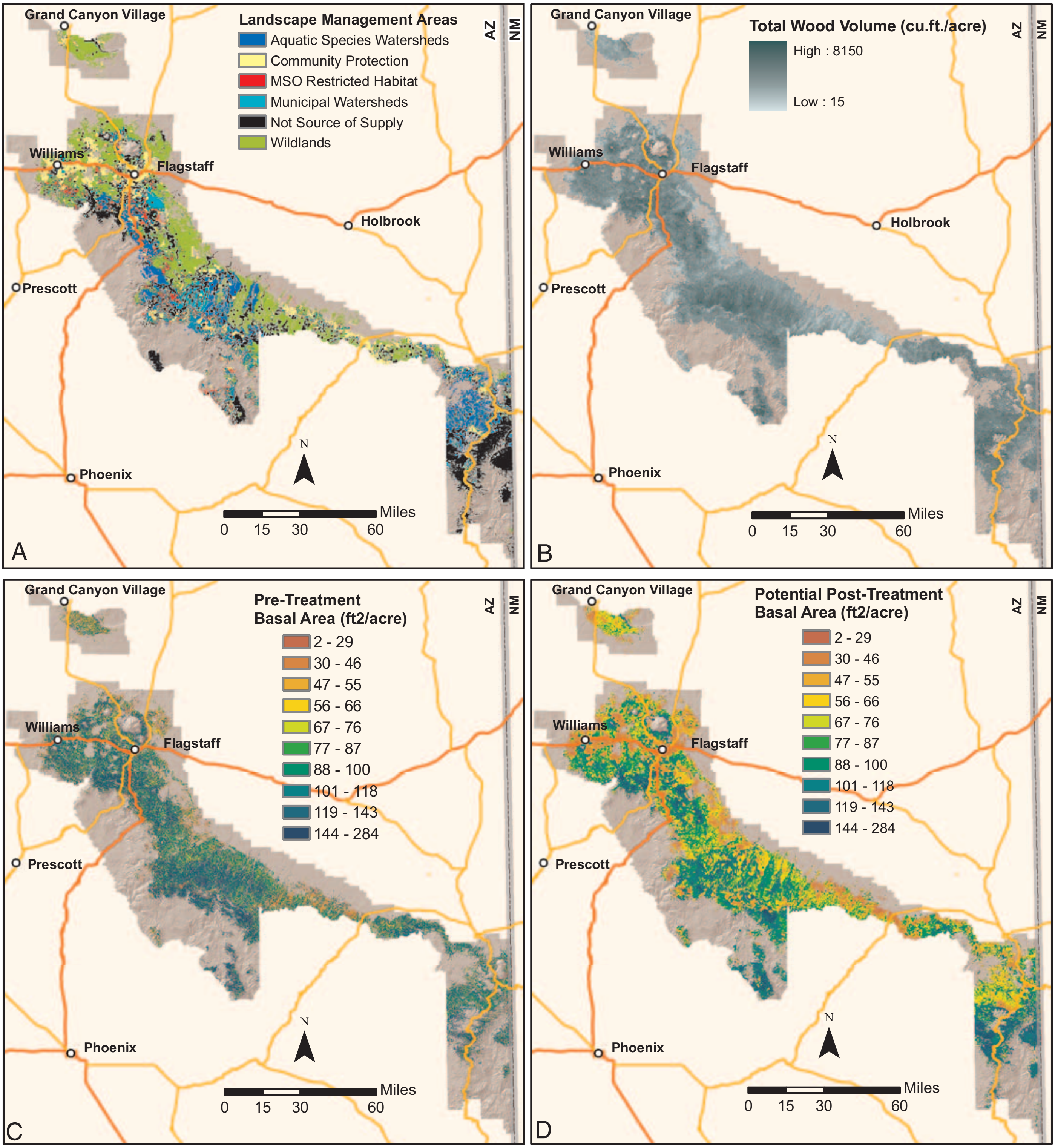


Figure 2. (A) Areas not considered a source of wood supply from mechanical thinning treatments (black) and landscape management areas (various colors) used to define desired posttreatment conditions in working group treatment scenarios. (B) Estimated ponderosa pine bole volume for 2006 across the analysis area. (C) Estimated ponderosa pine basal area in 2006. (D) Estimated ponderosa pine basal area following potential treatments defined in the majority scenario. Spatial data sources include the National Elevation Dataset (USGS), Arizona Land and Resource Information System roads and private lands, The Nature Conservancy Arizona native fish species richness data, National Resources Conservation Service sixth-level watershed boundaries, LANDFIRE existing vegetation data, and US Forest Service data on streams, soils, roads, MSO protected activity centers, and goshawk nests.

steering committee to form a 20-member working group representing a diversity of public and private land values (Table 1). Members of the steering committee were also integrated as stakeholders and all participants were included in a series of workshops

Table 2. Areas not considered a source of wood byproducts from mechanical restoration thinning treatments.

Landscape feature	Acres
MSO protected activity centers	182,000
Specially designated areas[a]	177,000
Steep slopes (>40%)	147,000
Forest thinned within 10 yr	113,000
Northern goshawk nest areas	63,000
Soil types restricted from mechanized treatment	126,000
Streamside management zones[b]	52,000
Total (excluding overlap between layers)	638,000

[a] Specially designated areas in the study area include wilderness areas, national game preserves, research natural areas, primitive areas, and inventoried roadless areas.
[b] Streamside management zones were defined as areas within 100 ft of perennial and intermittent streams.

that used a participatory geographic information system (GIS) process (Hampton et al. 2006, Sisk et al. 2006). This process involves the display and analysis of map layers portraying wildlife, watershed, and other criteria for use in developing land-management scenarios. The steering committee identified potential group members and came to full agreement on group membership by discussing the pros and cons of the participation of each individual or organization. Factors used to select a diverse group of stakeholders to participate were (1) area of expertise, (2) representation from a variety of organizations, (3) geographic purview, and (4) availability. The working group had representatives from environmental nongovernmental organizations, private forest industries, local government, the Ecological Restoration Institute at Northern Arizona University, and state and federal land and resource management agencies. We sent letters to each potential working group member or point of contact selected by the steering committee inviting the participation of an individual or organization. The composition of the group changed twice over the 6-month workshop period when a member retired and another passed away.

Seven full-day workshops were held monthly from June through November 2007. Workshops were open to the public and rotated between three locations spread throughout the analysis area to facilitate attendance. We used a "fish bowl" process at each workshop, in which members of the public were welcome to attend the entire workshop and could ask questions or provide comments during a scheduled period. Public attendance varied from 1 or 2 individuals to upward of 10. The majority were industry, local government, and agency representatives (e.g., Bureau of Land Management). We distributed agendas and detailed workshop summaries to hundreds of stakeholders via e-mail and made handouts, slides, and other materials available on a project website. The public were also encouraged to provide comments via voice mail, e-mail, or US Postal Service, which were discussed at the following workshop. To keep elected officials and other key players in the region informed, the steering committee developed a list of contacts who received periodic updates on project progress. Maintaining a transparent and open process was a key element of the project.

A professional facilitator provided guidance to maximize participation and to define a consensus-based decisionmaking approach, which was refined and agreed on by the working group. Consensus was reached when each individual or organization fully agreed with a choice or at least found it acceptable, recognizing that compromises were necessary. If a group member disagreed on an issue, it was up to them to suggest alternatives. The dialogue then continued until everyone either agreed or decided they could live with the decision. Many issues took multiple workshops to resolve, especially if the group requested additional analyses or expertise from outside the group. The consensus process succeeded because each member of the group actively worked toward reaching agreement.

Topical experts from academia, research institutes, and land-management agencies augmented the working groups' significant level of expertise in forest restoration management by providing specialized information on wildlife issues, treatment impacts on soils, hydrologic considerations, conditions favorable to fire-only restoration treatments, and pre-European settlement and posttreatment forest conditions. Throughout the process, additional specialized topics arose. Subcommittees of working group members and invited experts worked between full group workshops to study these issues and draft spatial data products to assist the working group in their collective decisionmaking.

At the initial group workshop, we provided background and foundational information to the group. Each steering committee member commented on wood supply and utilization issues related to their respective organization and described how they hoped this analysis would aid in these issues. The US Forest Service Director of Forestry and Forest Health for the Southwestern Region described the importance of the study and how the US Forest Service intended to use project results. Agency experts provided information on how treatments might be constrained or influenced by regulations and guidelines related to wildlife, soils, and hydrologic factors. We summarized the importance of landscape-scale forest restoration assessments and reviewed the main task of developing one or more treatment scenarios that was the focus of the working group.

Table 3. Wood volume estimates summarized by total volume and three diameter classes for 2006,[a] The total wood volume layer was used to summarize cubic foot volume for the ponderosa pine type and each landscape management area in the study area.

Wood volume category	Total volume (million ft^3)[b]	Percent of total volume	Acres (millions)
Total volume in analysis area	4,561	100	2.4
Volume not considered in supply	1,302	28	0.6
Volume in management areas by dbh class			
<5 in.	79	2	
5- to 16-in. dbh	1,394	43	
>16-in. dbh	1,764	55	
Total volume in management areas	3,238		
Volume by landscape management area			
Community protection	643	14	0.35
MSO restricted habitat	504	11	0.24
Municipal watersheds	128	3	0.06
Aquatic species watersheds	668	15	0.31
Wildlands	1,317	30	0.79

[a] Total cubic volume estimates for the ponderosa pine type are from a single data layer and volume by diameter class is from three separate data layers. Discrepancies between estimates derived from the total volume layer those summed over diameter classes is a primarily result of lower computation accuracy in the <5-in. dbh volume layer.
[b] Tree bole cubic foot volume includes the entire length of the tree, with no deduction from the main stem for stumps or tops at specified diameter.

At the subsequent workshops, we provided detailed information on how other collaborative groups had built scenarios for previous landscape assessments and on the availability of spatial data on forest structure and other conditions. Methods to characterize and strategically place treatments across the landscape were presented to the working group. Building on the presentations by agency experts at the initial meeting, we presented maps depicting technical methods to incorporate treatment guidelines and regulations relevant to siting treatments. For selected landscape conditions (e.g., steep slopes and northern goshawk nest areas) we reviewed data layers and estimates describing how each factor might influence a treatment scenario. The group found this map-based presentation of various options useful and requested that we continue depicting progress in this manner.

Based on this input, the working group developed an overall goal for its scenario to restore fire-adapted (ponderosa pine) ecosystems and protect communities from destructive fires, while mitigating adverse impacts of treatments on soils, surface water, and wildlife. To accomplish this goal, the group divided the landscape into areas where restoration byproducts (i.e., wood supply) were or were not potentially available from mechanical tree thinning (Figure 2A). Potential wood supply areas were further divided into five types of landscape management areas (see section "Areas Appropriate for Mechanical Thinning"), each with management objectives including desired posttreatment conditions, based on the informed judgment of experienced restoration practitioners from land-management agencies and other organizations within the working group. Prescribed burning was generally assumed to follow thinning treatments. Posttreatment conditions were designed to put these ecosystems on a trajectory toward restored conditions supporting frequent low-intensity fire regimes and increased forest structural heterogeneity.

Areas Not Appropriate for Mechanical Thinning

The working group agreed that areas within the analysis area associated with seven landscape features would not be considered a source of restoration byproducts (i.e., wood supply) for the purposes of this study (Table 2; black areas in Figure 2A). These areas are typically not mechanically thinned because of steepness, sensitive soils, proximity to streams, recent tree harvesting, land-use restrictions, or wildlife regulations. Participants acknowledged that Mexican spotted owl (MSO) protected activity centers and other sensitive species habitats might be thinned lightly from below in some cases, resulting in minimal thinning byproducts. No changes were made numerically to wood supply estimates based on road access; however, the group expressed that they had low confidence that areas farther than ¼ mi from existing roads (constituting 241,000 ac) would be a source of thinning byproducts in the near term, because of increased costs, limits in harvesting technologies common in the region, and concerns over environmental impacts associated with new road construction and improvements.

Areas found that were not a potential source of wood supply made up 26% of the analysis area, less than the average value we observed in 27 NEPA-approved restoration projects (37%; US Forest Service 2002–2007). It was reasoned that the value derived via spatial analysis (26%) is conservative because several site-scale factors that limit mechanical thinning were not accounted for, such as archeological sites, historical sites, wildlife movement corridors, and areas with insufficient road access.

Toward identifying areas that would be excluded from mechanical thinning treatments, a subcommittee explored where prescribed and/or wildland fire use (WFU) could or should be used as an initial treatment option. At the group's request, we performed various GIS analyses to define possible fire-only treatment areas including (1) identifying areas below a specified basal area derived from either pre-European settlement conditions or expert opinion on expected surface-fire conditions, (2) assuming status quo planning levels for fire-only treatments based on the average in 27 NEPA planning areas (33%; US Forest Service 2002–2007), and (3) fire behavior model predictions under various weather scenarios. A complicating factor threaded throughout group discussions was the applicability, acceptability, and predictable effects of fire and smoke. Concerns were raised that adverse health effects of smoke and exceeding air quality threshold limits prescribed burning activities, and, furthermore, that locating potential fire-only areas was not relevant to the wood supply analysis and outside the scope of the project. Given these uncertainties and lack of time to arrive at a mutually agreeable modeling method within the 6-month workshop period, the subcommittee decided not to recommend a specific approach and advocated instead that there are areas of the landscape where fire only will continue to be the preferred treatment over mechanical thinning and that wood supply estimates needed to be adjusted downward correspondingly.

Areas Appropriate for Mechanical Thinning

The working group divided and ranked lands for receiving mechanical thinning treatments, which were considered a potential source of wood supply (colored areas in Figure 2A). Selected areas were categorized as five landscape management areas with different restoration objectives. Community protection management areas (CPMA) received the highest ranking for tree thinning, meaning that management objectives for CPMAs took precedence wherever they overlapped with another management area. The group struggled with how to geographically represent areas identified in community wildfire protection plans because the different plans used inconsistent approaches and delineations. Ultimately, the group created a new designation. The group defined CPMAs by assigning a ¼-mi protection buffer around all private lands, with ½- to 1½-mi buffers around "high priority" private lands identified in community wildfire protection plans—the default WUI definition of the Healthy Forests Restoration Act of 2003. MSO restricted habitat management areas (rank 2) were defined as lands with pine-oak vegetation and used in tandem with the group's basal area management objectives designed to follow MSO Recovery Plan guidelines (US Department of the Interior Fish and Wildlife Service 1995) at a regional scale. Municipal watersheds management areas (rank 3) contained sixth-level watersheds with community surface water supplies. The working group defined aquatic species watersheds management areas (rank 4) as sixth-level watersheds in which native fish presence has been documented. The wildlands management area (rank 5) was a catchall for areas not defined by the other four (Table 3).

For each landscape management area, the working group specified a posttreatment basal area probability distribution appropriate for the area's management objectives

(Figure 3). For example, the proposed thinning for the CPMAs, where tolerance for fire is low, is more aggressive than the thinning goals in wildland areas, while desired posttreatment distributions in MSO restricted habitat allow for denser conditions to promote MSO target/threshold habitat. Reductions in basal area over initial conditions determined thinning intensity. Posttreatment basal area distributions follow a beta-distribution function in which minimum, maximum, and mode were used rather than a target basal area (average) to maintain landscape heterogeneity as described in early studies of ponderosa pine (Pearson 1950).

Basal area distributions within a particular management area were developed with the aid of experts and include forest management regulations and provisions for critical wildlife species habitat. For example, the MSO restricted habitat posttreatment distribution of 45–190 ft^2/ac (mode, 100 ft^2/ac) was designed to implement current (1996) National Forest Plans and the 1995 MSO Recovery Plan. The curve for MSO restricted habitat retained 10% of this management area with basal area of $>$150 ft^2/ac to meet US Fish and Wildlife Service guidelines for maintaining critical habitat. The relatively low posttreatment basal area range of 30–60 ft^2/ac (mode, 40 ft^2/ac) for CPMAs was chosen to reduce fire risk significantly (e.g., Fiedler 2002, Fulé et al. 2002a, 2002b). Curves are based on forest thinning regimes that are presently being applied in the southwest (e.g., US Forest Service 2002–2007) and all basal area ranges are more heavily weighted to lower values with distribution tails tapering off more gradually to the right (skewed to the right).

The distributions are not precise determinations or silvicultural prescriptions; rather, they are realistic assumptions that allow for the estimation of wood supply at the regional scale. The group endeavored to balance key land-management issues that included the desire to (1) reduce the threat of uncharacteristically intense fire to human communities, wildlife habitat, and other ecosystem components; (2) minimize potential negative impacts of treatments (Allen et al. 2002, Chambers and Germaine 2003); (3) restore forests to a more naturally heterogeneous structural condition (Pearson 1950, Savage 1991, Covington and Moore 1994); and (4) recognize that changes in the last 100 years, such as global warming, the spread of invasive species, and anthropogenic edge effects and fragmentation, have provided novel conditions that may result in unexpected ecosystem trajectories (Beier and Maschinski 2003). For example, the desired posttreatment basal area distribution outside of CPMAs included areas of higher tree densities to provide a variety of habitat conditions for wildlife including threatened, endangered, and sensitive species that may specialize in habitats "atypical" of those described by current reconstructions of pre-European settlement forest conditions (Beier and Maschinski 2003).

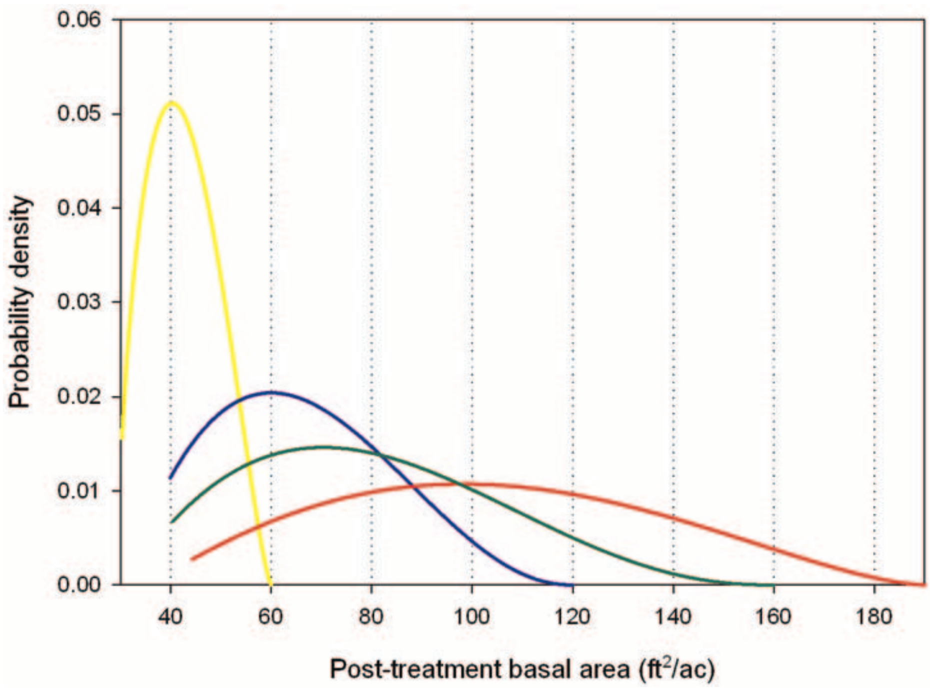


Figure 3. Continuous probability distributions of desired posttreatment ponderosa pine basal area for each landscape management area used in consensus and majority scenarios. Locations with pretreatment basal areas lower than levels described by these curves were not decreased after potential treatments. CPMAs (yellow), aquatic and municipal watersheds (blue), MSO restricted habitat (red), and wildlands (green).

Consensus Reached

The group reached full agreement that 26% of the 2.4 million–ac analysis area should not be considered a source of wood supply and that 41% should be considered a potential source of byproducts generated by mechanical harvesting as part of restoration or fuel reduction treatment (Figure 4). The 41% is an analysis area average, with higher percentages applied to community protection areas and lower elsewhere, as described in the next paragraph. In addition, a majority of working group members believed that some portion of the remaining 33% of the landscape (up to a total of 74% of the analysis area) should be considered for mechanical thinning. The strategy underlying the consensus scenario was to apply nonmechanical restoration options where feasible in the remaining 33% of areas, including fire-only treatments and WFU to minimize

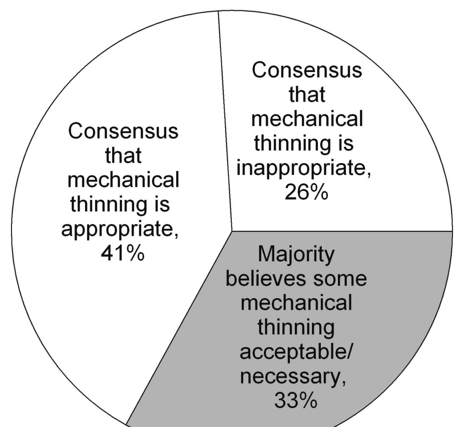


Figure 4. Pie chart representing the level of agreement among stakeholders as a percentage of the entire analysis area. Areas in white represent full agreement over a total of 67% of the landscape. Areas in gray represent the remaining 33% of the landscape where there is a lack of consensus, but for which the majority of working group members believed some mechanical thinning would be acceptable and/or necessary.

Table 4. Wood supply estimates derived from the "consensus" and "majority" treatment scenarios (see text for explanation) as of 2006.[a] Potential treatments occur in the ponderosa pine type on 41% of the total analysis area acres for the consensus scenario and on 74% of the area for the majority scenario. The majority scenario was applied to all 74% of the area considered for restoration treatments; however, 5% was below a minimum amount of basal area and did not have thinning treatments.

Management area	Percent of management area	Wood volume[b] (ft^3)	Crown weight[c] (green tn)	Acres treated[d]	Percent area treated	Ave harvested[e] (ft^3/ac)
Consensus scenario						
Community protection	70%	368,975,519	3,479,963	314,017	32%	1,175
MSO restricted habitat	30%	56,832,525	536,384	113,076	11%	503
Municipal watersheds	40%	37,448,212	355,581	34,471	3%	1,086
Aquatic species watersheds	35%	189,626,094	1,788,160	187,157	19%	1,013
Wildlands	35%	194,426,007	1,831,347	338,486	34%	574
Total		847,308,357	7,991,436	987,206	100%	858
Majority scenario						
Community protection	74%	371,401,419	3,503,137	335,206	20%	1,108
MSO restricted habitat	74%	83,647,154	789,558	225,773	14%	370
Municipal watersheds	74%	47,206,561	448,773	58,031	3%	813
Aquatic species watersheds	74%	242,247,408	2,284,993	323,531	19%	749
Wildlands	74%	270,810,528	2,550,706	718,927	43%	377
Total		1,015,313,070	9,577,167	1,661,467	100%	611

[a] Wood supply estimates are from 2006 data and have not been projected forward with forest growth information.
[b] Tree bole cubic foot volume includes the entire length of the tree, with no deduction from the main stem for stumps or tops at specified diameter.
[c] Crown weights from restoration byproducts include all tree foliage, limbs, and bark from limbs.
[d] Percent of total area potentially treated in each scenario located in each landscape management area. For example, 32% of the potentially treated areas in the consensus scenario are located in the community protection management areas.
[e] Average volume of bole and crown material per acre for differ between consensus and majority scenarios because the majority scenario covers an additional 34% of the landscape with generally lower pretreatment basal area.

potential negative impacts of mechanical treatments, whereas the majority scenario intends to provide a higher level of control and precision by using mechanical thinning to reduce the threat of uncharacteristic crown fire and achieve the group's desired conditions in these areas.

The working group partitioned the area to be restored using mechanized thinning for the consensus and majority scenarios into various proportions of each landscape management area (column 2, Table 4). The proportional breakdowns for the consensus scenario were based on informed judgment and were part of a three-tiered landscape restoration strategy in which (1) intensive mechanical thinning treatments are placed across all the CPMAs where thinning would be feasible, (2) additional mechanical thinning treatments are placed strategically across 30–40% of each of the remaining landscape management areas to significantly reduce uncharacteristic fire behavior (e.g., Finney 2006 and Finney et al. 2007), and (3) other restoration options are used where feasible and needed in the remaining areas, including prescribed burn-only treatments, WFU, and noncommercial thinning (or thinning that would not add to wood supply). The 74% for the majority scenario was based on the portion of the analysis area remaining after areas deemed not appropriate for mechanical treatments were removed from consideration.

Assessment of Current Forest Conditions

Calculations of existing ponderosa pine wood volume and basal area per acre were a priority for estimating the potential wood supply from forest restoration treatments. Because up-to-date forest inventory data were lacking for the study area, we developed an integrated forest mapping system (IFMS) to map forest structural characteristics by combining US Forest Service National FIA plots with multidate Landsat Thematic Mapper (TM) imagery (Box 1). FIA plots provided a large-scale, consistent and systematic measurement (4.8 × 4.8-km sample grid) of forest conditions that is periodically updated (Hicke et al. 2007). Landsat TM data provided a recent (2006), low-cost multispectral and multitemporal platform for mapping ponderosa pine structural characteristics across all management jurisdictions in the study area. The integration of these data sources allowed statistical imputation using *k*-nearest neighbor (*k*-nn) algorithms to map forest structural condition for the ponderosa pine type (Box 1). The *k*-nn methods are increasingly used to map forest structure over large areas from inventory and remotely sensed data for a variety of forest types (Ohmann and Gregory 2002, Tomppo et al. 2008).

Digital forest structural layers resulting from IFMS were systematically evaluated for accuracy by comparing *k*-nn predictions of the value of each plot from all other FIA plots in the reference data set. Total forest volume estimates (Figure 2B) from digital grids resulted in an $R^2 = 0.78$ and mean and median residual error of $\pm 228/\pm 195$ ft^3/ac by comparing the imputed value to that observed from corresponding FIA plots. The mean residual error was influenced by plot locations with high volume and was lower (± 189 ft^3/ac) for comparisons using 80% of the FIA plot data for validation. Total basal area estimates (Figure 2C) showed an $R^2 = 0.72$ with a mean and median residual error of $\pm 15/\pm 11$ ft^2/ac in ponderosa pine forest. Summarized data from the digital volume layer resulted in a total of 4.56 billion ft^3 for ponderosa pine forest in the study area (Table 3). The total volume estimate was also compared with other recent regional and state wood volume assessments. Bailey and Ide (2001) calculated that 4.1 billion ft^3 of ponderosa pine volume existed within the four counties overlapping much of the wood supply study area, which include most of state's ponderosa pine forest, and O'Brien (1999) estimated that 5.4 billion ft^3 existed statewide. Although the spatial location of prior volume estimates do not overlap entirely with the wood supply study area, wood volume calculated using *k*-nn imputation for ponderosa pine forest in the study area compared well with previous estimates. Recent disturbances from large forest fires before 2006 and corresponding decreases in wood volume were also well represented in digital forest volume and basal area layers (Figure 2).

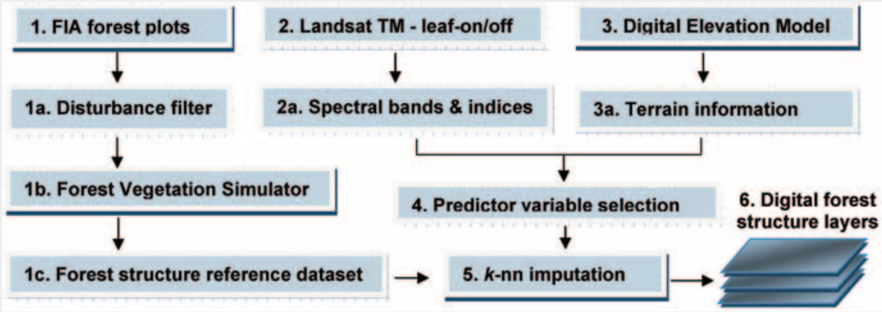
A central objective of the wood supply estimate was to determine the amount of wood supply from thinning small-diameter trees. For the purposes of this study, the group selected a 16-in. dbh threshold because of its common use within the analysis area as a break differentiating "small"- and "large"-diameter trees in the ponderosa pine forest type. To examine the amount of land area and volume where thinning could meet posttreatment conditions by harvesting small-diameter trees (i.e., trees of <16-in. dbh), three additional basal area layers were derived with the IFMS for three diameter classes of <5-in. dbh ($R^2 = 0.45$), 5- to 16-in. dbh ($R^2 = 0.51$), and >16-in. dbh ($R^2 = 0.50$). We assumed that 10 and 20% of the basal area per acre must be retained after thinning from trees of <5-in. dbh and 5- to 16-in. dbh, respectively, to promote tree age and size class diversity. Wood supply estimated from thinning treatment scenarios in the following section were used to assess the amount of volume and proportion of analysis area that would meet posttreatment basal area conditions by thinning small-diameter trees.

Potential Wood Supply from Restoration Treatments

Based on the working group's specifications for percent area treated and desired posttreatment conditions within five landscape management categories, we estimated potential wood supply generated from the consensus and majority treatment scenarios. It was acknowledged that treatments should focus on removing small-diameter trees as the central objective, but no fixed diameter limitation was placed on restoration scenarios or supply calculations. For example, there was no concurrence within the group that trees over 16 in. should be cut and removed from areas outside the CPMAs.

We first needed to identify prethinning forest characteristics from IFMS data layers and estimate thinning levels to achieve desired posttreatment conditions. We fit the pretreatment basal area distribution for each landscape management area to the desired posttreatment probability distributions defined by the working group, while maintaining the original order of low to high basal area conditions. For example, the pretreat-

Integrated Forest Mapping System for combining US Forest Service FIA and remotely sensed data to model and map ponderosa pine forest structural characteristics across the study area.



1. **FIA forest plots**—Georeferenced FIA forest inventory plots on National US Forest Service lands and live tree measurements (trees of ≥1-in. dbh) from years 1996 to 2005 were used to develop a region-scale ground reference data set for mapping ponderosa pine forest structure.
   a. **Disturbance filter**—FIA plots were selected by using remote sensing change detection techniques to identify plots without severe wildfire, timber harvest, and other disturbance events since the date of establishment.
   b. **Forest Vegetation Simulator (FVS)**[1]—Selected FIA forest plots representative of the ponderosa pine forest type ($n = 420$) were grown forward in time to match the Landsat TM image year (2006). The Central Rockies Variant of FVS provided species-specific growth models for the southwestern United States (Dixon 2002) to estimate tree basal area and cubic foot volume per acre. Plots were established between years 1996 and 2005 (i.e., <10 years of simulated growth).
   c. **Forest structure reference data set—**Plot basal area and volume were used to model forest structural conditions from sampled to unsampled locations using a set of predictor variables and *k*-nn imputation methods discussed next.
2. **Landsat TM data**—Twelve Landsat TM scenes from 2006 (6 leaf-on and 6 leaf-off for deciduous tree species) were assembled to cover ponderosa pine forest type in the study area.
   a. **Spectral bands and indices**—Spectral bands and indices were derived from leaf-on and leaf-off TM images including TM bands 1–5 and 7, normalized difference vegetation index (NDVI) and derivatives such as corrected NDVI (NDVIc; Pocewicz et al. 2004) and NDVI ratio (leaf-on/-off), bands from a tasseled cap transformation (i.e., wetness, greenness, and brightness), and minimum noise fraction bands 1–3. These variables were initially selected because of their potential usefulness for predicting forest structural parameters (e.g., Cohen et al. 1995, Moisen and Frescino 2002, Tomppo et al. 2008).
3. **Digital Elevation Model (DEM)**—A 30-m DEM was used to derive four variables related to the biophysical environment that were likely to be important predictors of forest structure.
   a. **Terrain information—**Terrain variables included percent slope, elevation, surface roughness, and aspect. Aspect was cosine transformed for use as a continuous index of solar radiation related to site moisture conditions (Moisen and Frescino 2002).
4. **Predictor variable selection—**All spectral and terrain predictor variables (grids) were resampled to a 90-m grid cell size and used to attribute each reference plot for developing models and digital data layers. As part of statistical imputation (below), we used the random forest regression tree algorithm (Breiman 2001) to estimate variable importance. Therefore, a reduced subset of the best predictor variables was selected for use in a final model predicting each structural variable (see also Cutler et al. 2007, Sesnie et al. 2008a, 2008b, Evans and Cushman 2009). Predictor variable importance indicated that minimum noise fraction band 1 (leaf-on), NDVIc, and NDVI ratio in addition to TM bands 1–5, 7 from both leaf-on and leaf-off TM images, were necessary for generating accurate basal area and wood volume estimates. Elevation and roughness (elevation SD in a 3 × 3 pixel window) variables taken from a DEM were also important and used in forest structure imputations.
5. **The *k*-nn imputation**—Statistical imputation has become increasingly important for mapping forest characteristics across large areas from existing forest inventories and remotely sensed data. The *k*-nn imputation techniques used for the wood supply assessment accessed a set of reference data (y = forest structural variable on FIA plots) attributed by predictor variables (x = spectral and terrain predictors) to estimate y for many unsampled locations (pixels) with x variables only. The yaImpute package in R statistical software (The R Foundation for Statistical Computing 2007) was used to implement the random forest regression tree algorithm (Breiman 2001) for *k*-nn imputation for deriving forest structural layers (see also Crookston and Finely 2007).
6. **Digital forest structure layers**—The IFMS produced digital data layers of ponderosa pine basal area and volume (Figure 2, B and C) that were passed to a GIS for the wood supply assessment. Forest restoration treatments were applied as reductions in basal area to estimate wood supply.

[1] We used USDA FIA forest inventory plots for study on national forests in the FVS file format (US Forest Service 2007). Georeferenced FIA plot locations on National Forestland were obtained under a written agreement with the USFS Forest Inventory and Analysis program office. Ogden, UT and the USFS Southwestern Regional office in Albuquerque, NM.

ment basal areas in CPMAs were reduced to a minimum basal area of 30 ft^2/ac and a maximum of 60 ft^2/ac, with the mode set at 40 ft^2/ac (Figure 3). The pretreatment basal area was reduced unless it was below a minimum desired condition (e.g., <40 ft^2/ac in wildlands) in which case the values were left unchanged. The difference between pre- and posttreatment basal area represented thinning intensity. The dominant thinning level ranged from heavy in the CPMAs, which were designed to buffer communities from severe wildlife behavior, to light in MSO restricted habitat, reflecting a preference for denser conditions. The modeled treatments, especially the high-intensity treatments in the CPMAs, interspersed with areas not thinned, created a heterogeneous pattern of potential posttreatment basal area across the landscape (Figure 2D).

To obtain estimates of wood volume harvested as a byproduct of treatments, nonlinear regression was used to determine the cubic foot volume from the amount of basal area removed. To establish these relationships, we used basal area and log transformed total wood volume from FIA plots in the reference data set ($n = 420$). A final model showed a good fit to the data ($R^2 = 0.81$; $P < 0.0001$). A range of wood supply volumes was estimated for each management area, integrating the two working group scenarios and thinning levels (Table 4). In the consensus scenario, the highest basal area locations were thinned in each landscape management area up to the percent areas specified by the working group. This was not necessary in the majority scenario because each entire landscape management area was available for treatment.

Thinning treatments considered under the majority scenario produced 17% more wood supply (1.015 billion ft^3) than that of the consensus scenario (0.847 billion ft^3). The greater number of acres treated with the majority scenario included locations with lower basal area, which reduced the average volume harvested. Average supply volumes ranged from 611 ft^3/ac (majority) to 858 ft^3/ac (consensus), which closely matched the amount of harvest volume estimated from US Forest Service timber cruise data and recent thinning treatments within the study area (White Mountain Stewardship contract, 2008, US Forest Service, unpublished data). Differences between pre- and posttreatment landscape conditions (basal area) for the majority scenario indicate the locations treated, which cover a total of 69% of the study area where minimum basal area conditions were met (Figure 2, C and D).

From our analysis of wood supply generated from small-diameter trees we found that 1.44 million ac (81% of the area treated) had sufficient basal area from trees of <16-in. dbh, meaning that only small trees would be harvested. This accounted for 90% of the total wood supply volume (917 million ft^3) in the majority scenario. High-intensity treatments in CPMAs were the principal locations where thinning larger trees would be necessary to meet desired posttreatment conditions. The consensus scenario, which was comprised of areas having the highest initial basal area over 41% of the analysis area, resulted in similar outcomes.

In addition to stem volume, forest biomass removed by treatments was also estimated because potential wood products may be derived from residual materials. To estimate crown biomass (limbs, bark, and foliage) that is in addition to wood supply from tree boles, a relationship between bole and crown weights from FIA plots was developed via nonlinear regression. Stem weight was generally three times greater than biomass comprised of crown material. Estimates of crown biomass for the consensus and majority scenarios ranged from 8.0 to 9.6 million green tn, respectively (Table 4). Per acre volume and biomass estimates were similar to harvest volumes taken from existing forest restoration activities (White Mountain Stewardship contract, 2008, US Forest Service, unpublished data).

Harvesters removed a total of 319,800 tn of nonresidues and 12,900 tn of residues from the Kaibab, Coconino, and Apache-Sitgreaves National Forests in 2006 (unpublished data provided by the four National Forests) equivalent to 1.2% of the total bole biomass and 0.2% of the total crown biomass that would potentially be generated from treatments in the consensus scenario. A simple linear extrapolation of year 2006 harvest levels over 10 years would result in 3,198,000 and 129,000 green tn, which is 12 and 1.6% of the respective bole and crown biomass from the consensus scenario. Therefore, wood supply defined by stakeholders exceeded current utilization levels by >88% when extrapolated over the next 10 years.

Wood supply estimates based on the working group scenarios represent a snapshot in time. Forest growth will likely add to potential wood supply, averaging about 40 ft^3/ac per year including self-thinning mortality. Simple volume multipliers can be used to adjust these published values. However, increasing frequency and severity of western wildfires (Westerling et al. 2006), expected continued drying of the southwestern climate (Seager et al. 2007), and associated insect outbreaks and tree mortality (van Mantgem et al. 2009) could drive down biomass stocks and growth rates.

Conclusions

A primary goal of this case study was to build agreement on the location and type of ecologically appropriate forest restoration treatments that could supply wood byproducts to new and existing businesses and markets. Maintaining forest structural heterogeneity across the landscape and restoring fire-adapted conditions were the two guiding principles used to design broad-scale thinning treatments. The working group reached full consensus across 67% of the landscape (26% not appropriate for mechanical thinning and 41% appropriate), which is a remarkable achievement considering such diverse stakeholder interests. In addition, a majority of working group members believed that some portion of the remaining 33% of the landscape (up to a total of 74%) should be considered for mechanical thinning. The entire group also agreed on the intensity of mechanical treatments that could be applied within five landscape management categories. Where a difference of opinion occurred for 33% of the analysis area, the estimated bole volume of restoration byproducts potentially available differed by 17% (ranging from 847 to 1,015 million ft^3).

Lessons learned include the importance of involving participants with broad representation among stakeholder groups and close contact with decisionmakers in their organizations. In addition, to ensure that the process and methods used to reach project objectives make sense to participants, time should be allocated up front to involve participants in their development. Finally, facilitation techniques that encourage contribution from each participant and minimize dominance by one or several groups are essential for permitting critical issues to surface.

The consensus scenario produced estimates of potential wood byproducts from restoration treatments that greatly exceed current thinning levels. The outcome of the study catalyzed new forest restoration initiatives and planning mechanisms to achieve the intent of the wood supply analysis. On Nov. 13, 2008, Janet Napolitano, then Governor of Arizona, endorsed accelerated restoration across northern Arizona in a letter to the Regional Forester, asking that the consensus reached in this study be institutionalized. On Mar. 2, 2009, US Representative Ann Kirkpatrick requested the US Forest Service work with stakeholders toward releasing a request for proposals to accelerate treatments. In a Mar. 6, 2009, letter, the Regional Forester announced the intent of four Forest Supervisors with management authority for lands in the wood supply analysis area to develop a strategy to substantially accelerate the rate of restoration treatments across 750,000 ac of the analysis area, followed by a "Sources Sought" notice released by the Southwestern Region of the US Forest Service on April 23rd to gather information to design contract options for the "Four Forest Restoration Initiative Project." In a letter dated May 6, 2009, Arizona Governor Janice Brewer asked the Regional Forester to work with the Governor's Forest Health Council, (6 of the 20 council members were working group members on this study), to implement the restoration goals of the consensus scenario. On June 26, 2009, Arizona Senate and House of Representatives requested that the Director of the US Forest Service and the Governor "… clearly identify additional federal appropriations needed to support acceleration of consensus-supported and scientifically informed forest restoration treatments." Challenges remain, such as, securing funding, designing effective contracts, and stepping region-scale analyses down to project level prescriptions; however, based on the unprecedented alignment of stakeholder and policymaking interests, the success of achieving landscape-scale restoration in northern Arizona's ponderosa pine forests looks promising.

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Tree and opening spatial patterns vary by tree density in two old-growth remnant ponderosa pine forests in Northern Arizona, USA

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A B S T R A C T

Forest spatial patterns influence many ecological processes in dry conifer forests. Thus, understanding and replicating spatial patterns is critically important in order to make these forests sustainable and more resilient to fire and other disturbances. The labor and time required to stem-map trees and the large plot size (> 0.5 ha) needed to study tree spatial patterns have limited our examination of how these patterns change as a function of site conditions and tree densities. We stem-mapped all trees > 40 cm DBH within two large relict (minimally logged) pure ponderosa pine study sites on experimental forests at Long Valley (73 ha) on sedimentary soils and Fort Valley (32 ha) on basalt soils in northern Arizona, USA. We also simulated 1,000 4-ha plots from models of each study site incorporating field data parameters. Using cluster analysis and field data, we found that an inter-tree distance (ITD) of 9–11 m best separated single trees and groups within our study sites. Using a fixed 10-m ITD, the more productive Long Valley (LV) site had 62 trees ha^{-1} and groups of up to 113 trees, compared to the Fort Valley (FV) site, which averaged 41 trees ha^{-1} and had 22 trees in the largest group. However, the sites differed only slightly in terms of single trees ha^{-1} (LV 7.3; FV 5.6) and group of tree ha^{-1} (LV 7.2; FV 8.1). Simulation results indicated that when tree densities are equal, the spatial patterns were very similar between the two sites, suggesting that tree spatial pattern variability is a function of tree densities and only indirectly related to site productivity. As the number of trees increased, the additional trees integrated into existing groups rather than creating new groups. In addition to tree spatial patterns, we quantified gaps (defined as > 30 m wide stem-to-stem) and openings (defined as ≥ 30 m wide stem-to-stem) within the two study sites. Although both sites were dominated by small openings most of the open area was found within a few large openings. Our large plots allowed us to incorporate variability and capture a larger range of tree and openings spatial patterns than have been captured in previous studies to provide insights on spatial heterogeneity that can inform management of this important forest type in North America.

1. Introduction

Across the western United States, dry forests historically evolved with frequent low severity fires every 5–25 years (Swetnam and Baisan, 1996; Covington et al., 1997). Since the exclusion of these fires and subsequent logging, these forests have become increasingly dense with young trees, reducing open space and herbaceous production (Weaver, 1951; Cooper, 1960; Covington and Moore, 1994). Unlike historical forests, these novel dense conditions are characterized by abundant fuels, including fuel ladders that can, under dry and windy conditions, support both passive and active crown fires. The extent of area characterized by these conditions has in some places resulted in large uncharacteristic stand-replacing fires (Graham, 2003; Finney, et al., 2005; Mallek et al., 2013). The increase of fuels at the stand level and the increased homogeneity of forest conditions at landscape levels are among the most pressing management issues across frequent-fire-adapted forests in the western United States (Agee and Skinner, 2005; Stephens et al., 2016). Moreover, if seasonal average temperatures increase as projected, these forests are likely to be subjected to fires of greater severity and other disturbances exacerbated by climate impacts (Seager et al., 2007; Jolly et al., 2015; McDowell et al., 2016; Singleton et al., 2019). To minimize such disturbances and their effects on ecosystems, managers are emphasizing fuels reduction as well as restoration of the historical spatial structure of ponderosa pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson var. *scopulorum* Engelmann) forests across the western United States (Moore et al., 1999; Allen et al., 2002; Graham et al., 2004; Agee and Skinner, 2005).

Trees within ponderosa pine forests have long been noted to have a unique spatial pattern that has only recently been quantified. For example, scientists working in the western United States in the first half of the 20th century often commented on the open nature of these forests (Pearson, 1933; Cooper, 1960). The open conditions were due to low tree densities and an aggregated spatial pattern. Historical tree densities in ponderosa pine forest ranged from 10 to 200 trees ha^{-1} (TPH), as documented by numerous studies (Fulé et al., 1997; Covington et al., 1997; Mast et al., 1999). Tree spatial patterns in ponderosa pine forests have also been described using traditional spatial pattern analysis and were summarized by Larson and Churchill (2012). These studies found that ponderosa pine forests were most often dominated by trees aggregated at scales between 2 and 40 m. However, some studies have

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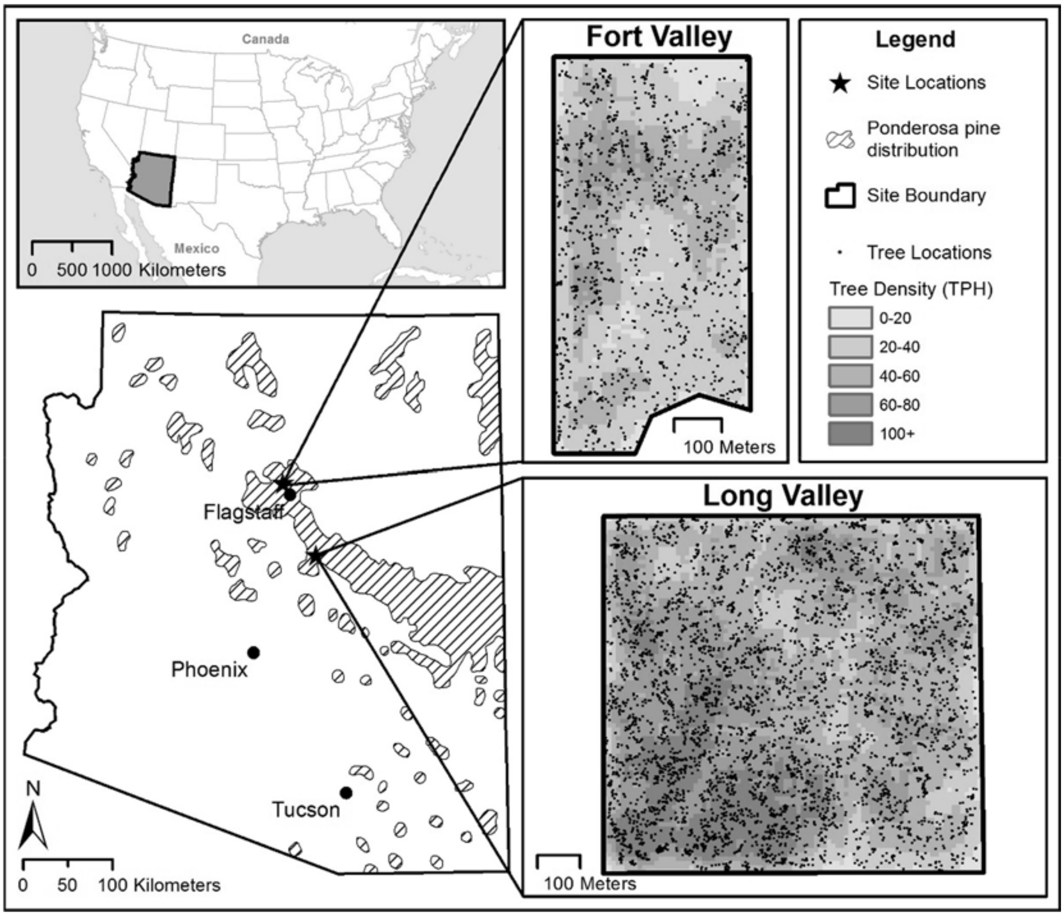

Fig. 1. Map of tree locations within the Long Valley and Fort Valley study sites in Northern Arizona. Along with stem map locations (black dots in inset maps of each site) and tree density (trees ha^{-1}; TPH), microsite variability is represented by different shades of gray.

also found global random spatial patterns in forests, particularly among larger and older groups (Youngblood et al., 2004; Schneider et al., 2016).

Gaps and openings are also recognized as important components within frequent fire forests because of the understory plant diversity they support (Matonis and Binkley, 2018) and wildlife habitat they provide (Reynolds et al., 2013). Quantifying the shape and size of these components, however, has been notoriously difficult (Larson and Churchill, 2012). This non-forested space has been broadly described by other studies using simple metrics such as percent open, while more recent studies have used the "empty space" concept (Clyatt et al., 2016; Matonis and Binkley, 2018; Pawlikowski et al., 2019). The empty space method is easy to understand and a good broad or global method to describe the amount of open space, but fails to quantify the distribution of these open spaces. Therefore, in addition to the open space method, some studies differentiate the open space into gaps and large openings (Churchill et al., 2017). Identifying large openings as a distinct component facilitates assessing the size distribution to determine if the open space is concentrated in one large opening or in several smaller ones.

Understanding and replicating tree and openings spatial patterns is critically important, but research on the subject has yet to capture the variability and factors responsible for pattern variability. These patterns directly influence ecological processes such as fire behavior (Graham et al., 2004), tree competition and growth (Biondi et al., 1994; Boyden and Binkley, 2015), regeneration (Sánchez Meador et al., 2009, Malone et al., 2018; Pawlikowski et al., 2019), understory development (Matonis and Binkley, 2018), wind flow, and creation of wildlife habitat (Reynolds et al., 2013). Only relatively recently, however, have attempts been made to quantify and replicate this pattern in treatment prescriptions (Churchill et al., 2013). One unique aspect of quantifying spatial pattern within frequent-fire forests has been the need to capture and implement these patterns at larger scales compared to traditional silvicultural or other forestry activities (Sánchez Meador et al., 2009). For instance, typical forestry studies use 0.01- to 0.1-ha plots to sample tree densities and basal area, based on the assumption that trees are arranged in a random spatial pattern (Smith et al., 1997). Yet, small plot analyses may underestimate the size of the largest groups of trees as well as the size of openings. The aggregated spatial pattern of most dry forests (Larson and Churchill, 2012) requires sampling using larger plots (> 0.5 ha) (Knapp et al., 2013, White, 1985). Larger plots, and the time-consuming process of stem-mapping trees, has limited replication across sites and conditions. As a result, sampling across a wide range of conditions and tree densities is needed to understand their impact on tree and opening spatial patterns (Sánchez Meador et al., 2009; Reynolds et al., 2013).

Tree and open space metrics often differ between sites; however, it is not clear whether these differences are directly due to site conditions (e.g., soils, precipitation, topography, region, or past disturbances) or indirectly related to changes in tree densities. For example, Abella and Denton (2009) compared spatial pattern between "ecosystem types," defined as areas with similar parent material and precipitation patterns. They found strong relationships between tree density and certain tree spatial metrics, but also found substantial variation within ecosystem types. Following the recommendations by Larson and Churchill (2012), recent papers have introduced new metrics to describe tree spatial patterns (Lydersen et al., 2013; Clyatt et al., 2016; Tinkham et al., 2017). These new metrics have been largely focused on the density, frequency, and distribution of single trees and groups. While studying multiple plots in Montana, USA, Clyatt et al. (2016) found a positive relationship between tree density and group size as well as percentage of trees within groups. Clyatt et al. (2016) also noted differences in the group size frequency distribution between regions and attributed those differences to changes in tree density related to historical fire regimes. In general, there is still a need to determine how forest spatial metrics differ within and between sites, and better understand the main drivers responsible for these differences (Sánchez Meador et al., 2010). Managers and researchers need this information to make adjustments when implementing or evaluating treatments across varying site conditions and tree densities. Understanding the spatial pattern and variability of ponderosa pine forests is critical for providing guidance to land management plans designed to create the desired forest structural and spatial patterns that are less prone to stand-replacing crown fires (Churchill et al., 2013).

By sampling two large relict (minimally logged) pure ponderosa pine study sites the goal of this study was to assess tree and opening spatial patterns both between and within sites. Our intent was to capture the heterogeneity within each site including sub-areas with similar densities (Fig. 1). The objectives of the study were to: (1) establish definitive characteristics for the grouped arrangement of ponderosa pine trees greater than 40 cm DBH in old-growth (yellow-barked) stands in the Southwest, (2) compare overall tree spatial pattern between the two sites, (3) determine how spatial patterns change as a function of tree densities within and between sites, and (4) quantify the area of openings, gaps and "empty space" in each study site.

2. Methods

2.1. Study area

To study the historical spatial structure of ponderosa pine forests, we selected a study site within each of two experimental forests with similar species composition and disturbance history. The Fort Valley site was within the Fort Valley Experimental Forest and the Long Valley site was within Long Valley Experimental Forest, both in the Coconino National Forest in northern Arizona, USA (Fig. 1). Fort Valley is 11 km northwest of Flagstaff, Arizona at an elevation of 2 250 m on soils derived from basalt and cinders (Avery et al., 1976) with an average annual precipitation of 51 cm (Western Regional Climate Center, 2019). The Long Valley site is 90 km southwest of Flagstaff at an elevation of 2 100 m on soils developed from weathered sandstone with limestone inclusions (Wheeler and Williams, 1974); annual precipitation averages 67 cm (Western Regional Climate Center, 2019). In general, the precipitation pattern in this region is bimodal, received primarily as late summer rain and winter snow.

Within Fort Valley we sampled a 32-ha area that was set aside as the "control" for other studies shortly after the experimental forest was established in 1906. Within Long Valley we sampled a 73-ha site that was first inventoried in 1937. At Fort Valley, livestock grazing was eliminated in 1926 and there has been no logging except for localized firewood cutting (Covington and Sackett 1984; Sutherland et al. 1991). At Long Valley, a light "sanitation cut" removed diseased or insect-infested trees in 1967 (Sackett 1980). Both sites still contain most trees that established during a period of natural frequent fires (prior to 1880) and are part of the few remaining "intact" old-growth forests in the Southwest. Between 1700 and 1900 the mean fire-return interval for widespread fires (fires that scarred 25% of the fire scar samples) was 7 and 5 years at Long Valley and Fort Valley, respectively (Swetnam and Baisan, 1996). Both study sites are dominated by ponderosa pine with scattered alligator juniper (*Juniperus deppeana* Steud.) and Gambel oak (*Quercus gambelii* Nutt.) shrubs.

2.2. Field methods

The tree populations of interest within each relict site were old-growth ponderosa pine trees that established under a frequent fire regime. We defined "old growth" as trees > 40 cm diameter at breast height (DBH: at 1.45 m height) with "old morphology characteristics" such as yellow bark, flattened top, and tall crown base height (sensu Brown et al., 2019). The DBH cutoff was based on guidelines adopted in restoration projects in the Southwestern United States (e.g., Coughlan, 2003; Abrams and Burns, 2007). When we started fieldwork, the two most commonly mentioned cutoff definitions for old-growth were 37 or 40 cm DBH (White, 1985; Abella et al., 2006; Schneider et al., 2016). We chose 40 cm DBH for stem-mapping data collection even though some old-growth, yellow-barked trees are less than 40 cm DBH, and some relatively young trees are less than 40 cm DBH but not yellow-barked.

Within each study site we recorded DBH and the geographic position, in meters, as Universal Transverse Mercator (UTM zone 12N) coordinates using North American Datum (NAD 83) projection, of all ponderosa pine trees with a DBH less than 40 cm. The stem-mapping process began by first establishing a reference point within a relatively open area for improved satellite reception using high precision (sub-meter) global positioning system (GPS) units (Trimble® Geo XH, Trimble, USA). Once the reference point was established, this location was "off-set" using a laser rangefinder (TruePulse™ 360° B, Laser Technology Inc., USA) to determine the distance and direction to the outermost edge of individual trees. Each GPS point was differentially corrected to an estimated average accuracy of less than 0.2 m. In addition, canopy measurements were conducted for 156 randomly selected trees (> 40 cm DBH) at each site. Canopy radius was measured from the stem to the edge of the canopy, and canopy intersection with another canopy was documented. These were measured and recorded along the four cardinal directions as well as the maximum and minimum canopy distances.

2.3. Simulation model

We were also interested in evaluating changes in spatial pattern metrics as a function of tree density within each study site. We therefore simulated 1,000 4-ha plots from fitted models of each study site incorporating field data parameters. For the fitted models, we assumed that points were distributed as a Neyman-Scott process such that tree groupings are formed as clusters of points arising from spatially Poisson-distributed cluster center points (Diggle 2014). The cluster member points in turn have a specified spatial distribution about the cluster center points. The distribution of cluster center points within both Long Valley and Fort Valley were spatially inhomogeneous with no simple eastward or northward trend. This precluded the use of stem density models containing linear directional trends. We therefore adopted a flexible nonparametric third-order spline function that allowed for greater complexity in the trend surface (Hastie 1992).

To simulate the spatial distribution of cluster members about each cluster center, we adopted a variance-gamma relationship with a cross-sectional density that is greater near the cluster center and attenuates as a function of distance from the cluster center (Baddeley et al. 2015). From available cluster models, the variance gamma model showed the best fit between the fitted model and the actual Long Valley and Fort Valley observed stem locations. We confirmed the goodness of fit of the final model using the following three metrics, which compared observed and model-predicted spatial point distributions: (1) $G(r)$, the nearest neighbor distance function; 2) $L(r)$, Besag's transformation of Ripley's $K(r)$; and 3) $g(r)$, the pair correlation function (Schabenberger and Gotway, 2005). For each metric, we performed Diggle-Cressie-Loosmore-Ford (DCLF) tests to assess goodness of fit (Baddeley et al., 2014). The DCLF test evaluates the probability that the observed and modeled point patterns are from the same distribution. Therefore, a small p-value is indicative of a poor fit (Table 1). Modeled and observed point intensities are shown in Appendix A. All models were estimated using the R statistical computing platform (R Core Team, 2018) and R

Table 1
p-values for G(r), L(r), and g(r) for Diggle-Cressie-Loosmore-Ford test confirming model used for simulations. Smaller p-values represent poor fit between the predicted and observed spatial distributions.

Summary Function	Long Valley	Fort Valley
G(r)	0.236	0.071
L(r)	0.970	0.660
g(r)	0.510	0.770

library spatstat (Baddeley et al., 2015).

2.4. Defining trees and groups

Tree spatial pattern descriptions must differentiate between single trees and tree groups. Defining groups is rooted in the idea that trees within a group are "connected," thereby facilitating migration or spread between trees within the group. For example, in the context of fire spread, a group could be defined where crown fire could spread between crowns under certain conditions. A group could also be defined by the distance needed for dwarf mistletoe (*Arceuthobium* spp.) seeds to spread between trees (Robinson and Geils, 2006). One often cited group definition is in regards to wildlife habitat, where a group is defined as two or more trees with interlocking or nearly interlocking crowns within which tree squirrels could travel while avoiding the forest floor (Reynolds et al., 2013). A number of recent studies that have described reference tree spatial patterns use this definition, although it is still unclear how and when tree canopies are measured. Tree canopy radius varies as a function of tree diameter and competition (Sánchez Meador et al., 2011). Most of the recent literature has defined groups based on a fixed inter-tree distance (ITD), meaning that two trees are within a group when the distance between them is less than or equal to the ITD (Lydersen et al. 2013; Brown et al. 2015; Clyatt et al. 2016).

To narrow in on possible threshold inter-tree distance levels for use in defining the final group, we considered statistical and ecological factors. Statistically we first created groups using hierarchical cluster analysis based on the geographic locations (UTM easting and northing) for each tree. The distance matrix of (Euclidian) inter-tree distances between all trees was created using PROC Cluster in SAS/STAT 90.4 based on the single linkage method. In this analysis, initially each tree is an individual, then the two trees separated by the shortest distance are joined to form a group. This process is repeated until all trees are part of a single group, similar to a method used by Larson and Churchill (2008) to create tree groups. Proc TREE in SAS/STAT 9.4 was then used to produce a dendrogram which included all trees to visually identify the most distinct tree groups and to determine possible threshold distance levels. The groups identified using cluster analysis were ecologically evaluated in the field and compared to canopy measurements before we decided on the final ITD group criteria.

2.5. Comparison between sites

Global tree spatial patterns within each site were analyzed using Ripley's K point pattern analysis in the spatstat package (Baddeley et al., 2015) in R v.3.4.1. The null hypothesis of this test is that points are randomly distributed. To determine whether trees were distributed in a random, clustered or dispersed fashion, we used the inhomogeneous Ripley's K(r). Due to the spatial trend within both sites we used univariate $L_{inhom}(r)$ function specifically designed for inhomogenous point processes. The K-function was normalized to L(r)-r in order to simplify interpretation (Besag, 1977). The neirnorbohood radius r about each point was limited to distances of 0–100 m in Fort Valley and 0–200 m in Long Valley (half the shortest plot dimension; sensu Dixon, 2002) to minimize the influence of unobserved points near observed points close to the plot edge (Boots and Getis, 1988). Significant clustering or dispersion was determined by comparing observed $L_{inhom}(r)$ - r transformation values to a 95% confidence envelope based on 999 permutations of simulated complete spatial randomness (Upton and Fingleton, 1985).

To compare tree spatial patterns between the two study sites we conducted two distinct but complementary analyses. The first analysis compared the two sampled study sites using the collected field data. The second analysis focused on simulations generated from the fitted model for each study area. For each of the two study sites, we randomly located 1,000 4-ha plot (200 m × 200 m). Each randomly located plot was therefore characteristic of the modeled density of cluster centers at that location. The simulations were then used to calculate various spatial metrics. Four hectares has previously been identified as the optimal plot size for measuring tree spatial pattern in dry forests (North et al. 2007; Larson and Churchill 2012). For both the field data and the modelled iterations we defined a tree group as two or more trees within a specified ITD (stem-to-stem). Trees that did not have neighboring trees within the specified distance were identified as singles. Single trees were described according to the following spatial metrics: singles ha^{-1}, and % singles. Tree group spatial metrics included: groups ha^{-1}, % of trees within groups, mean group size, maximum group size, and mean nearest neighbor distance (NND) within groups. The spatial relationship between trees was compared using the mean NND between all trees within each site, mean NND among trees within groups, and mean NND among singles.

In addition to tree spatial patterns we also quantified gaps and openings within the two sites. We defined openings as non-canopy areas that include a core without tree competition. According to Boyden and Binkley (2015) , competition is strongest within 14 m from ponderosa pine trees; therefore we first created a polygon of all areas greater than 15 m from any tree stem. We then delineated openings by buffering the polygon by 10 m which expanded the area of the opening to the edge of the tree canopy (5 m away from the tree stem). Intersecting and adjoining polygons were then merged to form continuous polygons. This method, described by Churchill et al. (2017), ended up identifying openings that were at least 30 m wide on all sides (tree-stem to tree-stem). The number and size of openings was then calculated for each site, and described in terms of opening size distribution, total area within openings and percent of total site area within openings. In addition to openings we also measured gaps, defined as areas beyond the tree canopy (> 5 m from a tree stem) and not part of an opening. Therefore by definition gaps are less than 10 m from a tree canopy (or < 15 m from a tree stem).

In addition to gaps and openings, we also quantified the distance to the nearest tree for each site by creating buffers at different distances (Matonis and Binkley, 2018; Churchill et al., 2017). We then calculated the "empty areas" within each of the following distance from tree classes: 0–3 m, 3–5 m 5–10 m, 10–15 m, and 20 + m. The percentage of area within each of these classes was then calculated for each site and compared graphically.

3. Results

In general, both Long Valley and Fort Valley exhibited similar global tree spatial patterns, but at different scales (Fig. 2). That is, both sites showed a clustered spatial pattern at short distances, a random pattern at medium distances, and a dispersed pattern at long distances. In Long Valley, the clustered pattern was exhibited up to 70 m, with a random pattern from 70 to 90 m, and a dispersed spatial pattern at distances greater than 90 m. In Fort Valley, the clustered pattern was between 1 and 50 m, while the dispersed pattern extended beyond 60 m.

The cluster analysis showed that a 9–11 m (threshold) ITD was optimal for separating tree groups across both sites. This 2-meter range was judged to best meet descriptive statistical separation on the dendrogram and visual separation between tree groups in the field. With these large data sets, a 2-meter variation was necessary to prevent

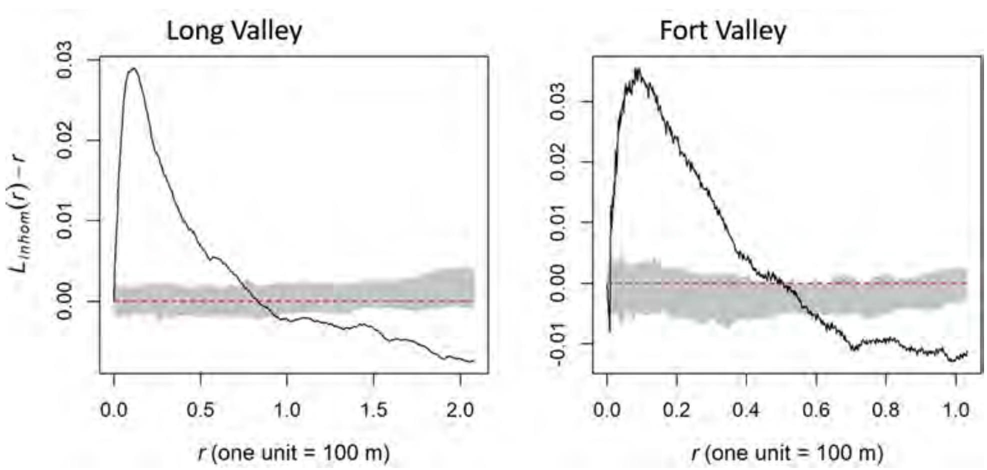

Fig. 2. Global tree spatial pattern within Long Valley and Fort Valley study sites. Ripley's K transformed values (L_{inhom} *(r)* – r) across lag distances in meters. Observed (solid line) above the shaded area indicated distances at which trees are clustered, while observed values within the shaded area are considered random and observed values below the shaded are considered dispersed.

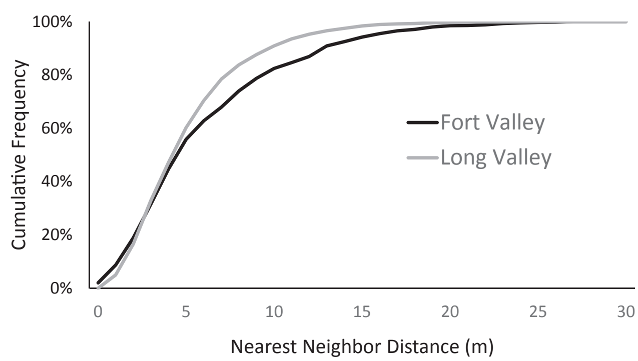

Fig. 3. Percent cumulative frequency of trees within Long Valley and Fort Valley based on nearest neighbor distance (meters).

splitting a group, or combining two groups that were distinct graphically on the dendrogram as well as visually in the field. The cumulative number of trees placed in groups also tended to flatten out at the 9–11 m ITD threshold (Fig. 3). For the following analyses, we defined groups using an ITD of 10 m based on two considerations (Fig. 4). First, field data collected within both sites show that the maximum canopy radius was 4.3 m among non-interlocking crowns. Moreover, 60% of these trees had a maximum canopy radius of at least 5 m (Appendix B). Hence, we consider this to be the potential achievable canopy radius for mature ponderosa pines in the absence of crown competition. Second, we observed during field visits that a 10-m ITD best represented tree groups with overlapping canopies. Thus, we define a group as all trees less than 10 m from other trees. Trees less than 10 m from its nearest neighbor are classified as single trees (Fig. 4). To facilitate comparisons with other studies we also used a 6-m ITD and calculated the same tree spatial metrics.

3.1. Tree spatial patterns compared between sites

Tree spatial metrics are sensitive to the methods used to identify groups. In some respects the ITD is directly related to the NND. For example, 82% of trees in Fort Valley are less than 10 m from another tree (Fig. 3), meaning that at an ITD of 10 m, 82% of trees are in groups while 18% of trees are singles. Moreover, in Fort Valley the average TPH was 41, so on average there were 7.3 singles ha^{-1} (Table 2). Using the same 10-m ITD to define groups in Long Valley, 91% of trees are within groups and 9% are singles, or an average of 5.6 singles ha^{-1} (Table 2). At an ITD of 6 m, in Fort Valley 63% of trees would be in

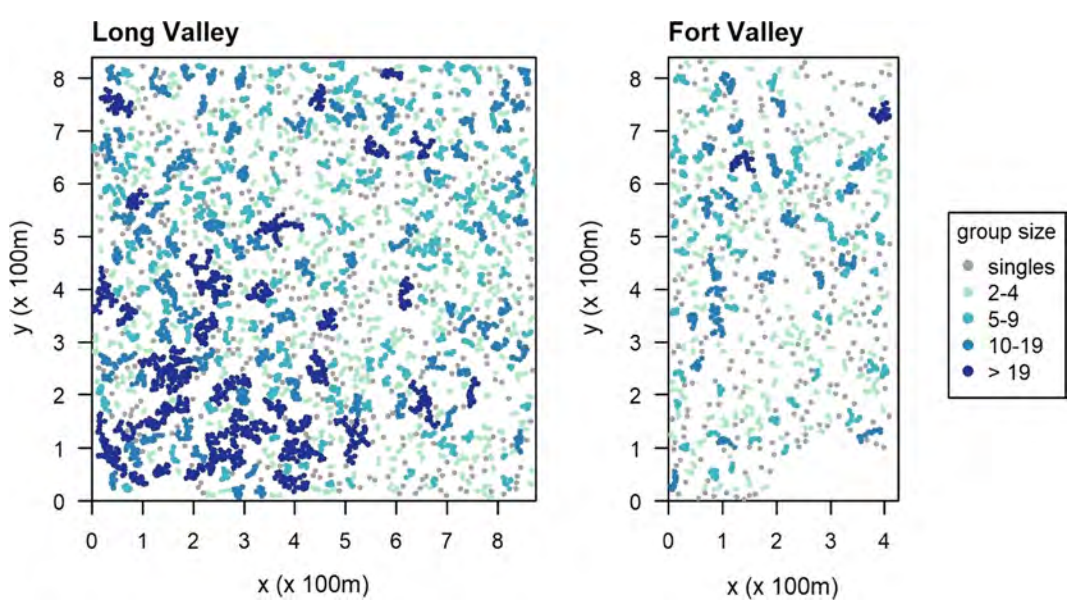

Fig. 4. Tree groups in Long Valley (left) and Fort Valley (right) sites based on 10 m inter-tree distance (5-m buffer around each point) with overlapping buffers creating tree groups. Each dot represents an individual tree location (all *Pinus ponderosa*) and adjacent dots with similar colors are members of the same group.

Table 2
Comparison of tree spatial pattern metrics between Fort Valley and Long Valley based on stem-mapped tree data.

	Fort Valley	Long Valley
Total trees ha^{-1}	40.9	61.7
Singles ha^{-1}	7.3	5.6
% Singles	17.9%	9.1%
Groups ha^{-1}	7.2	8.1
Trees within Groups ha^{-1}	33.6	56.1
% trees within groups	82.1%	90.9%
Maximum Group Size	22	113
Mean Group Size	4.7	6.9
Mean NND (all trees)	6	5
Mean NND (trees within groups)	4.1	4.2
Mean NND (just singles)	14.3	13

groups, meaning that 37% of trees would be classified as singles, while in Long Valley the split would be 70%/30% between trees in groups versus singles (Fig. 3). These dramatic differences between spatial metrics based on the same spatial data highlight the sensitivity of these metrics to definitions of groups and singles. However, Fig. 3 also illustrates a potentially simple but powerful method for comparing spatial patterns between studies and inter-tree distance definitions (Sánchez Meador et al., 2011).

Overall the number of groups per area was similar, but the group size distribution differed between sites. The average number of groups ha^{-1} was similar between Long Valley and Fort Valley (Table 2); however, Long Valley generally had more trees per group. In Long Valley groups averaged 6.9 trees per group, or > 2 additional trees per group compared to Fort Valley (Table 2). The group size distributions were skewed toward smaller groups (2–4 trees $group^{-1}$) at both sites (Fig. 5). Long Valley had a greater proportion of larger groups (≥10 trees $group^{-1}$) compared to Fort Valley. Long Valley contained 24 groups with ≥24 trees, and the largest group had 113 trees, while the largest group we found in Fort Valley contained 23 trees. Based on the field data, the mean NND for all trees differed by 1 m between the two sites (Table 2). When considering only the trees within groups, the maximum NND is of course < 10 m, thereby reducing the mean NND to 4.1 m within Fort Valley and 4.2 m within Long Valley. Therefore the total NND difference between sites was mainly due to singles, which were on average 1 m farther apart in Fort Valley (Table 2).

The diameter distribution pattern was relatively similar between the two sites, but differed for single trees and trees within groups (Fig. 6). In Fort Valley, single trees averaged 61 cm DBH compared to trees within groups which averaged 59 cm DBH. Similarly, in Long Valley single trees had an average diameter of 59 cm while trees within groups averaged 56 cm DBH. In regards to the diameter distributions, in Fort Valley 18% of single trees were larger than 80 cm DBH, whereas such

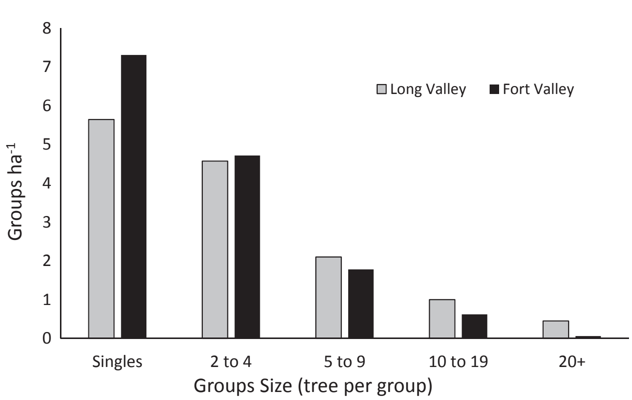

Fig. 5. Singles and group size distribution on a ha^{-1} basis for Long Valley and Fort Valley sites in northern Arizona.

large trees made up only 7% of the total trees within groups. Similarly, in Long Valley, trees larger than 80 cm DBH accounted for 12% of all singles, but only 5% of all trees within groups (Fig. 6). At Fort Valley the total basal area was 11.8 $m^2 ha^{-1}$, 80.5% of which was in trees within groups and 19.5% in singles. In Long Valley basal area was 16.2 $m^2 ha^{-1}$, and 90% was in trees that were part of a group.

3.2. Changes across tree densities within and between sites

By generating 1,000 model simulations of each study site based on the same spatial attributes as the original field data and sampling each iteration using 4-ha plots, we examined how ponderosa pine spatial metrics change as a function of tree density at each site. We found that in Long Valley tree densities ranged from 35 to 100 TPH, while in Fort Valley densities ranged from 10 to 70 TPH (Fig. 7). Despite differences in the range of tree densities, spatial pattern metrics changed consistently across tree densities at both sites. In terms of singles ha^{-1}, Long Valley and Fort Valley differed only slightly (< 1 single ha^{-1}) at any given tree density (Table 3). In Fort Valley, at tree densities between 10 and 30 TPH, singles ha^{-1} increased as total tree densities increased (Fig. 7a). Where the TPH ranges overlap (40–60 TPH) between sites, singles ha^{-1} decreased at a general rate of one fewer single for every increase of 15–20 TPH. In Long Valley at densities greater than 70 TPH, singles ha^{-1} continued to decrease with increasing tree densities, but at a slower rate (Fig. 7a). Differences in singles ha^{-1} were more pronounced when we consider singles as a percentage of all trees. For example, in Fort Valley, singles on average constituted 37.5% of all trees at 20 TPH, but only10% at 60 TPH (Table 3).

The number of groups ha^{-1} tended to increase from low to mid tree densities and decline from mid to high densities (Fig. 7b) within both sites. Between 20 and 40 TPH, the number of groups ha^{-1} increased with increasing overall tree densities from 4.2 to 8 groups ha^{-1} (Table 3). Where their ranges overlapped group ha^{-1} differed between the two sites by less than 1 group ha^{-1} for any given TPH. The number of groups ha^{-1} peaked at tree densities around 60 TPH, but started to decrease at higher densities. The average number of groups ha^{-1} peaked at slightly different tree densities within each site. Moreover, Long Valley, which had sub-sites with higher TPH, showed a slight decrease in groups ha^{-1} at higher tree densities (Fig. 7b).

Our simulation results suggest that increasing tree densities did not result in more groups or singles but instead resulted in larger groups. That is, in both sites, the number of trees within groups increased proportionally with increasing tree densities (Table 3). The relationship between the number of trees within a group and TPH is essentially the same between the two sites (Fig. 7c). Increasing tree densities also resulted in significant changes to the group size distribution. The general pattern of these changes was again consistent between the two sites. In general, areas with the lowest tree density were dominated by small groups consisting of 2–3 trees $group^{-1}$ (Fig. 8). In addition, larger groups (10 trees $group^{-1}$) were generally underrepresented in areas with low tree densities (< 40 TPH). As tree densities increased, the proportion of small groups generally declined and the frequency of larger groups increased. Plots with the highest tree densities (80 TPH) had an almost flat group size distribution; no size group was dominant (Fig. 8). In such cases, however, most trees not only were part of a group but were more likely to be part of a large group (> 15 trees $group^{-1}$).

3.3. Gaps and openings

The area not occupied by tree canopies (> 5 m from a tree stem) accounted for 68% and 77% of the total area within Long Valley and Fort Valley, respectively. In Long Valley 42% of the total area was in openings and 26% in gaps, whereas in Fort Valley 58% of the area was openings and 19% percent gaps. At both sites, the size distribution of openings was dominated by small openings with more than half of all

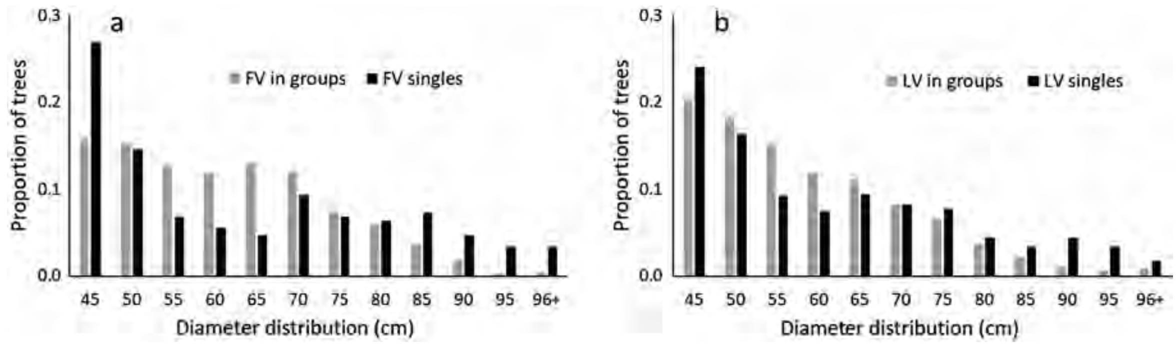

Fig. 6. Diameter distribution of single trees and trees within groups in (a) Fort Valley and (b) Long Valley.

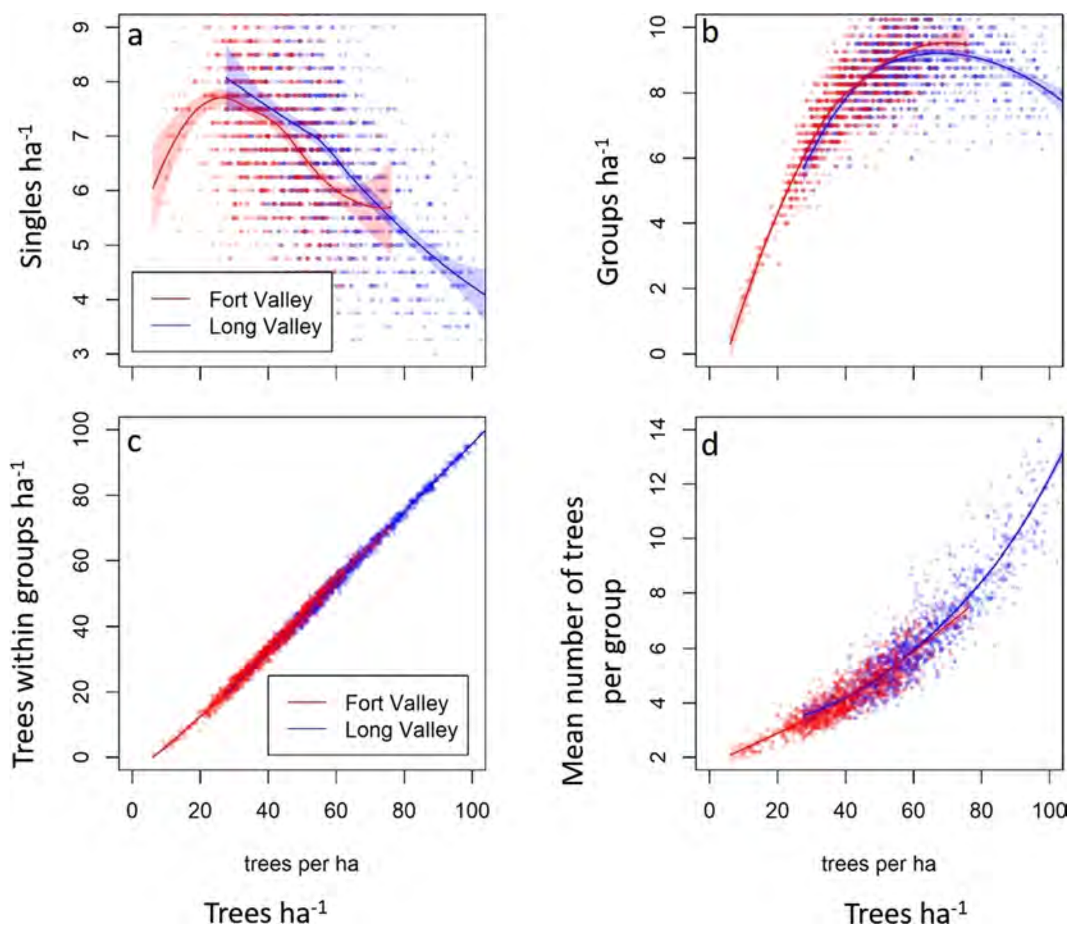

Fig. 7. Relationship between tree densities (trees ha^{-1}) and (a) singles ha^{-1}, (b) groups ha^{-1}, (c) trees within groups ha^{-1} and (d) mean group size within Long Valley and Fort Valley based on 1,000 simulations modelled using field data. Each point represents a value sampled using 4-ha plots within each simulated landscape.

openings being < 0.1 ha (Fig. 9a). Although large openings were less common, they occupied more than one third of the total area in Fort Valley (Fig. 9b). Small openings tended to be round, whereas medium openings tended to be elongated and large openings tended to be interconnected and sinuous (Appendix C).

Due to the greater tree density at Long Valley, this site tended to have more of the total area within 5 m of a tree compared to Fort Valley (Fig. 10). Conversely, Fort Valley had a greater percentage of areas that were > 15 m away from trees (Appendix D). However, at both sites the majority of the site was 5–15 m from a tree stem.

4. Discussion

4.1. Tree spatial pattern differences between sites

Our results based on field data showed differences between the two sampled sites. As expected, the difference between sites was most obvious in terms of total tree densities; Long Valley had on average 20 more trees ha^{-1} than Fort Valley. Although the two sites differed slightly in singles and groups ha^{-1}, the difference in tree density was manifested most sharply in the shift from the dominance of singles and small groups in the low tree-density Fort Valley site to the dominance of large and extra-large groups in the Long Valley site. If we consider solely the field data collected over large areas, the two sites appear to

Table 3
Comparison of average forest spatial pattern based on different tree densities within Fort Valley and Long Valley. These average estimates are based on conditions sampled within 1,000 simulations of each site sampled using 4-ha plots within each simulated site.

Total trees ha^{-1}	Fort Valley 20	40	60	
Singles ha^{-1}	7.5	7.3	6.0	
% Singles	37.5%	18.3%	10.0%	
Groups ha^{-1}	4.2	8.0	9.3	
Trees w-in Groups ha^{-1}	12.5	32.7	54	
% trees w/in groups	62.5%	81.8%	90.0%	
Mean Group Size	3.0	4.1	5.8	
	Long Valley			
Total trees ha^{-1}		40	60	80
Singles ha^{-1}		7.6	6.6	5.3
% Singles		19.0%	11.0%	6.6%
Groups ha^{-1}		7.8	9.1	9.0
Trees w-in Groups ha^{-1}		32.4	53.4	74.7
% trees w/in groups		81.0%	89.0%	93.4%
Mean Group Size		4.2	5.9	8.3

have very different tree spatial patterns. Moreover, these differences could have been attributed to productivity differences related to parent material and precipitation. Such differences have also been found on other studies in the southwestern United States (Abella and Denton, 2009; Rodman et al., 2017). For example, Schneider et al. (2016) sampled limestone soils in northern Arizona and found higher tree densities compared to sites adjacent to Fort Valley sampled previously by Sánchez Meador et al. (2011). Results of both studies also show some spatial pattern differences, with more groups ha^{-1} found in the limestone site compared to the basalt site. However, the analysis of our field data and simulations provides other insights into the drivers of tree spatial patterns.

4.2. Comparison across similar tree densities within each site

As previously noted, sedimentary soils tend to hold more moisture, supporting greater tree densities. Within each site, however, we found that tree densities are highly inhomogeneous due to a combination of factors including topography and past disturbances such as fire, insects, or mistletoe (Abella and Denton, 2009). Stem-mapping of relatively large sites allowed us to capture this microsite variability and better understand how spatial patterns vary within each site as a function of tree density. The sub-sampling results suggest that the range of tree densities overlap between the two sites, meaning that some sub-areas within the two sites share similar tree densities. The overlap between sites occurred at tree densities between 35 and 65 TPH. Therefore, within this overlapping range we can compare spatial tree patterns

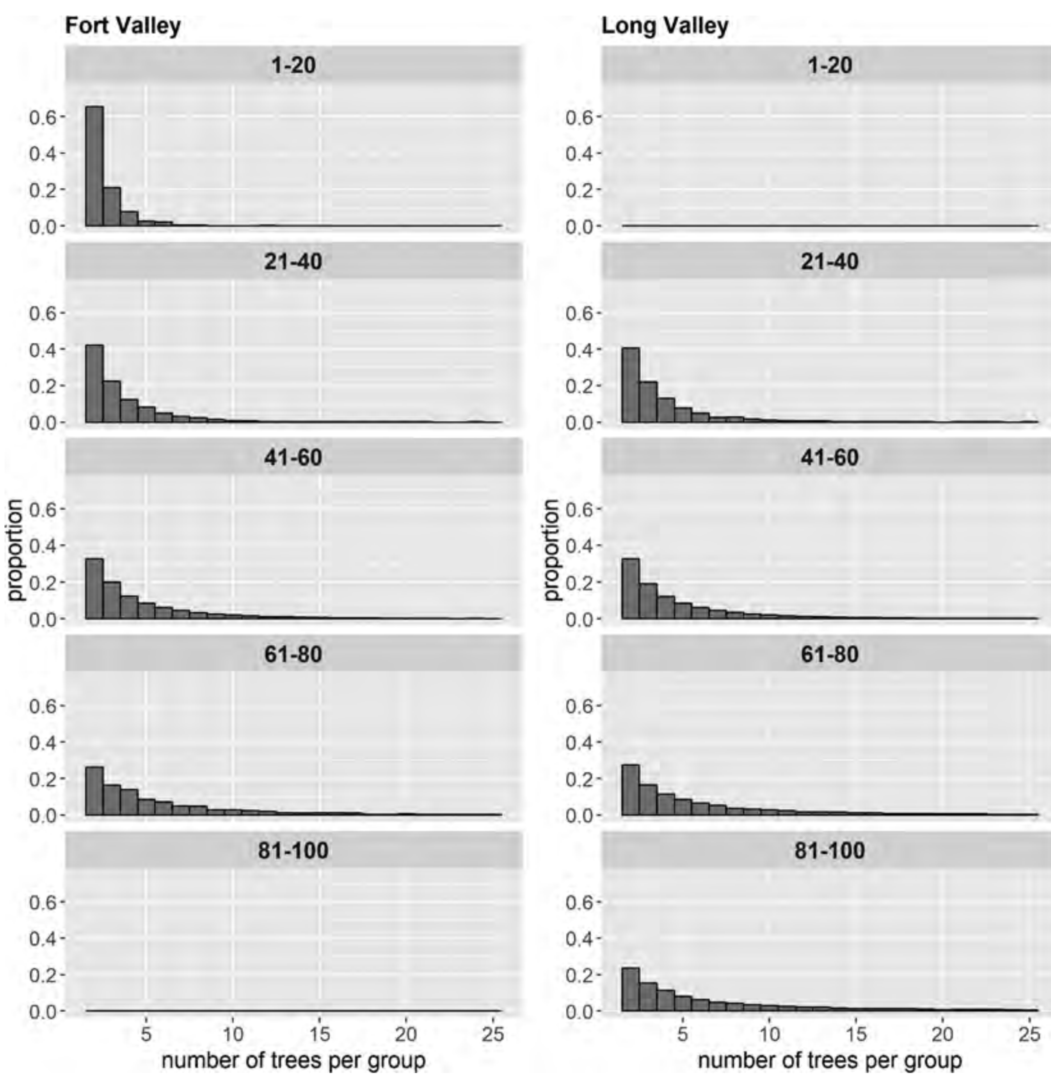

Fig. 8. Group size (number of trees group^{-1}) distribution as a function of different tree density (trees ha^{-1}) classes for (a) Fort Valley and (b) Long Valley based on 1,000 simulations models of the field data. Each graph is based on a 4-ha sample area within each simulation.

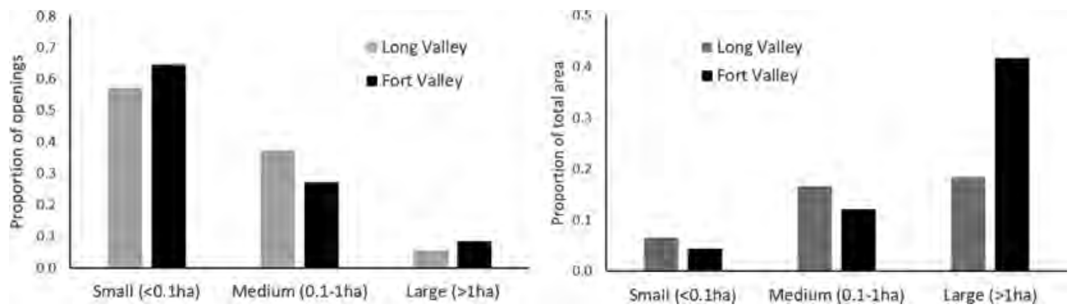

Fig. 9. Opening size distribution and proportion of the total area occupied by different sized openings within Long Valley and Fort Valley.

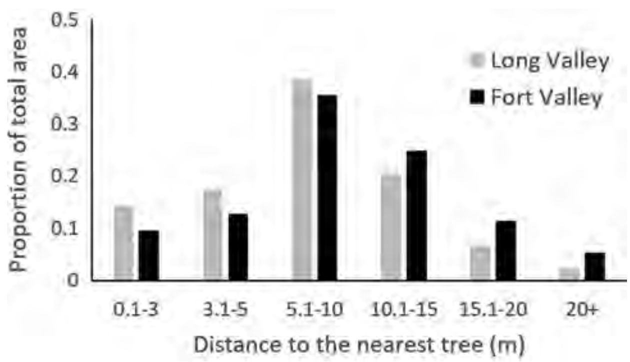

Fig. 10. Empty space distribution described as the distance from the nearest tree (m) within Long Valley and Fort Valley.

between sites while controlling for tree density. Averaged results from the simulations indicate that when tree densities are equal, the spatial patterns are actually very similar between the two sites. For example, at a density of 35 and 65 TPH, the difference between the two sites is less than one single and one group ha^{-1} (Table 3). The percentage of trees within groups is similar when TPH are equal and decrease at a similar rate as tree densities increase at both sites. For example, at a TPH of 40 both Long Valley and Fort Valley average about 81% of trees within groups, while at 60 TPH that increases to around 90%. The same synchronous relationship applies to mean group size, which increases with increasing tree densities (Table 3).

The within-site subsampling suggests that the differences in spatial pattern observed between sites is actually a function of tree density rather than site properties such as parent material or precipitation. That is, each site showed high within-site variability in tree density, yet at similar densities, spatial patterns were similar on the two sites. Likely due to sedimentary soils and greater precipitation, a larger portion of Long Valley had high tree densities compared to Fort Valley (Fig. 1). However, when we examined spatial patterns at similar tree densities on the two sites, the spatial attributes were very similar. These results suggest that it is important to consider microsite variability within sites and adjust spatial patterns according to the desired tree densities to produce more heterogeneous and resilient landscapes (Churchill et al., 2013).

4.3. Where do the “additional trees” go?

As tree density increases, we need to understand how “additional trees” are distributed among singles and tree groups. In theory, the additional trees could result in more singles, more groups, or larger groups. Our field data indicated that despite large differences in total tree densities, the two sites differed only marginally in singles and groups ha^{-1}. These results suggest that as the number of trees increased, these additional trees integrated into existing groups (Fig. 7c) rather than creating new groups. This pattern led to a general increase in group size (Fig. 7d), hence fewer small groups and more large groups at Long Valley (Fig. 8). Further, as groups become larger, they are more likely to “merge” with other groups, creating the extra-large groups of ≥20 trees. This pattern is also apparent in the simulated data, where tree density increases tend to result in an increase in the number of large groups at both sites (Fig. 8). That is, areas with greater tree densities tend to have group size distributions with “longer tails”. In general, singles ha^{-1} marginally increase with increasing tree density, whereas singles as a percentage of all trees drastically decrease with increasing tree density (Table 3). For example, at low tree densities, up to 50% of all trees are singles, but at high densities singles can account for less than 10% of all trees (Table 3). This sizable difference in the percentage of singles with increasing tree density has also been found in other studies (Table 4) of tree spatial patterns (Brown et al., 2015).

4.4. Tree spatial patterns comparisons to other studies

Compared to other recent studies that have described tree spatial patterns using trees and groups, our results have both commonalities and new insights. In this study we have defined tree groups using an ITD of 10 m, however we have also included the same spatial metrics based on a 6-m ITD (Table 4; Fig. 11). This information is useful for comparing with other published studies as well as for considering management implications. A number of studies have previously provided attributes on singles and tree groups in dry forests across the western United States. All of these studies consistently report trees and groups ha^{-1}, yet there is no consistent use of other spatial metrics. For example, Brown et al. (2015) also reported % trees within groups, while Clyatt et al. (2016) reported % singles. To better understand general trends in tree spatial patterns across these studies, we used the values provided by these authors to calculate a standard set of spatial metrics and facilitate comparisons among studies from different sites (Table 4). Compared to these other studies, the tree densities we found at our two sites are on the lower end of a continuum ranging from 25 to 170 TPH. Contrary to our simulation results, the pattern among the literature appears to show a general increase in both singles and groups ha^{-1} with increasing tree density, although these values are highly variable. In relative terms, the proportion of trees within groups appears to increase (and % singles decreases) as total tree densities increase (Table 4). This pattern is identical to our findings based on the model simulations (Table 3) and support the idea that spatial patterns are a function of tree densities and are only indirectly related to site conditions.

4.5. Open spaces

Similar to tree spatial metrics, our results show that empty space is influenced by tree density. That is, Fort Valley had a greater percentage of areas greater than 5 m from a tree compared to Long Valley, where higher tree densities made it difficult to find areas greater than 15 m away from a tree. In some ways the distribution of openings was the inverse of the tree group size distribution. That is, the dominance of singles and small tree groups allowed for a greater proportion of the

Table 4
Tree spatial patterns found in Long Valley (LV) and Fort Valley (FV) compared to other studies across the western United States that have reported spatial pattern using metrics related to single trees and groups. The sites selected for this comparison were based on species composition similar to the sites sampled in this study and are presented from increasing tree densities from left to right. Each column represents the results for a specific plot provided within a study as follows: FV and LV are the same as provided in Table 2 except in this table those metrics are based on 6-m ITD. S1B and S1A were reported in Sánchez Meador et al. (2011), SCH was reported in Schneider et al. (2016), PRE was reported in Tuten et al. (2015), HE19, HE20, and HA01 were reported in Brown et al. (2015), L1 (LOLO1), B2 (Bitterroot 2), B3 (Bitterroot 3) were reported in Clyatt et al. (2016); and LYS is based on 3 plots reported in Lydersen et al. (2013).

Site	HE19	**FV**	S1B	**LV**	S1A	SCH	L1	HE20	B2	B3	LYS	PRE	HA01
Trees ha^{-1}	**25**	**41**	**44**	**62**	**67**	**77**	**102**	**110**	**125**	**129**	**133**	**142**	**170**
Singles ha^{-1}	*10*	**15**	*11*	**18**	*16*	**24**	*23*	*18*	*29*	*28*	**17**	**37**	*22*
% singles	*41%*	*37%*	*25%*	*30%*	*24%*	*31%*	**23%**	*16%*	**23%**	**22%**	**13%**	*26%*	*13%*
Groups ha^{-1}	**14**	**26**	**10**	**31**	**11**	**18**	**46**	**20**	**49**	**54**	**23**	**27**	**22**
Trees w/in groups ha^{-1}	*15*	*26*	*33*	*43*	*51*	*54*	*79*	*92*	*96*	*101*	*117*	*105*	**148**
% trees w/in groups	**59%**	*63%*	*75%*	*70%*	*76%*	*69%*	*77%*	**84%**	*77%*	*78%*	*88%*	*74%*	**87%**
Mean trees per group	*1.1*	*1.0*	**3.6**	*1.4*	**5.4**	*2.9*	**2.2**	*4.6*	**2.6**	**2.4**	**5.2**	*3.8*	*6.7*
Max trees per group	**5**	**11**	**12**	**27**	**19**	**7**		**15**			**27**	**16.3**	**11**
Reference Year	**1860**	**2009**	**1874**	**2009**	**1874**	**1883**	**1900**	**1860**	**1900**	**1900**	**1929**	**2015**	**1860**
Min DBH (cm)	**25**	**40**	**9.4**	**40**	**9.4**	**12.5**	**1.4**	**25**	**1.4**	**1.4**	**25**	**44**	**25**
Inter-tree distance (m)	**6**	**6**	**5.2**	**6**	**5.2**	**5.2**	**6**	**6**	**6**	**6**	**6?**	**5.2**	**6**
Plot size (ha)	**0.5**	**30**	**1**	**71**	**1**	**4**	**1**	**0.5**	**1**	**1**	**4**	**2.02**	**0.5**

Bold numbers were reported within each paper. Italic numbers were not provided in the paper but were calculated based on the reported figures. Blank fields indicate where data was not provided and could not be calculated.

total area in large openings within Fort valley, where as the dominance of large groups in Long Valley prohibited large openings. These and other similar methods (Lydersen et al., 2013) are still subjective, in that the user has to define what constitutes a large opening. These more detailed methods, however are likely to be useful in development and evaluation of treatment prescriptions.

The normal distribution of empty space across distances to nearest tree we found at both sites is consistent with other studies that have reported such values (Clyatt et al., 2016; Churchill et al., 2017; Matonis and Binkley, 2018; Pawlikowski et al., 2019). This suggests that most of the empty space within these frequent-fire forests was at distances between 5 and 15 m from a tree. Functionally, gaps or areas 5–15 m from a tree are where most regeneration is likely to occur given that regeneration is closely associated with distance to seed source (Owen et al., 2017; Malone et al., 2018). These areas are also more likely to be influenced by root competition and associated tree microclimates such as shadows and snow retention (Boyden and Binkley, 2015). Conversely, openings or areas beyond 15 m from a tree are likely to have the greatest plant species diversity and more likely to restrict crown fire spread (Matonis and Binkley, 2018). It is clear, however, that the amount and distribution of empty space, gaps and openings is influenced by tree density. That is, low density sites will have less area at short distances from trees and more area at long distances from trees, such as Fort Valley. In turn, this pattern also results in a greater proportion of the area in large openings.

4.6. Limitations

One limitation of this study is that we sampled only trees that were > 40 cm DBH. Using this size cut-off likely underestimates tree densities and may explain why the tree densities we report are generally lower than those reported for other ponderosa pine forests (Table 4). White (1985) actually sampled age structure within a small section of the Fort Valley site and cored yellow bark trees less than 37 cm DBH finding that half of the trees established under a frequent fire regime (prior to 1880). This suggests that by excluding trees less than 40 cm, we underestimated tree densities, while including yellow bark < 40 cm would overestimate tree densities. Another limitation of this study is that we described tree spatial patterns, groups and gaps but did not explore how these features developed or changed over time. We could potentially explore such topics in the future by separating trees into different size/age classes similar to other studies (Youngblood et al., 2004; Boyden et al., 2005; Knapp et al., 2013). Such analysis however, were beyond the scope of the current study. Finally, there is also a need to further explore the minimum plot size required to capture spatial patterns in this forest type. Our use of a 4-ha plot for the analyses allowed us to capture large tree groups and openings, but it is possible that the spatial patterns could be captured with less effort in smaller plots.

4.7. Management Implications

The 10-m ITD is best at defining trees and groups within mature forests such as the sites sampled here. However, expecting the same tree

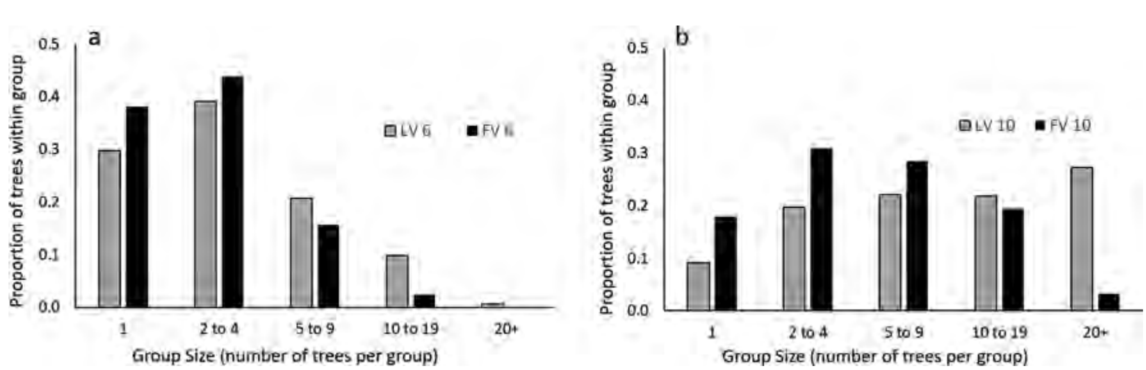

Fig. 11. The distribution of trees among singles and groups of different sizes changes drastically depending on whether they are based on ITD of (a) 6-m or (b) 10-m when comparing spatial patterns between Fort Valley and Long Valley. (Based on field data).

spatial pattern after restoration treatments within a typical second-growth fire-excluded forest would not be realistic because those trees lack the large canopies found within our sites. Instead we would suggest replicating the tree spatial pattern provided in Table 4 and Fig. 11a, where we calculated the same tree spatial matrices, but using an ITD of 6 (Fig. 11), which better matches the actual maximum canopy radius of immature forests.

Although no study has been conducted expressly to determine the optimal plot size for sampling dry forests, the recent literature and our own analysis (not presented here) suggest that 4-ha is the minimum plot size to observe unique spatial patterns (North et al., 2007; Larson and Churchill, 2012). One of the main advantages of larger plots is that they allow us to capture a greater proportion of large tree groups (5+ trees) and openings. That is, these components are likely to be "cut off" if smaller plots are used, unless they happen to be in the middle of the plot. Similarly, we believe that attempting to replicate these spatial patterns on the ground will be best served by creating heterogeneous conditions at spatial scales of at least 4 ha because many of these spatial metrics are difficult to interpret at the per hectare scale. For example, it would be difficult to replicate 0.38 groups ha^{-1}. Implementing these spatial patterns at larger scales will also result in more heterogeneous landscapes that incorporate both macro and micro-scale variability.

In regards to replicating these natural tree spatial patterns it is important to emphasize single trees and the overall group size distribution of both tree groups and openings. The lack of a normal group size distribution translates to a greater number of small tree groups and openings. Conversely, although large tree groups and openings are not frequent they actually account for a large portion of area and should therefore by emphasized according to the desired density. Overall our results suggest a range of conditions from a savanna matrix with small group-tree islands and large openings in low density conditions to areas dominated by large tree-patches and smaller openings in more dense forests.

5. Conclusions

Based on stem maps from two large sites, each with different soil parent material and precipitation, we conclude that these two sites differed in terms of tree groups, gaps and openings. Overall, the more productive Long Valley site had higher tree densities and slightly fewer singles ha^{-1}, but similar numbers of groups ha^{-1} compared to the Fort Valley site. The most important difference between the two sites was in regards to the tree group size distribution, where large (10–19 trees) and extra-large (20+ trees) tree groups were more frequent in Long Valley compared to Fort Valley. Another major difference was that the largest group in Fort Valley included 22 trees, whereas a group of 113 trees was found in Long Valley.

Despite these overall differences between sites, sub-sampling of simulated sites based on the field data showed high inter-site variability with some overlap in the range of tree densities between the two sites. Our simulated sub-sampling also showed that the spatial pattern (groups and singles) varied according to tree density, with similar rates of change between sites. Furthermore, sub-sites with similar tree densities tended to have similar spatial patterns across both Long Valley and Fort Valley. These results suggest that the overall differences we observed between sites were due to differences in tree densities and were only indirectly related to productivity. Tree densities vary at macro and microscales due to both biotic and abiotic factors; therefore spatial patterns should also be adjusted accordingly.

In general, areas with lower tree densities to have a greater proportion of trees as singles, smaller tree groups and more open space including gaps and larger openings. On the contrary, more productive areas with higher tree densities will support a greater proportion of trees in large and very large groups, with open spaces closer to trees and smaller openings. Furthermore, these results suggest that it is important to consider microsite variability within sites and adjust spatial patterns according to the desired tree densities to produce the variation in spatial patterns that characterized these old-growth forest remnants. Managers can use this variation to create heterogeneous, and hence, potentially more resilient, landscapes to better cope with an uncertain climatic future.

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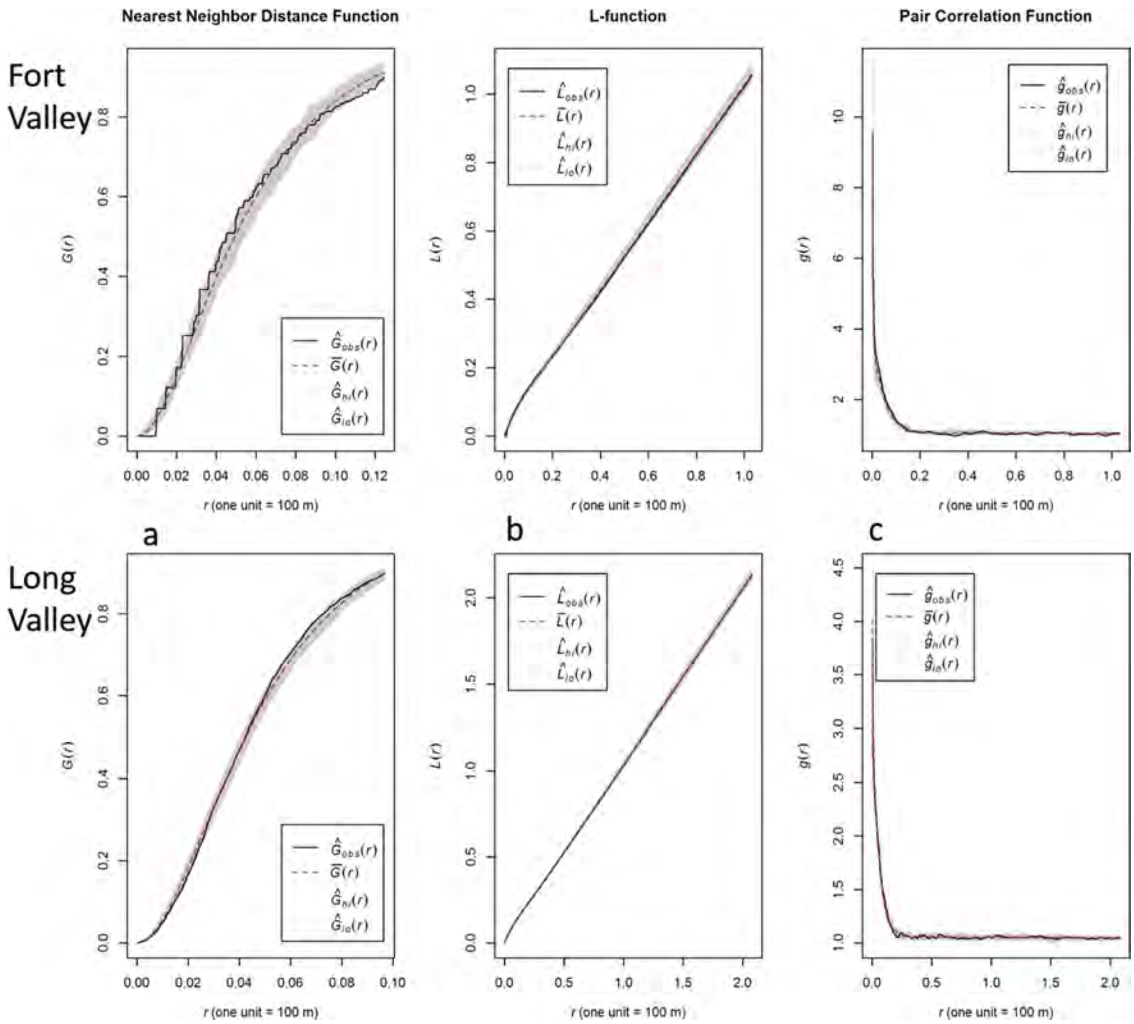
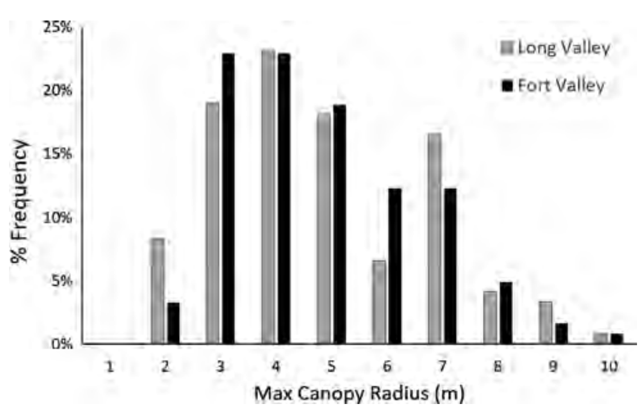
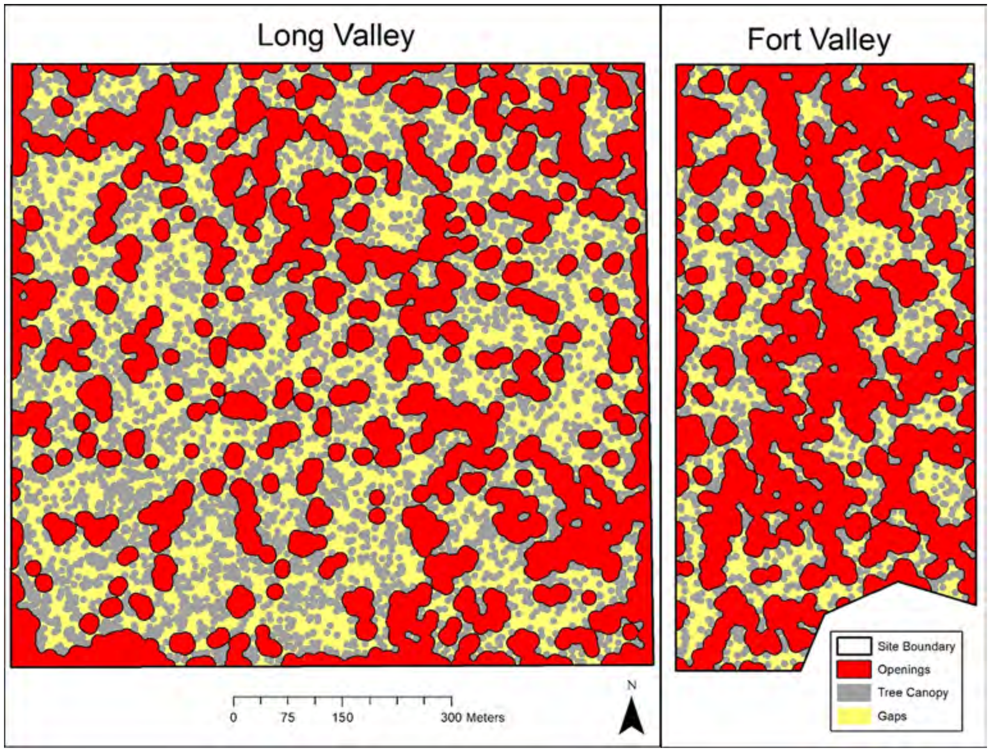
Appendix A. Evaluation of goodness of fit for the final model based on three metrics comparing observed and model-predicted spatial point distributions: (a) *G(r)*, the nearest neighbor distance function; (b) *L(r)*, Besag's transformation of Ripley's *K(r)*; and (c) *g(r)*, the pair correlation function, for Fort Valley and Long Valley spatial data sets.



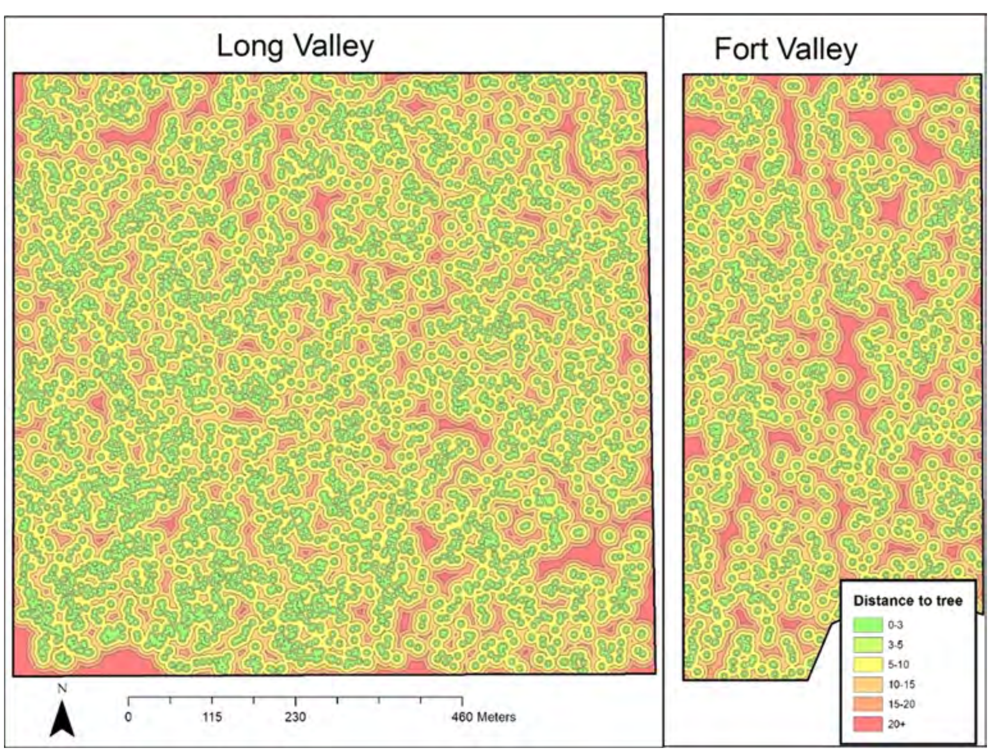
Appendix B. Maximum canopy radius percent frequency distribution for tree canopies not intersecting another tree canopy in ponderosa pine forest in Long Valley and Fort Valley sites in northern Arizona.



Appendix C. Visual of areas dominated by tree canopies (5 m from tree stem), gaps (less than 30 m wide stem-to-stem) and openings (opening at least 30 m wide stem-to-stem) within Long Valley and Fort Valley.



Appendix D. Empty space defined as the distance to the nearest tree in both Long Valley and Fort Valley.



Appendix E. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.117502.

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Review

Perpetuating old ponderosa pine

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Abstract

We review current knowledge about the use of management treatments to reduce human-induced threats to old ponderosa pine (*Pinus ponderosa*) trees. We address the following questions: Are fire-induced damage and mortality greater in old than younger trees? Can management treatments ameliorate the detrimental effects of fire, competition-induced stress, and drought on old trees? Can management increase resistance of old trees to bark beetles? We offer the following recommendations for the use of thinning and burning treatments in old-growth ponderosa pine forests. Treatments should be focused on high-value stands where fire exclusion has increased fuels and competition and where detrimental effects of disturbance during harvesting can be minimized. Fuels should be reduced in the vicinity of old trees prior to prescribed burns to reduce fire intensity, as old trees are often more prone to dying after burning than younger trees. Raking the forest floor beneath old trees prior to burning may not only reduce damage from smoldering combustion under certain conditions but also increase fine-root mortality. Thinning of neighboring trees often increases water and carbon uptake of old trees within 1 year of treatment, and increases radial growth within several years to two decades after treatment. However, stimulation of growth of old trees by thinning can be negated by severe drought. Evidence from young trees suggests that management treatments that cause large increases in carbon allocation to radial xylem growth also increase carbon allocation to constitutive resin defenses against bark beetle attacks, but evidence for old trees is scarce. Prescribed, low-intensity burning may attract bark beetles and increase mortality of old trees from beetle attacks despite a stimulation of bole resin production.

Keywords: Bark beetle; Forest management; Fire; *Pinus ponderosa*; Prescribed burn; Restoration; Thinning

Contents

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1. Introduction

Much of past forestry research has focused on obtaining information to increase the efficiency of wood commodity production. Consequently, the majority of past silvicultural research has been directed at treatments to hasten regeneration and improve the growth and wood properties of young trees (Smith et al., 1997; Nyland, 2002). Large, old trees were rarely included in this research agenda.

Interest in using silviculture to perpetuate the vigor and longevity of existing old trees is growing. This interest has arisen from the recognition that old trees are rare on the landscape (Bailey and Ide, 2001; Sesnie and Bailey, 2003), are a living testimony of past disturbance and climate change (e.g., Speer et al., 2001; Soulé and Knapp, 2006), provide unique wildlife habitat (Reynolds et al., 1992; Kelly et al., 1993; Humes et al., 1999; Mazurek and Zielinski, 2004; Molina et al., 2006), sequester carbon over centuries (Harmon et al., 1990), and provide spiritual inspiration to many people (Ostlund et al., 2005). In, dry, fire-prone, forests of the western U.S., Fiedler (2000) recommended that stands containing old trees receive priority for fuel-reduction treatments because of their rarity and ecological importance, and because they are currently threatened by fire, competition stress, drought, and associated bark beetle attacks. This review focuses on old ponderosa pine (*Pinus ponderosa*), the dominant species of these forests (Hardin et al., 2001).

Definitions of old-growth ponderosa pine forests vary among authors and agencies, yet all emphasize the existence of old trees (Kaufmann et al., 1992). For example, attributes of old-growth ponderosa pine forests include containing trees with a diameter at breast height (DBH) greater than 41 cm and at least 200 years old in the Front Range of the Rocky Mountains, DBH greater than 41 cm and at least 160 years old in the Black Hills, South Dakota, and DBH greater than 46 cm and at least 160 years old in Arizona and New Mexico (Mehl, 1992). The mean age of ponderosa pines in old-growth stands in Arizona and New Mexico is about 279 years, with the oldest known tree 742 years old (Swetnam and Brown, 1992). In southern Oregon, mean age of ponderosa pine in two mixed confer stands ranged from 230 to 315 years, with the oldest tree over 400 years (Agee, 2003; Perrakis and Agee, 2006). In Montana, mean age of ponderosa pine in old-growth mixed conifer stands ranged from 179 to 374 years with the oldest tree over 450 years (Arno et al., 1995, 1997; Keeling and Sala, unpublished data). Trees older than about 400 years in remote unlogged areas are rare, perhaps because of extensive mortality from severe drought in the late 1500s (Swetnam and Brown, 1992). In addition to age, crown characteristics differ between old and younger, but mature trees. Height growth is slow in old trees producing a flattened crown top compared to the more conical crown top of younger trees with more rapid height growth (Keen, 1936; Bond, 2000). In this review, we use the term ‘‘old’’ to refer to ponderosa pines that are at least 160 years old or have a DBH greater than 40 cm, and the terms ‘‘young’’ or ‘‘younger’’ to refer to trees that are less than 160 years of age or have a DBH less than 40 cm.

Old ponderosa pine in areas historically subjected to frequent low-severity fire regimes is currently threatened by several factors that are distinct from the logging that reduced their abundance over the past 150 years. The first of these factors is wildfire. Recent increases in wildfire activity and severity in the western U.S. that often kill old pines have been linked to temperature increases since the mid 1980s (Westerling et al., 2006) and fuel accumulation resulting from a century of fire exclusion (Habeck, 1994; Arno et al., 1995, 1997; Covington et al., 2001; Keane et al., 2002; Fulé et al., 2004; Moore et al., 2004). The increase in fuels due to fire exclusion, however, appears to be less predictable in old-growth forests of the northern Rocky Mountains relative to drier forests of the southwestern U.S. (Keeling et al., 2006). Increasing evidence also suggests that historic logging disturbance may also promote regeneration and increase fuel accumulation in the long-term beyond that caused by fire exclusion (Minnich et al., 1995; Kaufmann et al., 2000). In ponderosa pine forests where current fire regimes are clearly outside the historic range of variability, wildfire severity and frequency are expected to increase in the future in the western U.S. as temperatures rise and relative humidity decreases (Brown et al., 2004). Restoration treatments, consisting of thinning or prescribed burning to reduce fuels and modify fuel structure, have been recommended to reverse the current trend of large, stand-replacing wildfires (e.g., Covington, 2000; Fiedler, 2000; Fulé et al., 2001; Allen et al., 2002; Fitzgerald, 2005).

A second threat to old ponderosa pine is competition with mid- or under-story trees. This threat may be natural, or non-anthropogenic, in some mixed-species higher elevation forests containing ponderosa pine whose fire regime does not deviate much from historic variability (Brown et al., 1999; Schoennagel et al., 2004), but is of anthropogenic origin in regions where fire exclusion has increased tree density beyond its natural range of variability. For instance, increased tree density in the understory and in former openings and meadows over the last century of fire exclusion has increased competition between old and younger trees in some areas (Biondi, 1996; Feeney et al., 1998; Stone et al., 1999; McDowell et al., 2003). The use of silvicultural treatments to reduce competition stress on old trees is a relatively new idea (Harrington and Sackett, 1992;

Kaufmann et al., 1992; Fiedler, 2000). Several experiments have been started recently to address impacts of thinning and prescribed burning on old ponderosa pine (Covington et al., 1997; Oliver, 2000; Ritchie, 2005), yet only a few conclusive results have been published and synthesis of these results is currently lacking. Information on the growth rate of old trees in low-competition environments is scarce for all tree species (Bond, 2000).

The last significant threats to old ponderosa pine are drought and bark beetle attacks. Mortality of ponderosa pine attributed to drought and associated bark beetle attacks has increased recently (e.g., Macomber and Woodcock, 1994; Savage, 1994; Agee, 2003; Guarin and Taylor, 2005). Bark beetle attacks interact with fire damage and increase the probability of post-fire tree mortality (McHugh et al., 2003; Parker et al., 2006). Climate change forecasts include an increase in the frequency and severity of drought in the western U.S. (Houghton et al., 2001; Coquard et al., 2004), which may increase bark beetle attacks (Breshears et al., 2005). Partial cutting has been recommended to increase resistance of ponderosa pine to bark beetles (Schmid and Amman, 1992; Fettig et al., 2007), yet information to support this recommendation for old trees is scarce.

Our objectives are to review current knowledge about the use of management treatments to reduce human-induced threats to old ponderosa pine in the western U.S. Specifically, we address the following questions: Are fire-induced damage and mortality greater in old trees than younger trees? Can management treatments ameliorate the detrimental effects of fire, competition-induced stress, and drought on old trees? Can management increase resistance of old trees to bark beetles?

2. Response of old ponderosa pine to fire

Impacts of prescribed fire on growth of ponderosa pine have been addressed in several studies of trees that were mature but younger than our definition of an old tree. Studies on old trees are rare. In Oregon, height, basal area, and volume growth of young ponderosa pine were reduced over an 8-year period after prescribed fire, and the effect was more pronounced in burned areas with higher duff consumption (Landsberg et al., 1984). In northern Arizona, prescribed fire reduced radial growth of young, mature ponderosa pine for several years after burning even in the absence of obvious crown damage from fire, after which growth recovered to pre-burn rates (Sutherland et al., 1991). Prescribed fire with and without prior thinning had little effect on radial growth of young ponderosa pine in Montana (Sala et al., 2005). Prescribed fire intervals of 4 or 6 years have been reported to stimulate radial growth of young trees slightly, whereas intervals of 1, 2, 8 and 10 years decreased growth relative to no burning (Peterson et al., 1994). Prescribed, low-intensity fire rarely kills young ponderosa pine unless fire intensity is severe enough to girdle the tree by killing cambium or removing much of the canopy by scorch or consumption (Ryan, 1982, 1990; McHugh and Kolb, 2003; Sieg et al., 2006).

Whereas impacts of low-intensity fires are expressed in young ponderosa pine primarily in growth responses, the effects of such fires on old pine are often expressed by increased tree mortality. In Oregon, mortality of ponderosa pine over 70 cm diameter, 4 years after a prescribed fire, significantly exceeded that in adjacent unburned areas (Thomas and Agee, 1986). In the same areas, Agee (2003) measured mortality of ponderosa pine for 13 years. The average size and age of ponderosa pines that died in the first 4 years after burning were 10–20 cm and less than 100 years old. Between the 4th and 13th post-fire years, those averages increased to 45–100 cm and 100–400 years. Precipitation was below average in every year but one between post-fire years 4 and 13, suggesting a role of drought in the delayed mortality of the old trees.

Prescribed burning at Crater Lake National Park in Oregon between 1976 and 1986 increased mortality of old ponderosa pine compared with control, unburned stands (Swezy and Agee, 1991). In burned stands, mortality was moderately high for the smaller diameter classes, declined as diameter increased, and then increased sharply for the largest diameter trees. Mortality of trees with diameters greater than 100 cm in burned stands varied between 21 and 50%, and trees in the oldest class with moderate to low vigor class had mortality of 71–100% (Swezy and Agee, 1991). A majority (68%) of dead trees after a fire in 2002 had evidence of western pine beetle (*Dendroctonus brevicomis*) attacks (Perrakis and Agee, 2006). Crown vigor, measured with Keen's crown vigor classes, was significantly related to mortality after burning—mortality was highest for low vigor trees.

Similar to experiences in Oregon, prescribed fire also can increase the mortality of old ponderosa pine in northern Arizona. Prescribed fire applied to a stand in northern Arizona after 100 years of fire exclusion resulted in 39% mortality of old trees compared with 16% in a control, unburned stand, within 20 post-fire years (Sackett et al., 1996). This mortality was associated with complete consumption of the forest floor from the bole to the dripline. Mortality of the old trees started 1.5 years after the fire and continued for 20 years after fire. Prescribed fire at Grand Canyon National Park, Arizona, increased mortality of old ponderosa pine (10–23% depending on stand) compared with control, unburned stands (1–3%) (Kaufmann and Covington, 2001). Following thinning and prescribed burning on shallow, lava-derived soils in northern Arizona, Fulé et al. (2002) reported 67% mortality of large (>50 cm diameter) ponderosa pine compared with 19% mortality for small (<50 cm diameter) pine within 2 years of burning.

Old ponderosa pines are often more susceptible to mortality after fire than younger, mature trees. For example, a "U-shaped" relationship between post-fire mortality and diameter at breast height (Fig. 1) was reported for ponderosa pine in both southern Oregon (Agee, 2003) and northern Arizona (McHugh and Kolb, 2003). In Arizona, mortality 3 years after fire was highest for trees with the smallest diameter (<20 cm) as would be expected because of their thin bark. Mortality decreased as diameter increased between 20 and 50 cm as would be expected due to increasing bark thickness. However, mortality increased as diameter increased between 50 cm and the largest trees at 80 cm. A very similar relationship was found in the Oregon data which included larger diameter trees (Fig. 1). While Harrington (1993) reported decreasing mortality with increasing diameter

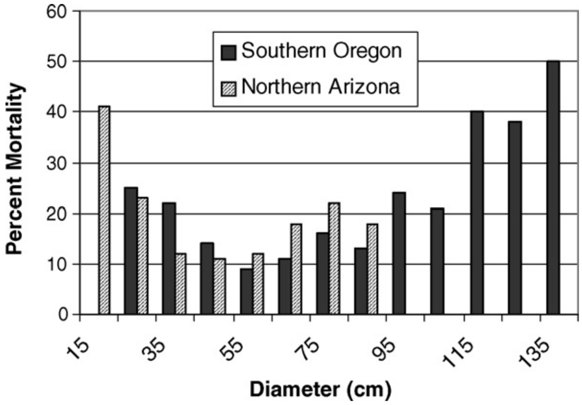

Fig. 1. The U-shaped mortality trend in Southern Oregon (Agee, 2003) and Northern Arizona (McHugh and Kolb, 2003), showing highest post-fire mortality in the smallest and largest size classes of ponderosa pine. Missing columns indicate no data for that size class. A three-class running mean was used for the Arizona data to express it in the same classes as the Oregon data.

for ponderosa pine, the largest size class of trees he studied was 30 cm, which is consistent with Fig. 1. This ''U-shaped'' distribution between post-fire mortality and diameter has also been reported in another study of ponderosa pine (Finney, 1999), and for Scots pine (*Pinus sylvestris*) in Sweden (Linder et al., 1998). Relationships between the probability of post-fire mortality and total crown damage from fire for stands in northern Arizona suggest that fire can increase mortality of large-diameter, old trees more than smaller, younger trees even when crown damage from fire is standardized over tree size classes (Fig. 2).

What reasons may account for high levels of mortality in old ponderosa pine after fire? First, old, large trees may have previous fire and lightning scars, and damage from insects and fungi, that enable fire to extend deeper into the cambium and higher up the bole causing higher levels of crown damage (Weaver, 1943; Linder et al., 1998). Second, ponderosa pine sheds bark pieces annually, in contrast to the persistent bark of Douglas-fir (*Pseudotsuga menziesii*) or true firs (*Abies* spp.), and over decades the shed bark mixed with leaf litter can build up to 20 cm in thickness or more (Fig. 3). A single prescribed fire can consume much of this material, and these old trees can therefore experience greater root or cambial temperatures than younger trees (Sackett and Haase, 1998; Finney, 1999). Third, old trees may have low amounts of carbohydrate available to replace or repair damaged tissues because of low net photosynthetic rate (Yoder et al., 1994; Bond, 2000; Kolb and Stone, 2000), low leaf area relative to carbon sink demands (Ryan et al., 1997), and large carbon allocation to roots and mycorrhizae (Ryan et al., 1997). Fourth, large trees have thicker phloem than small trees (Kolb et al., 1998, 2006) and thus may be a better food source for phloem-feeding insects, such as the western pine beetle that can cause tree mortality after fire (Miller and Keen, 1960; McHugh et al., 2003; Breece, 2006).

Other factors may predispose old ponderosa pine to accelerated mortality after fire. Old trees with substantial fire scars can burn through to the cambium and die more easily than younger trees with fewer scars (Perrakis and Agee, 2006). Depending on the timing of drought (before or after the fire), stress may be exacerbated by a low-intensity fire that would have less effect during non-drought periods (Agee, 2003). Interception of precipitation prior to burning by the thick forest floor beneath old-growth ponderosa pine (Fig. 3) may cause additional water stress that exacerbates effects of fire. Older

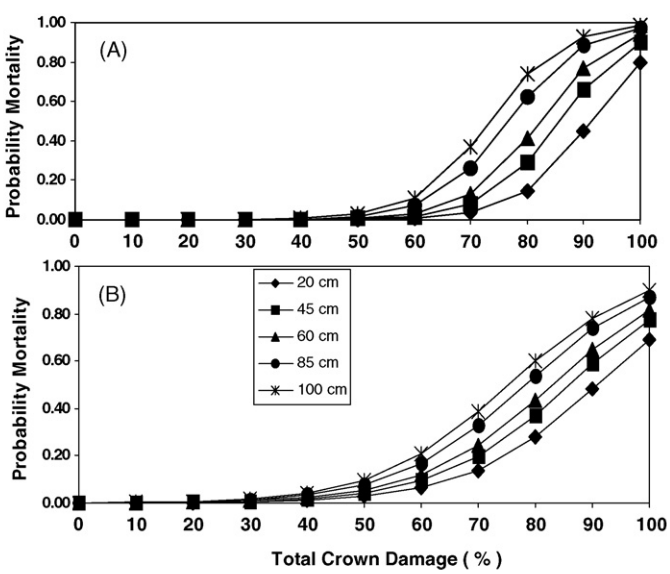

Fig. 2. Distribution of predicted probability of ponderosa pine mortality for logistic regression models using total crown damage (percent of crown scorched + consumed) and diameter at breast height for two wildfires (A, side wildfire; B, Bridger Knoll Wildfire) that burned in late spring, 1996, in northern Arizona shows that large-diameter trees had a higher probability of mortality than small-diameter trees. Derived from McHugh and Kolb (2003).

Fig. 3. Substantial buildup of organic material, including leaf litter and bark flakes, at the base of an old ponderosa pine can create substantial temperature increases around the base of the tree when burned by a prescribed fire. Photo by J.K. Agee.

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stands may be severely infested with dwarf mistletoe (*Arceuthobium* spp.), which can cause localized torching and may be associated with higher mortality after fire (Kaufmann and Covington, 2001; Parker et al., 2006).

3. Management amelioration of detrimental fire effects

The previous section showed that prescribed- and wild-fire often increase mortality of old ponderosa pine. Here, we address management treatments that have been used to reduce such mortality. The results have not been universally successful, and monitoring of mortality from such treatments has usually been short-term, despite evidence that post-fire mortality of old trees can continue over a 10–20-year period after burning (Sackett and Haase, 1998; Agee, 2003).

3.1. Raking

Raking of debris around the base of old trees before burning has been the most-studied management technique to ameliorate the effect of burning. All the studies we review have evaluated a first prescribed fire after many decades of fire exclusion, as subsequent prescribed fires may not require manual fuel removal.

Several studies have suggested that raking is a successful technique. In the southwestern U.S., the mortality incurred at Chimney Springs, Arizona after prescribed fires without raking (Sackett and Haase, 1998) prompted a recommendation that organic material be raked to a distance of 0.5–1 m away from tree bases to avoid potential girdling effects (Sackett et al., 1996). Kolb et al. (2001) reported little mortality of old trees at the Gus Pearson Natural Area in northern Arizona up to 6 years after prescribed fire when the lower layers (‘‘duff’’) of the forest floor were removed entirely, not just raked away from tree boles, and dried grass (to simulate presettlement understory fuel loading) was added to litter around the bases of presettlement trees prior to the first prescribed burn. Cambial temperatures measured with thermocouples did not reach lethal levels on most trees (Covington et al., 1997). Only 3 of 49 trees died, two from windthrow and one from bark beetles.

Other studies indicated that within burned areas, trees that were raked had similar mortality to those not raked. Kaufmann and Covington (2001) reported low mortality after prescribed burning at Grand Canyon, Arizona, but cautioned that their study extended only 5 years after burning. Perrakis (2004) found no difference in mortality of old trees for either spring or fall burning between trees with fuels raked around their base and control trees in Oregon.

Yet other studies have found that mortality of old trees was high on certain soils even with a raking treatment. Two years after a prescribed fire, 35% of all trees growing on shallow, lava-derived soils at Mount Trumbull in northern Arizona died, and 67% of the trees above 50 cm diameter died (Fulé et al., 2002). They observed that on other soils burned in the same fire, unusual levels of mortality did not occur. In Oregon on soils developed from avalanche deposits of gravel and pumice, raking of the surface organic horizons allowed the lower horizons to dry, so that a higher proportion of the forest floor was consumed in spring burns (Swezy and Agee, 1991). Fine-root biomass was lower in the rake-burn treatment than a burn-only treatment. These studies were conducted on soils derived from volcanic deposits where many of the roots are concentrated in surface mineral and organic horizons, and this may negate the effect of an ameliorating treatment, such as raking. The results of these studies suggest that the effects of raking treatment may be site specific.

Because raking can directly affect roots by removing live roots in the surface organic horizons, it may be useful to delay prescribed burning after raking. Raking 1 year, and perhaps burning the next year or several years later, may ameliorate the immediate loss of fine roots due to the raking treatment before further fine-root loss is incurred by burning.

3.2. Understory removal and pruning

Understory trees have the potential to torch and increase crown scorch to old trees during prescribed burning. Swezy and Agee (1991) suggested that felling, girdling, or removing small trees in the vicinity of old trees before prescribed burning might result in less heat damage to the older trees. In Oregon, understory shrubs are mown before burning to compact fuels and reduce fireline intensity (Fitzgerald, 2005). Similarly, pruning of low-hanging mistletoe branches can reduce the probability of torching of old trees (Youngblood et al., 2004).

3.3. Slash compression

We know of only one study that has evaluated the effect of compressing slash prior to prescribed burning on post-fire mortality of old ponderosa pine (Jerman et al., 2004). The study was performed in northern Arizona and the slash was compressed with a bulldozer. Slash and forest floor were removed for a distance of 0.5–1 m around the base of the trees, and the remaining slash (about 60 Mg ha^{-1}) from a thinning operation was either compressed or left uncompressed before a prescribed fire was applied. Crown scorch volume was 14% in the uncompressed slash burn compared to less than 1% in the compressed slash burn. After 2 years, mortality of old trees in the uncompressed slash area was 14% compared to 0% in the compressed slash area. This study (Jerman et al., 2004) and others (e.g., Hummel and Agee, 2003) suggest that arrangement of fuels, as much as total mass, may affect fireline intensity and mortality of old ponderosa pine after prescribed burning.

Understory trees have the potential to torch and increase crown scorch to old trees during prescribed burning (Scott and Reinhardt, 2001). Swezy and Agee (1991) suggested that felling, girdling, or removing small trees in the vicinity of old trees before prescribed burning might result in less heat damage to the older trees, and this recommendation has been incorporated into broad perspectives for restoring southwestern ponderosa pine forests (Allen et al., 2002). Fulé et al. (2002) developed operational guidelines for two levels of understory thinning around old pines in the Southwest. The intensive treatment included removing nearly all young trees in the

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vicinity of old trees, while the less intensive treatment cleared most young trees within a radius of 12–18 m of each old trees, with a longer radius in the downslope/downwind direction.

4. Stimulation of old-growth ponderosa pine vigor by management

It is well known that resource uptake and growth of young ponderosa pine can be increased by management treatments, such as thinning that reduce inter-tree competition (Schubert, 1971; Cochran and Barrett, 1993; Kolb et al., 1998; Sala et al., 2005; McDowell et al., 2006). Accelerating the growth of young trees by thinning and prescribed burning treatments has been recommended to promote more rapid development of old-growth conditions in ponderosa pine forests (e.g., Sesnie and Bailey, 2003; Skov et al., 2005).

Growth of old trees appears to be more limited by competition than for younger trees. For example, basal area increment (BAI) of old ponderosa pine declined more than BAI of young pine during a 70-year period in which tree density and stand basal area increased at the G.A. Pearson Natural Area (GPNA) in northern Arizona (Biondi, 1996). In 1920–1930 old pine was growing faster than young pine, but by 1980–1990 old pine was growing slower than young pine (Biondi, 1996). Consequently, the application of management treatments to current old-growth stands to increase the vigor of old trees has been proposed (Harrington and Sackett, 1992; Kaufmann et al., 1992; Covington et al., 1997), but little information exists on the response of old trees to such treatments.

4.1. Ecophysiology of old tree response to management treatments

A number of physiological changes occur as trees become older and larger that likely influence their response to management treatments. As the path length of water transport from the roots to the foliage increases with tree size, both frictional and gravitational constraints on water movement increase (Ryan et al., 2006). These constraints result in reduced stomatal conductance to avoid cavitation, which subsequently limits photosynthesis due to limited CO_2 diffusion from the atmosphere to foliage mesophyll. Decreased stomatal conductance and photosynthesis with increased tree size has been consistently observed in ponderosa pine (Yoder et al., 1994; Hubbard et al., 1999; Kolb and Stone, 2000; Skov et al., 2004; Sala, 2006). Moreover, cell turgor can decrease with increased tree size because tissue water potential becomes more negative (Koch et al., 2004; Woodruff et al., 2004). These hydraulic constraints on photosynthesis and cell growth have been proposed as mechanisms of the commonly observed decrease in growth efficiency, defined as stemwood growth per unit leaf area, at the individual tree- and stand-levels, with increasing tree age and size (Ryan et al., 1997, 2006; Martinez-Vilalta et al., 2007).

There are a number of changes in tree morphology and physiology that may compensate for the hydraulic constraints that occur in large, old trees (Mencuccini and Magnani, 2000; McDowell et al., 2002a; Mencuccini, 2003; Ryan et al., 2006). Examples include changes in carbon allocation that increase the ratio of root absorbing area to leaf area (Ewers et al., 2000; Hacke et al., 2000; Magnani et al., 2000), and increase the ratio of sapwood area to leaf area (Mencuccini and Bonosi, 2001; Fischer et al., 2002; McDowell et al., 2002b, 2006; Barnard and Ryan, 2003; Sala, 2006). Other potentially compensating changes include an increase in sapwood capacitance (Waring and Running, 1978; Goldstein et al., 1998; Phillips et al., 2003), sapwood conductivity (Pothier et al., 1989), and increased water potential gradient from soil to leaf (Hacke et al., 2000; McDowell et al., 2002a; Barnard and Ryan, 2003).

Decreased hydraulic conductance with increased tree size results in a more limited range of stomatal conductance for tall trees than short trees (McDowell et al., 2005). This can be demonstrated using a hydraulic corollary to Darcy's Law applied to trees, as originally developed by Whitehead et al. (1984):

$$g_s = \frac{k_l(\Psi_s - \Psi_l)}{\mathrm{VPD}}, \quad (1)$$

in which k_l is whole plant hydraulic conductance, Ψ_s the soil water potential (MPa), Ψ_l the daytime leaf water potential, and VPD is vapor pressure deficit (kPa). From the framework in Eq. (1) we made generalized predictions of how different size trees may respond to changes Ψ_s associated with thinning. We applied Eq. (1) in a similar fashion to McDowell et al. (2005). We assumed that Ψ_l is constant (isohydric) regardless of site water availability (Maherali and DeLucia, 2001; McDowell et al., 2006) and that hydraulic conductance of old, tall trees is half that of young, short trees. Young, short trees with high hydraulic conductance are predicted to have a broader range of stomatal conductance and a steep response of stomatal conductance to Ψ_s, whereas old, tall, trees are predicted to be less responsive (Fig. 4).

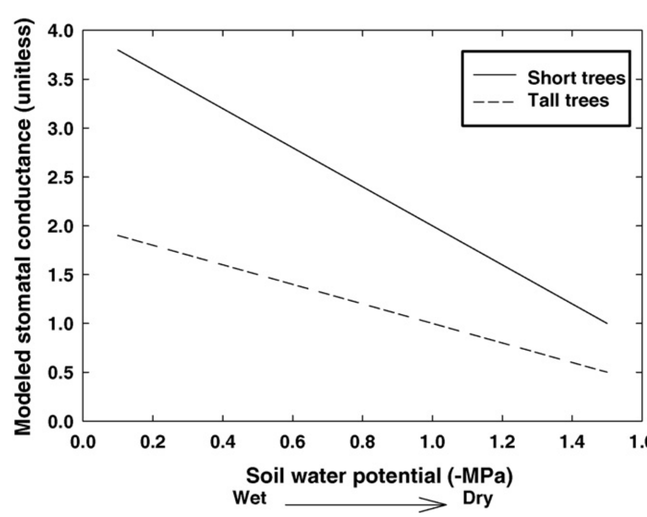

Fig. 4. Predictions of stomatal conductance verses soil water potential using the Whitehead et al. (1984) modeling approach shows that conductance of old, tall trees is less sensitive to drying soil than young, short trees. Hydraulic conductance of tall trees was set to 50% of that of short trees. Model adapted from McDowell et al. (2005).

The model results from Eq. (1) suggest that management actions in ponderosa pine forests that increase availability of soil water, such as thinning (Feeney et al., 1998; Kolb et al., 1998; Sala et al., 2005; McDowell et al., 2006), stimulate stomatal conductance of young, short trees more than old, tall trees. Stomatal response of old, tall trees to increased soil water content is constrained by lower hydraulic conductance from soil to leaf as a consequence of a longer path length compared with young, short trees. Because stomatal conductance is strongly related to photosythesis in ponderosa pine (Feeney et al., 1998; Skov et al., 2004), we should expect larger and faster stimulation of photosynthesis and growth in young, short trees than old, tall trees. This theoretical expectation is consistent with results of an experiment in northern Arizona where thinning stimulated stomatal conductance and net photosynthetic rate (Skov et al., 2004) and bole radial increment (Skov et al., 2005) of small, mature ponderosa pine more than for old pine in the same stand.

4.2. Empirical studies of response of old ponderosa pine to management

The theoretical prediction (Fig. 4) that old, tall trees should be less responsive to management treatments that increase availability of soil water than younger, shorter trees raises the question as to whether resource uptake and growth of old ponderosa pine are responsive to management treatments that reduce competition. In this section, we summarize results from recent experiments in Arizona, Oregon, and Montana that have evaluated the response of old ponderosa pine to thinning and prescribed burning treatments.

4.2.1. Arizona

Growth and physiological responses of old ponderosa pine to management treatments have been studied for 10 years after initial treatment at the Gus Pearson Natural Area (GPNA) in northern Arizona. The GPNA is managed as a Research Natural Area by the U.S. Forest Service because it contains a stand of large, old ponderosa pine (current average age 438 years, diameter at breast height about 75 cm) and it had received no silvicultural management or harvests prior to the recent experiment. The treatments, described in detail in Covington et al. (1997), consisted of thinned, thinned and prescribed burned, and control (untreated) portions of the same 4.7 ha stand.

The goal of the thinned treatment was to recreate as closely as possible the tree size class distribution and spatial pattern that occurred on the site before the start of Euro-American settlement of the region in 1876. The thinning removed most post-settlement trees, defined as trees that established after Euro-American settlement of the region in 1876. A small number of post-settlement trees were left on site to replace dead presettlement trees that were identified by old logs and stumps. In addition, no trees with diameter at breast height greater than 40 cm were cut. The thinning occurred in November 1993 and reduced tree basal area by about 62% (34.5–13.0 m^2 ha^{-1}) and tree density by 95% (3100–151 trees ha^{-1}).

The goal of the thinned + burned treatment was to recreate both the presettlement structure and fire disturbance regime. The treatment consisted of application of low-intensity prescribed burns to a portion of the thinned stand. The first burn occurred in October 1994, about 1 year after thinning. Fuels were manipulated in the first burn in order to keep fire intensity low and minimize damage to old trees. All thinning slash was removed from the site, and the forest floor (i.e., duff and bark flakes) was raked from the entire area to be burned in order to simulate forest floor conditions hypothesized to occur prior to before disruption of the frequent fire regime. Next, dried foliage of native grasses and forbs (672 kg ha^{-1}) was put on the raked forest floor in addition to the litter layer prior to burning to simulate forest floor fuels of presettlement forests which often contained a dense, herbaceous understory. These herbaceous fine fuels were ignited and produced a low-intensity fire with average flame length of 15 cm and a maximum length of 60 cm. The initial burn in 1994 was followed by three additional prescribed burns at a 4-year interval (1998, 2002, 2006). All of the subsequent burns were conducted in the fall and were low-intensity. Fire was applied directly to fine fuels produced by herbaceous growth (Moore et al., 2006). Most of the combustion in these subsequent burns occurred in fine herbaceous fuels, leaf litter, and coarse woody debris on the forest floor.

In the first growing season after treatment, thinning increased soil water content which led to greater water uptake by old trees as indicated by higher predawn water potential (Stone et al., 1999). Thinning also increased leaf nitrogen content (mass $area^{-1}$) of the old trees, which combined with greater water availability, increased stomatal conductance and net photosynthetic rate. Tree canopy growth also responded positively to thinning after one growing season; thinning increased length of current-year leaves by 12% and mass of terminal buds by 53% (Stone et al., 1999).

Old trees in the thinned alone and thinned + burned treatments at GPNA had similar water relations and rates of leaf gas exchange, but burning affected leaf nitrogen concentration. One and 2 years after the first prescribed burn, leaf nitrogen concentration (mass $mass^{-1}$) was higher for trees in the thinned + burned treatment compared with the thinned alone treatment (Feeney et al., 1998). However, the opposite result occurred after the second prescribed burn; leaf nitrogen concentration was greater for trees in the thinned alone treatment than the thinned + burned treatment (Wallin et al., 2004). The first prescribed burn was the first fire at the GPNA since 1876, and it likely caused a pulse of plant-available nitrogen from mineralization associated with fire (Covington and Sackett, 1986, 1992; Kaye et al., 1999). Trees at the GPNA may have been especially responsive to the pulse of mineralized nitrogen considering the slow rate of nitrogen mineralization at the GPNA in the absence of restoration treatments (Kaye and Hart, 1998). The negative impact of the second prescribed burn on tree leaf nitrogen concentration compared with the thinned only treatment may reflect losses of nitrogen from the site due to volatilization that exceeded nitrogen mineralization (e.g., Wright and Hart, 1997).

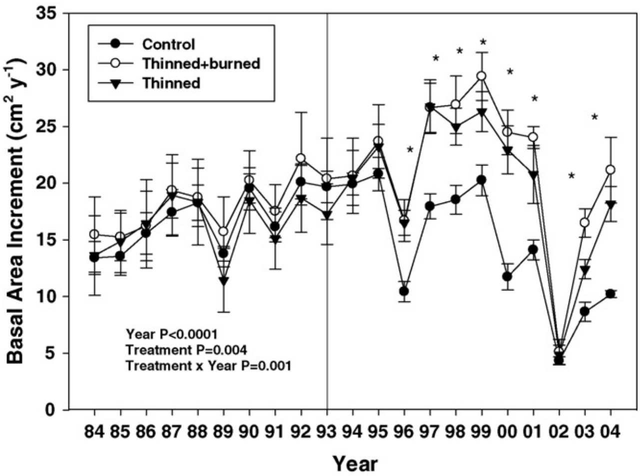

Fig. 5. Basal area increment of old ponderosa pine at the Gus Pearson Natural Area in northern Arizona was simulated by thinning treatments, and increment was similar for trees in thinned alone and thinned plus prescribed burned treatments. The vertical line shows the year of treatment. The *P*-values are from repeated measures MANOVA for the post-treatment years. Asterisk (*) indicates significant ($P < 0.05$) differences among treatments in ANOVA by year. Another MANOVA showed no difference in increment among trees in different treatments for the 10 pretreatment years (1984–1993). Error bars are one standard error of the mean.

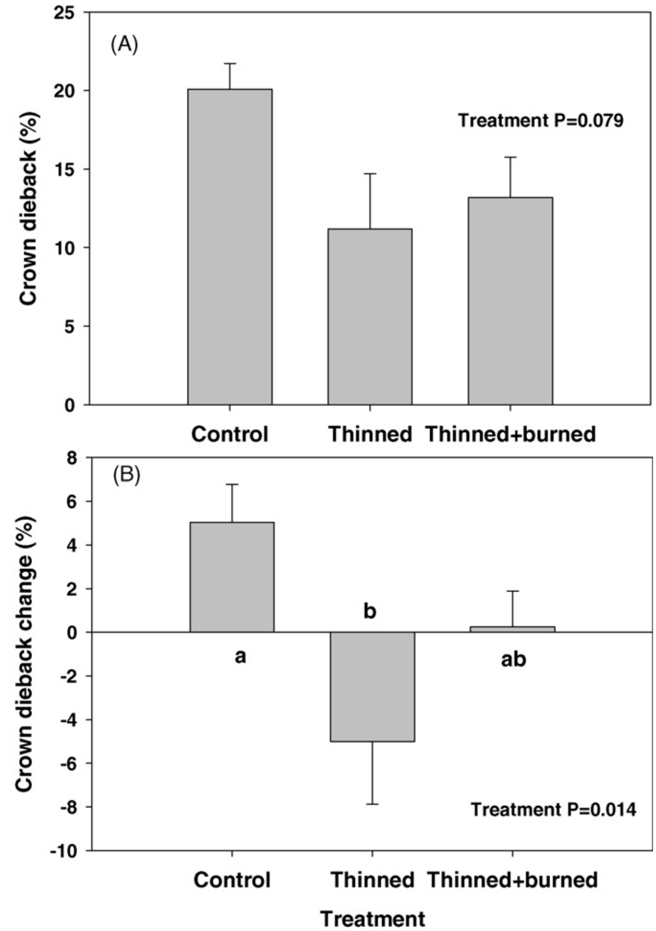

Fig. 6. Mean crown dieback (A) of old ponderosa pine at the Gus Pearson Natural Area in northern Arizona in year 2004, 10 years after treatment, was slightly greater in control compared with thinned alone and thinned plus prescribed burned treatments. Dieback increased for trees in the control between 1994 and 2004 (B), whereas dieback decreased (thinned) or did not change (thinned + burned) in the thinned treatments. The *P*-values are from ANOVA. Different letters indicate statistically significant differences among treatments (LSD, $P < 0.05$). The vertical bar shows one standard error of the mean.

Increased resource uptake by old trees in the thinned plots at the GPNA ultimately resulted in greater stem radial growth. Fig. 5 shows an update of an earlier analysis of the growth response of old trees at the GPNA (Feeney et al., 1998). Basal area increment of old trees did not differ significantly among the treatment plots before treatment (1984–1993), in the year of treatment (1994), nor in the first post-treatment year (1995) (Fig. 5). Starting with the second post-treatment year in 1996, trees in the thinned only and thinned + burned treatments typically had significantly greater increment than trees in the control treatment (Fig. 5). The only exception was the severe drought year of 2002 when increment was similar in all treatments. Increment was similar in the thinned only and thinned + burned treatments in all years, except 2003 when increment was higher in the thinned + burned treatment. A significant treatment × year interaction in increment (Fig. 5) resulted primarily from the larger negative effect of the 2002 drought on increment in the thinned only and thinned + burned treatments than the control.

Positive effects of the restoration treatments on resource uptake and growth of old trees at the GPNA are consistent with temporal changes in crown condition. Fig. 6 shows an update of an earlier analysis of crown condition at the GPNA (Kolb et al., 2001). Dieback in the upper crown was non-significantly less for trees in both thinned treatments than for trees in the control treatment in 2004, 10 years after thinning (Fig. 6). Comparison of the change in crown dieback over the 10 post-treatment years (1994–2004) shows an increase in dieback on trees in the control plot and a decrease (thinned) or no change (thinned + burned) in the treated plots (Fig. 6). Mortality of old trees at the GPNA over the 10 post-treatment years was 5.1% (3 of 59 trees) in the control, 8.1% (3 of 37 trees) in the thinned treatment, and 5.6% (3 of 53 trees) in the thinned + burned treatment. Broad inferences about treatment effects on mortality at the GPNA are limited by the small sample size, but our observations suggest greater incidence of tree mortality due to wind throw and stem breakage in the thinned treatments than the control. Between 1994 and 2002, three old trees in the thinned treatments broke or toppled during severe winter storms, whereas no mortality due to the storms occurred in the control (Kolb et al., 2001). In contrast, tree mortality in the control was preceded by a gradual decline of crown condition.

There is no evidence that careful, well-implemented thinning causes long-term stress to old ponderosa pine in Arizona or elsewhere. Thinning shock, or a negative effect of thinning on tree condition (Harrington and Reukema, 1983; Aussenac, 2000), has been documented in northern Arizona only for small, suppressed ponderosa pines as a reduction in sapwood hydraulic conductance per unit leaf area and canopy conductance after thinning during extreme drought (Simonin et al., 2006). This type of thinning shock occurred only in the 1st year after thinning, and thinning stimulated conductance in the 2nd year after thinning.

4.2.2. Oregon

Two studies in Oregon have been published recently on the response of old ponderosa pine to thinning treatments. In the first study (Latham and Tappeiner, 2002), old ponderosa pines, Douglas-fir, and sugar pines (*Pinus lambertiana*) in western Oregon increased diameter growth in response to thinning of understory trees or shelterwood thinnings compared with trees in untreated, control stands. The onset of increased growth after thinning for the old trees was often delayed and varied from 5 to 25 years after thinning. Thinning increased growth by 10% or more for 68% of trees, and by 50% or more for 30% of trees. Thinning decreased growth of only 1.5% of trees, which is consistent with studies of ponderosa pine in northern Arizona (Skov et al., 2005) that found little evidence of thinning shock in old ponderosa pine.

The second recent study in Oregon (McDowell et al., 2003) provides additional understanding of physiological mechanisms of the response of old ponderosa pine to thinning. This study compared BAI and water, carbon, and nitrogen relations of old trees between untreated stands and stands treated with shelterwood cuts that reduced basal area 61–82%. A retrospective reconstruction of leaf gas exchange in both types of stands modeled from carbon isotope ratios in tree rings and level–level gas exchange (McDowell et al., 2003) suggested that net photosynthetic rate (Fig. 7A) and stomatal conductance (Fig. 7B) increased in the 1st year after thinning and were elevated above rates of trees in unthinned stands for at least 15 years after thinning. Basal area increment (Fig. 7C) increased by two- to three-fold after thinning, and the increase was sustained for up to 15 years after thinning. The increase in BAI after thinning lagged behind the increase in net photosynthetic rate and stomatal conductance by 2 years (Fig. 7A–C). Thinning increased tree predawn water potential 15 years after treatment, indicating an increase in soil water content in the rooting zone, but had no effect on leaf nitrogen concentration (McDowell et al., 2003). These results show that heavy thinning can increase radial growth, water uptake, and leaf gas exchange of old ponderosa pine for at least 15 years after treatment if stand leaf area is not fully reestablished.

4.2.3. Montana

Visual symptoms of decline of old ponderosa pine in the Blackfoot River Valley in Montana in the early 1980s prompted the experimental application of thinning and prescribed burning to improve the vigor and survival of old trees (Fiedler, 2000). The thinning treatment in 1984 removed most understory ‘‘ladder’’ fuels, including most Douglas-fir. Half of the thinned plots were prescribed burned in the fall after thinning. Thinning of understory trees, with and without prescribed burning, reduced mortality of old trees compared with the unthinned controls (Fiedler, 2000). Mortality was 5.5-fold greater in control than in thinned or thinned and burned plots. Thinning also increased diameter growth of the old trees by about 2.6-fold.

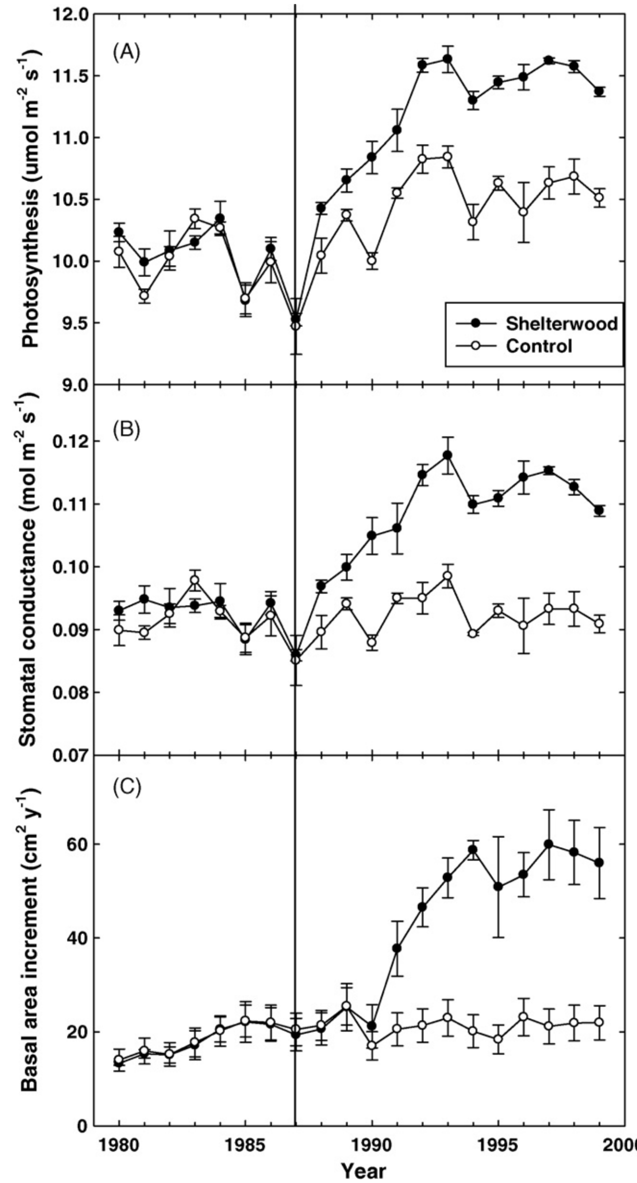

Fig. 7. Net photosynthetic rate (A), stomatal conductance (B), and basal area increment (C) from a study of old ponderosa pine in central Oregon (McDowell et al., 2003) shows that thinning stimulated leaf gas exchange and radial growth 1 year after thinning, and increases growth 4 years after thinning. The shelterwood stand was thinned in 1987, and the neighboring control stand was never thinned. Net photosynthetic rate and stomatal conductance were modeled using tree-ring carbon isotope ratios and leaf level gas exchange measurements of the response of photosynthesis to internal CO_2 concentration as described in McDowell et al. (2003). Bars are one standard error of the mean.

5. Management impacts on resistance of old ponderosa pine to insect attack

The ultimate measure of tree resistance to bark beetles is survival after bark beetle attacks. Large numbers of lethal bark beetle attacks occur episodically in ponderosa pine forests; however, such attacks rarely occur during experimental studies (e.g., Larsson et al., 1983). Consequently, mechanisms of resistance are typically measured to provide insight on resistance and to measure the likelihood of tree survival during attack. Resin, either released from storage in resin ducts located in phloem and xylem at the time of attack (preformed or constitutive resin), or synthesized in response to attack (induced resin), is generally hypothesized to be the most important mechanism of pine defense against initial attacks by bark beetles at low beetle densities (Raffa and Berryman, 1983; Lieutier, 2002). This hypothesis has been supported for young ponderosa pine by a negative relationship between resin flow and attack success of western pine beetle (Smith, 1975). After a successful initial attack, tree resistance to bark beetles depends in part on the attack density and the extent that current photosynthate can be quickly shifted to walling off blue-stain fungi introduced by the beetles (Christiansen et al., 1987; Franceschi et al., 2005).

A mixture of direct and indirect evidence suggests that management actions that cause large increases in stem radial growth rate of ponderosa pine also increase tree resistance to lethal bark beetle attacks. Most of this evidence is for trees that are younger than 100 years. Early research on the relationship between radial growth and bark beetle resistance emphasized the importance of tree vigor, defined as wood production per leaf area, with leaf area predicted from sapwood area (Larsson et al., 1983; Mitchell et al., 1983; Waring and Pitman, 1985). Attacks of mountain pine beetle decreased when vigor of ponderosa (Larsson et al., 1983) and lodgepole (*Pinus contorta*) pines (Mitchell et al., 1983) was greater than 100 g of wood produced per meter square of leaf area. McDowell et al. (2007) highlighted uncertainty in accurately predicting leaf area from sapwood area, and thus vigor as defined above, because of changes in the ratio of leaf area to sapwood area with tree competitive status (Simonin et al., 2006) and thinning (McDowell et al., 2006). Instead, McDowell et al. (2007) emphasized the use of more direct measurements of carbon allocation to stem radial growth, such as BAI, to predict tree carbon allocation to resin defenses in the stem.

The indirect evidence concerning positive effects of management, especially thinning, on ponderosa pine resistance to bark beetles is an association between stand structural conditions and tree mortality or resin flow after wounding. Stand conditions associated with high mortality of young ponderosa pine stands by mountain pine beetle (*Dendroctonus ponderosae*) in the inland western U.S. include high stand basal area and tree density (Sartwell and Stevens, 1975; Dahlsten and Rowney, 1983; Cochran and Barrett, 1993; Olsen et al., 1996; Fettig et al., 2007) which are known to reduce diameter growth (e.g., Larsson et al., 1983; McDowell et al., 2006). Probability of lethal attacks by mountain pine beetle (Negron and Popp, 2004) and roundheaded pine beetle (*Dendroctonus adjunctus*) increases with stand density and decreases with radial growth rate for ponderosa pine (Negron, 1997; Negron et al., 2000). Consistent with these reports, flow of preformed resin from phloem wounds, a key defense of many conifers against bark beetles (Smith, 1975; Raffa and Berryman, 1982, 1983), was positively related to BAI in a region-wide synthesis of five studies of ponderosa pine in northern Arizona (McDowell et al., 2007).

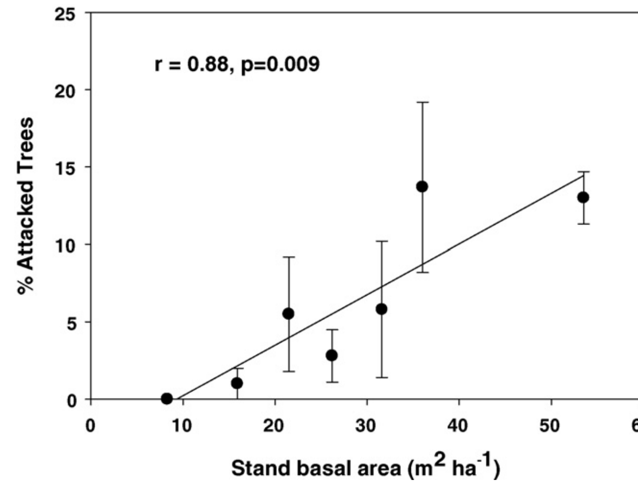

Fig. 8. The percentage of young ponderosa pine attacked by the mountain pine beetle decreased linearly with a decrease in stand basal area in a thinning experiment in central Oregon (derived from Larsson et al., 1983). The basal area levels were established by thinning 15 years prior to the measurement of bark beetle attacks and were maintained by periodic thinnings. The vertical bars show one standard error of the mean. Three stands were sampled for all thinned stands (basal area less than 40 m^2 ha^{-1}), and nine stands were sampled for the unthinned control (basal area = 54 m^2 ha^{-1}).

The direct evidence for a role of management in enhancing resistance of ponderosa pine to bark beetles consists of changes in bark beetle attacks, tree survival, or resistance mechanisms following experimental manipulation of tree density or stand basal area. Increased radial growth of young ponderosa pine in heavily thinned stands has been linked to fewer attacks and consequent tree mortality by mountain pine beetle in Oregon (Fig. 8) and South Dakota (Fettig et al., 2007), and greater resin flow from phloem wounds in Arizona (Kolb et al., 1998). However, heavy thinning (ca. 50% basal area) in Montana did not increase resin flow in June in spite of increases in radial growth (Peters, 2003). Similarly, relatively light (reduction of basal area by <30%) and infrequent thinning of young ponderosa pine stands can stimulate radial growth slightly, but is not effective at stimulating resin flow (Zausen et al., 2005).

With some exceptions, these results for young ponderosa pine are consistent with the hypothesis that trees in low density stands have greater resources, especially carbohydrates, to allocate to both radial growth and tissues bearing large numbers of resin ducts, such as phloem and xylem (Waring and Schlesinger, 1985; Christiansen et al., 1987). Other studies on young ponderosa pine suggest no strong trade-off between above-ground growth and differentiation processes, such as terpene concentration and resin production (Johnson et al., 1997; Gaylord et al., 2007). The lack of evidence for a strong trade-off between carbon allocation to growth versus resin for young ponderosa pine is not consistent with several reports for loblolly pine (*Pinus taeda*) that water stress shifts carbon allocation from growth to resin defenses and results in a positive relationship between stress and resin flow (Lorio, 1986; Blanche et al., 1992; Dunn and Lorio, 1993). The difference in results between loblolly pine and ponderosa pine may be explained by the different location of stress for each species on the bell-shaped relationship between carbon allocation to resin defense and water stress that has been described as the ''growth-differentiation hypothesis'' (Lorio, 1986, 1993; Lorio et al., 1990; Herms and Mattson, 1992). Studies of loblolly pine have compared resin flow between low and moderate water stress on this bell-shaped curve – thus stress and resin were positively related, whereas studies of ponderosa pine have compared resin flow between moderate and high water stress – thus stress and resin were negatively related.

Investigations at the GPNA in northern Arizona and Crater Lake National Park in Oregon have highlighted the influence of low-intensity prescribed burning on resin defenses of old ponderosa pine. At the GPNA, resin flow in response to wounding of the phloem for measurements taken in June two, three, and 7 years after treatment was higher for trees in the thinned + burned treatment than the thinned alone and control treatments (Feeney et al., 1998; Wallin et al., 2004). Higher resin flow for trees in the thinned + burned treatment may have resulted from stimulation of resin production in response to wounding of cambium or phloem by the understory burns, as has been reported for other pines (e.g., Santoro et al., 2001; Lombardero et al., 2006).

A recent study at Crater Lake National Park in Oregon (Perrakis and Agee, 2006) reported similar results on effects of prescribed burning on resin flow from old ponderosa pine. Both fall and spring prescribed burns increased resin flow in the first and second summers after treatment compared with unburned controls. The same burning treatments also increased tree mortality attributed to western pine beetle attacks, as has been found in other recent studies of prescribed fire in ponderosa pine forests in Arizona and New Mexico (Wallin et al., 2004; Breece, 2006). These results indicate that some species of bark beetles are attracted to burned stands and are successful at colonizing trees even when burning increases resin defenses, and suggest that tree resistance to bark beetles in burned stands cannot be predicted solely by quantitative changes in resin defenses.

Studies at the GPNA in northern Arizona also have investigated effects of management treatments on leaf toughness, an important resistance mechanism against foliage-feeding insects, such as pine sawflies (McMillin and Wagner, 1993; Wagner and Zhang, 1993). Both thinning and thinning + burning treatments consistently increased leaf toughness of old trees compared to trees in the control (Feeney et al., 1998; Wallin et al., 2004). This result suggests reduced performance of foliage-feeding insect on trees in thinned treatments, but this has not been verified with insect performance experiments. Tougher foliage appears to be a long-term effect of thinning at the GPNA as it was consistent in all measurements between one and 7 years after thinning.

6. Management amelioration of drought impacts on old ponderosa pine

Increases in mortality of both ponderosa pine (http://www.fs.fed.us/r3/resources/health/beetle/index.shtml) and pinyon pine (*Pinus edulis*) (Breshears et al., 2005; Shaw et al., 2005) have been reported during drought over the last decade (1996–2006) in the Southwest U.S. We utilized 3-PG, a physiologically based tree growth model (Landsberg and Waring, 1997), to contrast the implications of a reduction of nearly 50% in annual precipitation recorded near Los Alamos, New Mexico between the period from 1996 to 1999 (mean, 490 mm year^{-1}) and 2000 to 2003 (mean, 260 mm year^{-1}) on tree growth. The model predicted a one-third reduction in tree growth and a proportional reduction in maximum leaf area index (LAI) from 2.1 to 1.4. Similar reductions in the normalized difference vegetation index have been reported in the region during severe drought (Breshears et al., 2005). Self-thinning would necessarily increase, because, according to the widely applied $-3/2$ power law, the maximum standing biomass at which mortality begins is a function of maximum LAI (Landsberg and Waring, 1997). This simulation result suggest that the increased frequency of severe droughts that are predicted to occur with future climate change (Houghton et al., 2001; Coquard et al., 2004) will increase mortality of ponderosa pine in old-growth stands. This mortality can be reduced by thinning that reduces the high LAI of many current stands of 2.0 or greater by at least 33%. Removing younger trees by thinning will increase water available to old trees during drought (e.g., Feeney et al., 1998; McDowell et al., 2003; Wallin et al., 2004) and likely reduce their mortality.

Results from the GPNA in northern Arizona provide insight on how thinning treatments and drought interact to affect the performance of old trees. The second growing season after thinning, 1995, was unusually wet with winter–spring precipitation 42% higher than average. A severe drought occurred in 1996 with winter–spring precipitation 60% lower than average. The effect of thinning on net photosynthetic rate and BAI varied between years (Feeney et al., 1998). Thinning had little effect on net photosynthetic rate and BAI (Fig. 5) in the wet year (1995). In contrast, thinning increased photosynthesis compared with the control during the driest weeks of the drought year (1996) (Feeney et al., 1998), and also increased annual BAI (Fig. 5). Similar interactions between drought and the early response (i.e., within 3 years of treatment) of photosynthesis to thinning treatments for old ponderosa pine have been reported in related studies in northern Arizona (Skov et al., 2004). These results suggest that increases in water availability to old trees for at least the first few years after thinning ameliorates the negative effect of severe drought on tree photosynthesis and radial growth.

Effects of thinning on sensitivity of radial growth to drought of old trees likely varies with drought severity and changes in tree architecture induced by thinning. Fig. 5 from the GPNA illustrates this influence. The 1996 drought, which occurred in the third growing season after thinning, had a greater negative effect on BAI of trees in the control than both thinned treatments, and BAI was greater during the drought in the thinned treatments than the control. In contrast, the more severe 2002 drought had a greater negative effect on BAI of trees in both thinned treatments than the control (Fig. 5). The greater sensitivity of growth to the 2002 drought for trees in the thinned treatments resulted in similar BAI among treatments.

Changes in tree architecture after thinning may explain the variable effects of thinning on sensitivity of radial growth to drought. A recent study on young, mature ponderosa pine in northern Arizona showed that periodic thinning increased the ratio of leaf area to sapwood area (McDowell et al., 2006). This architectural shift of trees in thinned stands results in increased canopy demand for water relative to supply via the sapwood, which predisposes trees to severe leaf-level hydraulic (and hence photosynthetic) limitation during drought relative to trees in unthinned stands. The increase in the ratio of leaf area to sapwood area with thinning was documented by McDowell et al. (2006) about four decades after the onset of decadal thinnings applied to 40-year-old, pole-size trees. The occurrence of this type of response to thinning for old trees is unclear as studies of long-term architectural responses of old trees to thinning have not been conducted. However, the same response to thinning for old trees at the GPNA over one decade after thinning would explain the increasing sensitivity of BAI to drought for trees in thinned plots (Fig. 5).

Overall, results from the GPNA and related studies in northern Arizona (Feeney et al., 1998; Skov et al., 2004, 2005; McDowell et al., 2006) suggest that thinning reduces impacts of severe water stress on photosynthesis and growth immediately after treatment, but may actually increase the relative impact of drought on growth (i.e., percent change between non-drought and drought years) decades following treatment because of slow adjustments in tree leaf area to sapwood area ratio. However, this is a relative response, i.e., trees in thinned stands may show greater drought-related decreases than trees with low growth rates, but may still may higher absolute growth. Trees in heavily thinned stands typically have greater absolute BAI than trees in unthinned stands in both drought and non-drought years (Feeney et al., 1998; McDowell et al., 2003, 2006; Fig. 5). Therefore, resilience of growth to drought appears to be greater for trees in thinned than unthinned stands.

7. Management implications and recommendations for perpetuating old ponderosa pine

Our review provides evidence that careful management of old-growth ponderosa pine forests whose current stand structure deviates from historic conditions due to the effects of grazing and fire exclusion often enhances resource uptake and growth of old trees in the short term (up to 10 years). One might conclude that management involving thinning and burning of all old-growth ponderosa pine forests is in order. However, such management should be carefully considered. First, there is evidence that not all ponderosa pine forests are outside the historic range of variability, either because fire regimes were not completely disrupted (e.g., Grand Canyon; Fulé et al., 2003), or because some mixed-conifer forests containing ponderosa pine historically had relatively high density or infrequent fires (e.g., Colorado Front Range; Brown et al., 1999; Schoennagel et al., 2004). In such cases, thinning for the purpose of restoring historic structure would not be justified. Second, many old-growth forests in the western U.S. are located in remote areas, where management often causes unavoidable disturbances, such as road construction, soil compaction, and exposure to mineral soil. Even in areas where old-growth forests are clearly outside their range of natural variability the pros and cons of management need to be carefully weighted. For instance, road construction and subsequent increased access could increase invasive species (Korb, 2001), decrease native species diversity, alter fire regimes, or change resource availability (Levine et al., 2003). Third, financial costs of management treatments in old-growth forests can be high because of the careful attention required to individual trees. Finally, while long-term monitoring data is lacking, increasing evidence suggests that disturbance associated with harvesting may increase recruitment and density in the long-term, which could be counter productive (Minnich et al., 1995; Kaufmann et al., 2000). For instance, in an ongoing study across Montana and central Idaho, tree density in never-logged ponderosa pine stands not subjected to fire for the last 60 years was on average over 40% lower than in paired stands ($n = 23$ pairs) that had been subjected to historical logging (Naficy and Sala, unpublished data). These results serve only to highlight the need to consider long-term effects of disturbance, and the need for repeated maintenance actions, such as prescribed fire, prior to management actions.

We provide the following recommendations for the use of thinning and burning in dry, old-growth ponderosa pine forests where fire exclusion has increased fuels over time and where potential negative effects of management are minimized:

1. Results for removing the forest floor beneath old trees by raking prior to prescribed fire to reduce fuels and smoldering combustion appear to be site specific. Raking appears to ameliorate fire damage to old trees on fine-textured, basalt-derived soils in northern Arizona, but results for other soils are variable. Raking one or 2 years before burning may ameliorate the immediate loss of fine roots due to the raking treatment before further fine-root loss is incurred by burning.
2. Old ponderosa pine trees are often more prone to dying after prescribed burns and wildfires than younger, mature trees. Their death often occurs more slowly after burns than for younger trees. Fuels should be reduced in the vicinity of old trees prior to prescribed burns by thinning the understory and removing the slash, or by compressing the slash to reduce fire intensity.
3. Resource uptake and growth of old trees can be increased by careful thinning. Thinning often reduces water stress of old trees starting one or 2 years after treatment. Radial growth responses are slower, and often start several years to two decades after thinning. Growth response to thinning is slower for old trees than young trees. Stimulation of growth of old trees by thinning can be negated by severe drought. However, stimulation of growth by thinning returns shortly after drought ceases. Overall, these results for old ponderosa pine are consistent with a small, but growing number of experiments showing that resource uptake and growth of old trees of various species are responsive to thinning (Bebber et al., 2004; Martinez-Vilalta et al., 2007). An unresolved issue is whether stimulation of radial growth in

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old, large trees increases their susceptibility to windthrow and breakage due to an increase in above-ground mass or due to increased exposure.
4. Reduction of stand leaf area by management treatments should reduce mortality of old trees during severe drought because of increased water availability to remaining trees.
5. Careful thinning does not often cause ‘‘thinning shock,’’ or a negative physiological or growth response to thinning, in old ponderosa pine.
6. Management treatments that cause large increases in carbon allocation to radial xylem growth also increase carbon allocation to constitutive resin defenses against bark beetle attacks, based on studies with young ponderosa pine.
7. Prescribed, low-intensity burning that causes little crown scorch can stimulate bole resin production in old trees. The mechanism of this stimulation is not known. Such burning also tends to attract bark beetles and can increase tree mortality from beetle attacks.

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RESEARCH ARTICLE
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Optimizing Forest Management Stabilizes Carbon Under Projected Climate and Wildfires

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Key Points:
- Forests provide a range of ecosystem services, including climate regulation, that are dependent on ecosystem structure and function.
- Fire-exclusion has altered the structure of frequent-fire forests, and climate change is exacerbating the risk of uncharacteristic wildfires.
- Optimizing management can reduce high-severity fire risk and increase climate change mitigation by stabilizing forest carbon.

Supporting Information:
- Supporting Information

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Abstract Forests provide a broad set of ecosystem services, including climate regulation. Other ecosystem services can be ecosystem dependent and are in part regulated by local-scale decision-making. In the southwestern United States, ongoing climate change is exacerbating a legacy of fire-exclusion that has altered forest structure and increased high-severity wildfire risk. Management can mitigate this risk by reducing forest density and restoring frequent surface fires, but at the cost of reduced carbon stocks. We sought to quantify the role of management in building adaptive capacity to projected climate and wildfires and the carbon consequences in a forested watershed. We simulated carbon dynamics under projected climate and wildfires and two management scenarios: prioritized and optimized. The prioritized scenario involved thinning and prescribed burning in areas selected by stakeholders to mitigate high-severity wildfire risk. The optimized scenario used the probability of high-severity wildfires to locate thinning treatments and increased prescribed fire area burned relative to the prioritized scenario. Both scenarios reduced wildfire severity and significantly increased net photosynthesis relative to no-management. However, the optimized scenario decreased management-related losses by 2.4 $Mg \bullet C \bullet ha^{-1}$ and wildfire emissions by 2.9 $Mg \bullet C \bullet ha^{-1}$ relative to the prioritized scenario. By decreasing the area thinned and increasing the area burned relative to the prioritized scenario, the optimized scenario halved the time to realize a net carbon benefit relative to no-management. Given the increasing climatic and disturbance pressures impacting southwestern forests, management will play a critical role in building adaptive capacity and ensuring the continued provision of ecosystem services.

Plain Language Summary Forests provide a range of services to society, including carbon storage, which helps regulate the climate. Wildfires impact a forest's contribution to climate regulation by releasing carbon to the atmosphere through combustion and by killing trees, which reduces the amount of carbon removed from the atmosphere. In forests that historically experienced frequent-fire, fire-exclusion has increased tree density and the amount of biomass available to burn. These changes have increased the risk of stand-replacing wildfires, and ongoing climate change is making forests more flammable. Management to reduce stand-replacing fire risk typically involves thinning small trees and prescribed burning, both of which reduce the amount of carbon stored in the forest. We sought to determine how management would influence wildfire behavior and carbon dynamics for two different scenarios under projected climate for a municipal watershed in the Sangre de Cristo Mountains of New Mexico. The prioritized scenario-placed thinning and burning treatments based on stakeholder and manager input. The optimized scenario-placed thinning treatments based on the chance of stand-replacing wildfires and applied prescribed burning to all frequent-fire forest types in the watershed. Both scenarios reduced the occurrence of stand-replacing fire. However, the optimized scenario stored more carbon because 54% less of the watershed was thinned. This reduced carbon losses from management and halved the time it took the watershed carbon storage to surpass that of the no-management scenario. Informing management based on risk helps build adaptive capacity to changing climate and maintains the climate regulation benefits of forests.

1. Introduction

Forests provide a wide range of ecosystem services, including biomass production, habitat, climate regulation, and the provision and purification of water for society (Brockerhoff et al., 2017; Mori et al., 2017). The quantity and quality of these services is dependent on ecosystem structure and function (Mace et al., 2012), both of which can be compromised by land-use history and climatic change (Millennium Ecosystem Assessment, 2005). Since the 1950s, anthropogenic influence on the Earth system has resulted in rates of change to the climate system and ecosystem disturbance regimes that are without precedent

(IPCC, 2013; Ribes et al., 2017), causing ecosystem reorganization and altering the provision of ecosystem services.

The influence of changing climate on forests varies spatially as a function of abiotic stressors, directly causing a range of ecosystem responses (Allen et al., 2010). Climatic perturbations can also intensify disturbance processes creating an indirect pathway for changing climate to alter forest systems (Seidl et al., 2017; Vilà-Cabrera et al., 2018). The combination of these direct and indirect pathways may result in increased vulnerability to disturbance and disturbance intensity, placing many forested ecosystems at risk of significant reductions in productivity (Seppälä, 2009). Further, for those forests which already experience frequent water limitations, the potential outcomes of climate-related disturbance trend toward widespread tree mortality (Allen et al., 2015, Williams et al., 2013).

In seasonally dry forests, longer and hotter droughts have resulted in significant mortality events over the past 2 decades with hotspots in Australia (Brouwers et al., 2013; Semple et al., 2010), Europe (Čater, 2015), and more recently in the western United States (Anderegg et al., 2015; Asner et al., 2016; Hicke et al., 2015). These shifts in drought intensity and duration have amplified seasonal trends in fuels aridity in seasonally dry forests, increasing ecosystem flammability (Abatzoglou & Williams, 2016). In the semiarid southwestern United States, landscapes have been subject to a significant drought since the turn of the century, resulting in extensive and severe subsurface soil moisture anomalies due to the warming climate and snow pack reduction, resulting in increases in area burned across the region (Abatzoglou & Williams, 2016; Westerling, 2016).

The direct and indirect effects of changing climate interact with ecosystems shaped by over a century of fire-exclusion. The suppression of wildfires has transformed frequent-fire-adapted forests from systems historically characterized by open understories shaded by fewer, older trees, into high stem density conditions with nearly continuous forest canopy (Hagmann et al., 2013, 2014; Johnston et al., 2017). These shifts in ecosystem structure increase forest vulnerability to drought, as competition for water increases with tree density (Voelker et al., 2019). Further, the legacy of fire-exclusion has resulted in a forest and fuels structure that increases the probability that ignitions result in high-severity wildfires torching mature trees and significantly impacting the structure of the forest (Singleton et al., 2019). These structural vulnerabilities, combined with increased extent, duration, and intensity of climate change-type drought events (Seager et al., 2007; Williams et al., 2015), and a lengthening of the fire season (Jolly et al., 2015), set the stage for larger, hotter wildfires to impact the vulnerable forests of the southwestern United States. The severity of fire weather events (Collins, 2014), area burned (Westerling, 2016), and the frequency of high-severity fire (Singleton et al., 2019) continue to increase, suggesting that these trends will continue on a similar trajectory. Cessation of the increase of high-severity fire ultimately depends on the contemporary structure of forest and fuels distributions equilibrating with current climate and wildfire regimes (Liang et al., 2017), reducing the likelihood of uncharacteristic wildfires once the majority of forests either have experienced severe wildfires or have been influenced by management activities (Parks et al., 2016).

Management intervention at the local scale can result in immediate reductions in high-severity fire risk through changes in forest structure and in the distribution and quantity of fuels (Ager et al., 2014; Finney et al., 2005; Lydersen et al., 2017). In the frequent-fire-adapted forests of the southwestern United States, the management influence on fire behavior involves reducing tree density by mechanically thinning younger and shade-tolerant trees that can carry surface fire into the crowns of mature trees followed by prescribed burning on a regular interval to maintain forest structure (Agee & Skinner, 2005; Hurteau et al., 2016). Consequently, fuels reduction treatments initially remove carbon from the landscape, yet over time the compensatory growth attributed to the release of the remaining trees from competition, combined with the reduced likelihood of high-severity, stand-replacing wildfires can result in a net carbon gain across the landscape and facilitate climate regulation (Hurteau et al., 2016; Hurteau & North, 2010; Krofcheck et al., 2018).

The net ecosystem carbon balance (NECB), defined as the summation of the carbon inputs (i.e., net photosynthesis) and losses (e.g., management and wildfires) from the ecosystem, is a useful metric to understand the trajectory and stability of the forest from a growth and carbon accumulation perspective (Chapin et al., 2006). Further, because NECB incorporates changes to ecosystem structure from wildfires and management and ecosystem function from net photosynthesis, changes in NECB directly impact ecosystem services beyond climate regulation by affecting the quantity and quality of habitat, wood production, and so forth. The initial NECB cost of management, for example, through mechanical thinning to reduce tree density, is required to establish a forest structural condition that is capable of reducing losses from high-severity wildfires and subsequent post-fire reductions in net photosynthesis (Hurteau et al., 2016; North & Hurteau, 2011). Yet, decision-making with respect to how and where these treatments are placed and what type of treatments are implemented can help maximize treatment benefit while minimizing the landscape carbon losses from management and therefore decrease the time to a net carbon benefit (Krofcheck et al., 2018; Wiechmann et al., 2015). Given the extent of frequent-fire forest that has deviated from its fire-maintained condition is large, and the pace at which treatments are being implemented is slow (North et al., 2012), treatment placement optimization can help balance the need to mitigate high-severity wildfire risk, the climate-regulating role of forests, and the economic costs of management.

Here we used a process-based model of vegetation function at the landscape-scale to investigate how management intervention can build ecosystem adaptive capacity to projected climate and wildfires. We quantified the components of NECB to understand how treatment placement and carbon costs influenced the trajectory of net photosynthesis and wildfire carbon emissions. Specifically, we asked (1) how are net photosynthesis, management, and wildfire emissions related in terms of their contribution to landscape NECB? And (2) how does treatment optimization affect the time required to achieve a positive NECB?

2. Materials and Methods

2.1. Site Description

We chose to investigate the role of fuels reduction treatment placement in mitigating NECB losses in a fireshed (defined as an area where the social and ecological concerns regarding wildfire overlap) in northern New Mexico. The Santa Fe fireshed encompasses the city of Santa Fe's approximately 7,000 ha municipal watershed and has drawn considerable attention from managers and stakeholders because of the risk of high-severity wildfires and the threat it poses to the provision of municipal water supply. The Greater Santa Fe Fireshed Coalition (http://www.santafefireshed.org/), a group of federal, state, tribal, and nongovernmental organizations, has been using a collaborative process to develop a management strategy to mitigate the risk of high-severity wildfires within the Fireshed, including treatment type and placement. The Fireshed is approximately 45,000 ha and is located in the Sangre de Cristo Mountains, east of Santa Fe, New Mexico (Figure 1). The Fireshed spans an elevation range of 1,900–3,700 m and contains vegetation ranging from piñon-juniper woodlands (*Pinus edulis, Juniperus monosperma*) in the low-elevation foothills, transitioning to ponderosa pine (*P. ponderosa*) in the mid elevations, and with mixed-conifer forest and spruce-fir (*Picea engelmanii, Abies lasiocarpa*) at higher elevations, with some scattered stands of Gambel oak (*Quercus gambelii*) and quaking aspen (*Populus tremuloides*) occupying recently disturbed regions in the mid and high elevations. The soils range from silty clay skeletal mixture Sobordoro soils in the low to mid elevations, transitioning to more loam-dominated mixtures at higher elevations. For the period 1980–2015, mean annual temperature is 9.4 °C, and mean annual precipitation is 360 mm, with a larger fraction of precipitation falling as snow in the winter months at higher elevations (Thornton et al., 2012).

2.2. Model Description and Model Region Generation

We conducted landscape-scale simulations of forest growth, succession, and disturbance across the Santa Fe Fireshed at a spatial resolution of 1 ha using landscape disturbance and succession II (LANDIS-II; v6.2), a forest landscape disturbance and succession model with additional processes represented via modular extensions. The core LANDIS-II model simulates demography in terms of species-specific age cohorts, each with a unique set of parameters that govern their growth, succession, dispersal, and mortality across a spatially explicit landscape (Scheller et al., 2007). To increase the coupling between abiotic drivers and ecophysiology, we used the photosynthesis and evapotranspiration (PnET)-Succession extension (v2.0; de Bruijn et al., 2014) for LANDIS-II, which is based on elements of the PnET-II model (Aber et al., 1995) and affords the model the ability to drive succession and biomass accumulation based on an additional set of species-specific physiological parameters. We used the Dynamic Fuels and Fire extension (v2.1) to simulate wildfires and fuels interactions (Sturtevant et al., 2009) and the Biomass Harvest extension (v3.0) to simulate management (Gustafson et al., 2000). The Dynamic Fuels and Fire extension simulates stochastic wildfires, and the effects on the ecosystem are a function of the fuels, weather, and forest conditions when the fire occurs. The model calculates wildfire severity (the effects of fire on the vegetation) based on the proportion of tree cohorts that are killed. Severity classes range from 1–5, with classes 1 and 2 being surface fire and no, or low, tree

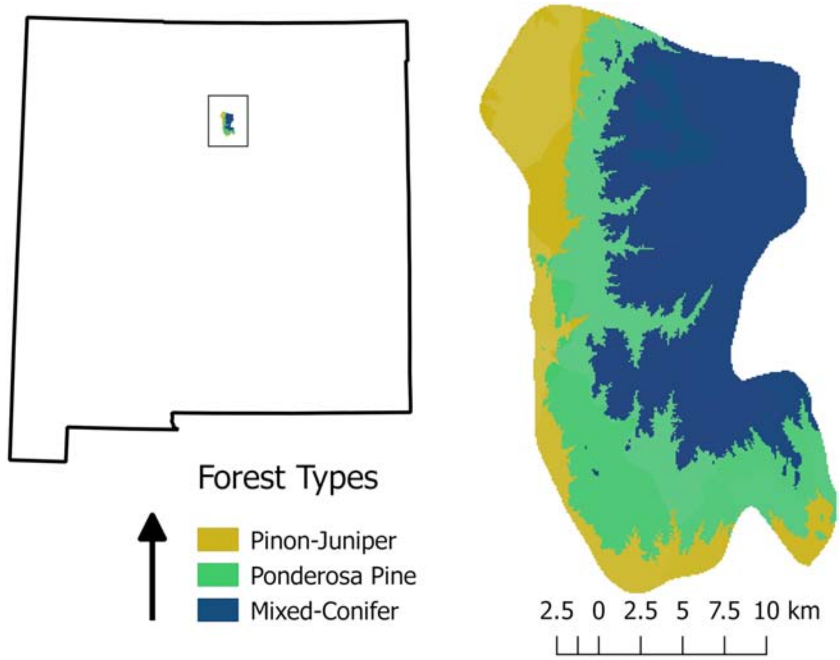

Figure 1. The Santa Fe Fireshed, located in Northern New Mexico, United States, is composed of three distinct vegetation types roughly ordered by increasing elevation: piñon-juniper woodlands (tan), ponderosa pine forest (green), and mixed-conifer forests (blue).

mortality; class 3 being mixed-severity fire that includes surface fire and some overstory tree torching that causes mortality; and classes 4 and 5 that include torching and crowning, resulting in a larger fraction of the overstory trees being killed by fire (see Supporting Information S1).

The LANDIS-II core and PnET-Succession extensions require the landscape to be separated into distinct "ecoregions," hereafter referred to as model regions. The model regions are defined by unique edaphic and climatic zones. For the growth and succession parts of the model, we chose to intersect elevation data (https://datagateway.nrcs.usda.gov/) roughly corresponding to the broad vegetation transitions determined by the Southwest Regional Gap Analysis (http://swregap.nmsu.edu/) with soil data (State Soil Geographic dataset, https://datagateway.nrcs.usda.gov/) across the Fireshed, resulting in the 18 unique model regions that resulted from the combination of three elevation bands and six soil types. The fuels and fire parts of the model require the landscape be divided into fire regions, which are areas with similar fire weather, fire size distributions, and ignition frequencies. We used the same three elevation bands to create three distinct fire regions.

2.3. Climate Data

The LANDIS-II core model and the PnET-Succession extension require climate inputs at a monthly time-step. We drove the model with climate projections from the Localized Constructed Analogs statistically downscaled climate projection from five climate models forced with Representative Concentration Pathway 8.5 from the Coupled Model Inter-comparison Project Phase 5. Specifically, we chose Community Climate System Model (CCSM), Centre National de Recherches Météorologiques (CNRM), Flexible Global Ocean-Atmosphere-Land System Model (FGOALS), Geophysical Fluid Dynamics Laboratory (GFDL), and Model for Interdisciplinary Research on Climate (MIROC5-ESM 2) given their projections represent the range of outcomes for the region. The Localized Constructed Analogs product is a daily, 1/16th degree resolution-downscaled product that has been shown to track local variability in precipitation better than the coarser resolution parent models (Pierce et al., 2014). The projections include data from 1950 to 2100, and we used data from 1950 to 2000 for model spin-up. We downloaded the data using the U.S. Geological Survey Geo Data Portal (http://cida.usgs.gov/gdp/), and computed weighted area grid statistics on a per-model region basis using the export service in the data portal.

Table 1
Total treatment area and rates for thinning and prescribed burning

Scenario	Thin area (ha)	Thin rate (ha yr^{-1})	Prescribed fire area (ha)	Prescribed fire rate (ha yr^{-1})
Prioritized	13,273	1,327	16,531	1,657
Optimized	6,006	1,201	21,054	1,958

The PnET extension also requires radiation and atmospheric carbon dioxide concentrations as inputs to the model. We downloaded spatially explicit shortwave radiation from Daymet using the U.S. Geological Survey Geo Data Portal, and created a distribution of mean monthly shortwave radiation on a per-model region basis (Thornton et al., 2012). We then converted the shortwave radiation to photosynthetically active radiation following Britton and Dodd (1976). We used historic CO_2 concentrations for model spin-up (https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html) and concentrations from the Representative Concentration Pathway 8.5 for model projections (Riahi et al., 2007).

2.4. Model Parameterization and Validation

We developed the initial communities layer, which is the spatial distribution of species-specific age cohorts, using U.S. Forest Service Forest Inventory and Analysis data and Southwest Regional Gap Analysis data (see Supporting Information S1). We parameterized the Dynamic Fire and Fuels extension using regional fire size data from Geospatial Multi-Agency Coordination, previously published fuels data, and climate projections from the Multivariate Adaptive Constructed Analogs v2 collection to develop fire weather distributions (see Supporting Information S1). We obtained species-specific parameters for the PnET ecosystem succession extension from previously published data and the TRY database, then validated the model against eddy-covariance tower data (Gustafson et al., 2015, Kattage et al., 2011, Remy et al., 2019, see Supporting Information S1).

2.5. Management Treatment and Scenario Development

We developed management treatments for the Biomass Harvest extension to approximate common thinning and prescribed burning treatments implemented in the region. We simulated thinning-from-below by removing approximately 30% of the biomass from each pixel identified for treatment (Hurteau et al., 2011; Hurteau et al., 2016). Thinning treatments preferentially removed biomass from the youngest cohorts. Prescribed fires were simulated such that initial-entry burns were implemented in the year following mechanical treatments and were simulated using a fire return interval consistent with the historical data, ranging from 10–17 years depending on whether the forest types were ponderosa pine or higher elevation stands co-dominated by ponderosa pine or Douglas-fir. Thinning treatments were only applied to forest types that historically burned at high frequency (i.e., ponderosa pine-dominated stands).

To answer our questions, we developed three different scenarios (no-management, prioritized, and optimized). Prior to this analysis, the Santa Fe Fireshed Coalition used a collaborative process to develop a proposed fuels treatment plan for the fireshed. We based our prioritized treatment scenario on implemented, planned, and potential treatment locations provided by the Fireshed Coalition. Given the Fireshed Coalition's objective of mitigating the risk of high-severity wildfires, we used a procedure similar to Krofcheck et al. (2017, 2018) to develop an optimized treatment placement scenario. To develop the optimized scenario, we used the initial vegetation community representing the dominant vegetation types, the operational constraints to mechanical thinning of vegetation (slope >30%), and the probability of high-severity fire under progressive fire weather (see the supporting information, Figure S1). We then used the calculated probability of high-severity fire across the Fireshed to determine the treatment priority for the landscape (see Supporting Information S1). The areas identified for thinning in the optimized scenario are a subset of those identified for thinning in the prioritized scenario. Additionally, the optimized scenario includes a larger area identified for prescribed burning because prior research has demonstrated widespread prescribed burning, coupled with targeted thinning treatments, can modify the risk of high-severity wildfires (Krofcheck et al., 2018, 2019).

The resulting treatment areas and rates for mechanical thinning and prescribed burning are described in Table 1. The area treated by prescribed fire is larger than the thinned area because prescribed fire treatments were not limited by slope (Figure S1). In both scenarios, mechanical thinning was constrained to ponderosa pine-dominated areas.

2.6. Simulation Experiment Description and Analysis

We ran 25 replicates of each of the three scenarios (no-management, prioritized, and optimized) using five climate projections for years 2000–2050. Fire weather distributions tracked projected climate and were updated each decade to account for changes in temperature and precipitation (see Supporting Information S1). We calculated the mean fire severity of all three scenarios by using annual raster outputs of fire severity from all replicate simulations for each of the five climate projections used in our modeling environment. Similarly, we calculated the cumulative sums of landscape net photosynthesis, carbon removed due to management, and carbon lost due to wildfires. We compared these outputs between treatments by subtracting each management output from the no-management scenario. Because we compared all the model outputs for the management scenarios to the no-management scenario, cumulative net photosynthesis differences that are negative indicate the management scenario sequestered more carbon relative to the no-management scenario. We calculated the cumulative NECB for each management scenario by subtracting the carbon losses from the system (management and wildfires) from cumulative net photosynthesis and subtracted no-management cumulative NECB to obtain the difference from no-management. Positive cumulative NECB values indicate that the management scenario cumulative NECB was higher than the no-management cumulative NECB. We conducted data processing, statistical analysis, and figure generation in Python 3.6.

We compared mean fire severity by treatment scenario using annual raster outputs of fire severity from all replicate simulations for each of the five climate projections used to drive each management scenario. We compared cumulative photosynthesis between the management scenarios by subtracting cumulative photosynthesis from the prioritized and optimized scenarios from the no-management scenario. The differencing of the management scenarios from the no-management scenario means that a negative cumulative photosynthesis value means the management scenario is taking up more carbon than the no-management scenario. We calculated the cumulative NECB for all scenarios by subtracting carbon losses from the system (management and wildfires from net photosynthesis. We then differenced cumulative NECB by subtracting the no-management scenario from the two management scenarios. Positive cumulative NECB values indicate that the management scenario cumulative NECB was higher than the no-management cumulative NECB. We conducted data processing, statistical analysis, and figure generation in Python 3.6.

3. Results

Combinations of mechanical thinning and prescribed burning in both management scenarios resulted in large and significant reductions to landscape-scale fire severity (Figure 2). As expected, the largest reductions in fire severity occurred where treatments were implemented. The optimized scenario resulted in 29% more of the landscape having reductions in mean wildfire severity greater than 20% relative to the prioritized scenario due to the additional 4,523 ha that received prescribed fire (Table 1). However, the prioritized and optimized treatment scenarios did not significantly differ from each other in terms of the proportion of wildfires that burned at high-severity. There were no significant differences in the total number of fires or the wildfire size distribution across scenarios, because we held those distributions constant for all simulations.

The implementation of thinning treatments caused the cumulative *Psn* to decrease relative to no-management during the first decade when thinning treatments were implemented (Figure 3). Between 3 and 5 years following completion of the thinning treatments, both management scenarios had increased the cumulative landscape Psn relative to no-management because of reduced resource competition and decreased disturbance pressure, a trend that persisted throughout the 50 year simulation period (Figure 3). The cumulative difference in the landscape Psn of both treatment scenarios was significantly higher in the prioritized (6.6 ± 0.08 Mg • C • ha^{-1}) and optimized (6.8 ± 0.08 Mg • C • ha^{-1}) scenarios than in the no-management scenario. At the landscape-scale, this is equivalent to 0.32 Tg C for the prioritized and 0.33 Tg C for the optimized scenarios (Figure 3).

By the end of the simulation period, both treatments resulted in significant reductions in carbon (C) losses due to wildfires relative to no-management (prioritized 3.0 Mg • C • ha^{-1}, optimized 5.9 Mg • C • ha^{-1}), equivalent to 0.15 Tg C for the prioritized and 0.33 Tg C for the optimized scenarios across the landscape (Figure 4). The total C removed due to thinning and prescribed burning was higher for the prioritized scenario (8.4 Mg • C • ha^{-1}) than the optimized scenario (6.8 Mg • C • ha^{-1}, Figure 4), due to the combined

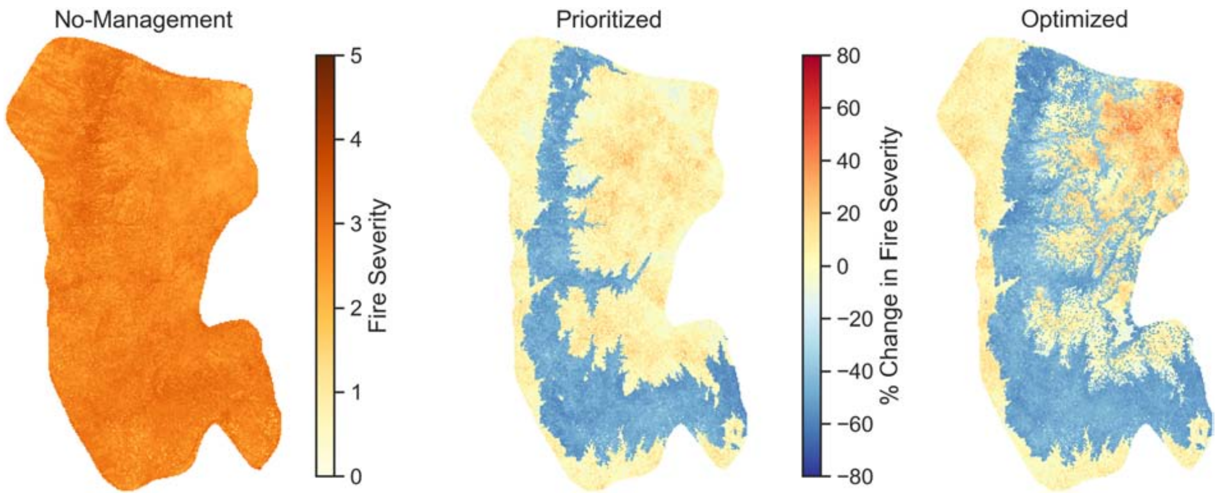

Figure 2. Mean wildfire severity across the Santa Fe Fireshed for the no-management scenario (left) and the percent reduction in mean wildfire severity from no-management for the prioritized (center) and optimized (right) scenarios. Fire severity ranges from 1 to 5, with 1 and 2 being surface fire, 3 being surface fire and some overstory tree torching, and 4 and 5 including crowning and high overstory tree mortality.

impact of a reduction in mechanical thinning of 7,267 ha and an increase in prescribed burning of 4,523 ha under the optimized scenario (Table 1).

At the end of the 50 year simulations, the cumulative NECB benefit relative to no-management was 1.2 Mg • C • ha^{-1} for the prioritized scenario and 5.9 Mg • C • ha^{-1} for the optimized scenario, equivalent to 0.06 Tg C for the prioritized and 0.29 Tg C for the optimized scenarios across the landscape (Figure 5). Throughout the simulation period, this relative benefit was dynamic in both treatments as a function of stochastic wildfire, climate and fire weather projections, and management prescriptions, with the mean time to net benefit for the prioritized scenario occurring at simulation year 45, and at year 24 for the optimized scenario.

4. Discussion

Forest management in fire-prone, semiarid ecosystems is an exercise in mitigating the potential loss of ecosystem services that can occur from high-severity wildfires. A legacy of fire-exclusion, which has increased the sensitivity of frequent-fire-adapted forests to climatic change and climate-driven disturbance, presents a significant challenge for many forests in the western United States. Maintaining these fire-prone forests and the broad suite of ecosystem services they provide hinges on restoring forest structural heterogeneity and reducing fuels, the maintenance of which is dependent upon restoring frequent-fire regimes (Hurteau

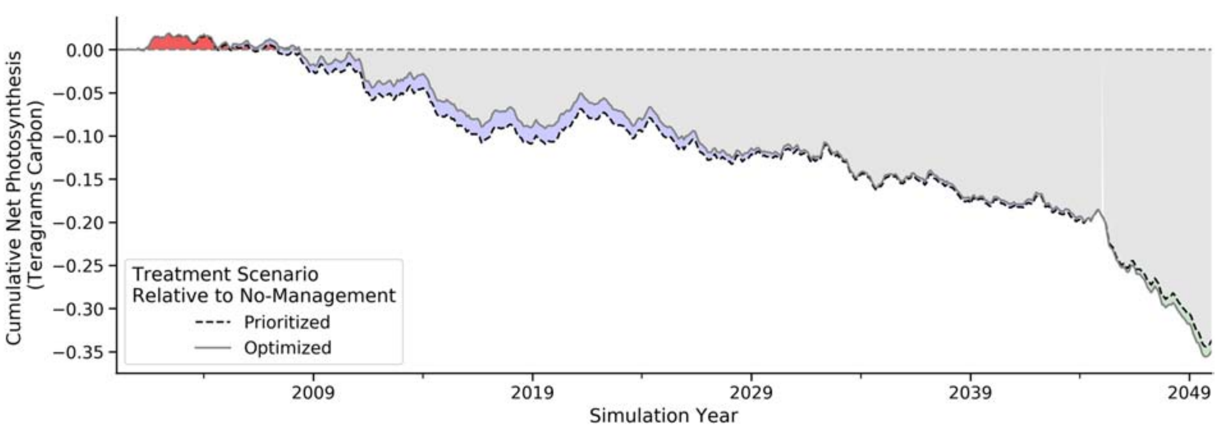

Figure 3. Net photosynthesis integrated across the Fireshed over time, relative to the no-management scenario (0 line) for both the prioritized (dashed black) and optimized (solid gray) scenarios. Positive values indicate the no-management scenario sequestered more carbon than the management scenario (red shading).

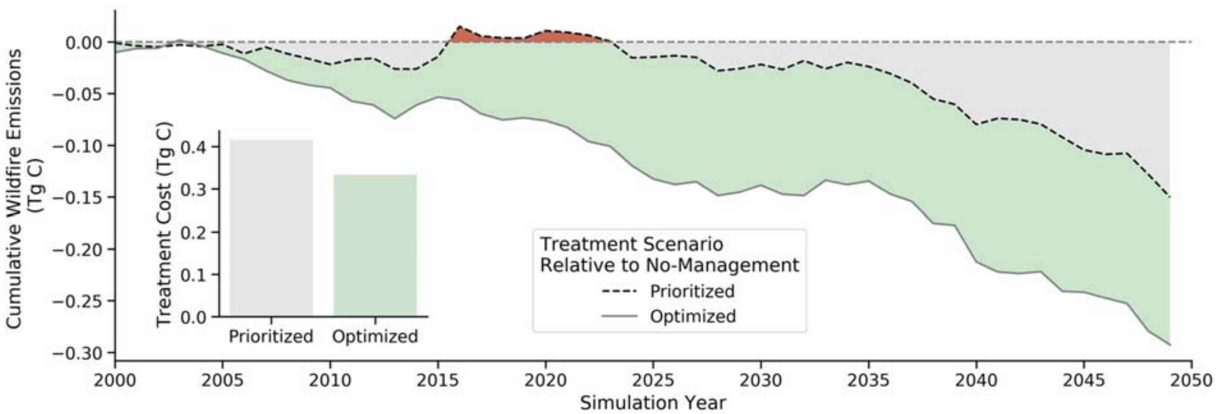

Figure 4. Differences in carbon (C) loss due to wildfires integrated across the Fireshed over time, relative to the no-management scenario (0 line) for both the prioritized (dashed black) and optimized (solid gray) scenarios. Positive values indicate the management scenario had higher wildfire C emissions relative to the no-management scenario. The total C removed by mechanical thinning and prescribed burning associated with each treatment scenario is shown in the inset bar graph.

et al., 2014). Further, the contemporary record of drought and wildfire impacts on forested ecosystems in the semiarid southwestern United States suggests that the ecosystem instability borne from combinations of fire-exclusion and climatic change will result in large structural changes and reductions in ecosystem function (Allen et al., 2015; Hurteau, 2017).

While mitigating human impacts on the climate system requires a global effort, mitigating the impacts of changing climate and disturbance regimes on forests is inherently a local process. These intervention strategies require an upfront carbon cost, an initial detriment to NECB, but can help stabilize forest carbon and contribute to global climate change mitigation efforts. Our results demonstrate that informing management decisions by optimizing treatment locations can provide the same reduction in high-severity wildfire risk as prioritizing treatment using a nonquantitative approach (Figure 2) and do so with reduced upfront carbon costs (Figures 4 and 5). Focusing thinning treatments in areas that have the highest probability of high-severity fire allows for a large reduction in the area thinned (7,267 ha reduction in the optimized scenario). However, achieving the reduction in mean fire severity (Figure 2) requires an additional area be treated with prescribed burning (4,523 ha) over the prioritized scenario. Treating the additional area with regular prescribed burning has the effect of reducing surface fuels and maintaining a lower density of small trees that facilitate the movement of fire from the surface into the canopy. This yielded a mean net reduction in the carbon costs associated with treatment of 1.6 Mg • C • ha^{-1}. While the carbon costs of treatment will vary by geographic location and ecosystem type, identifying areas where the most carbon costly treatments

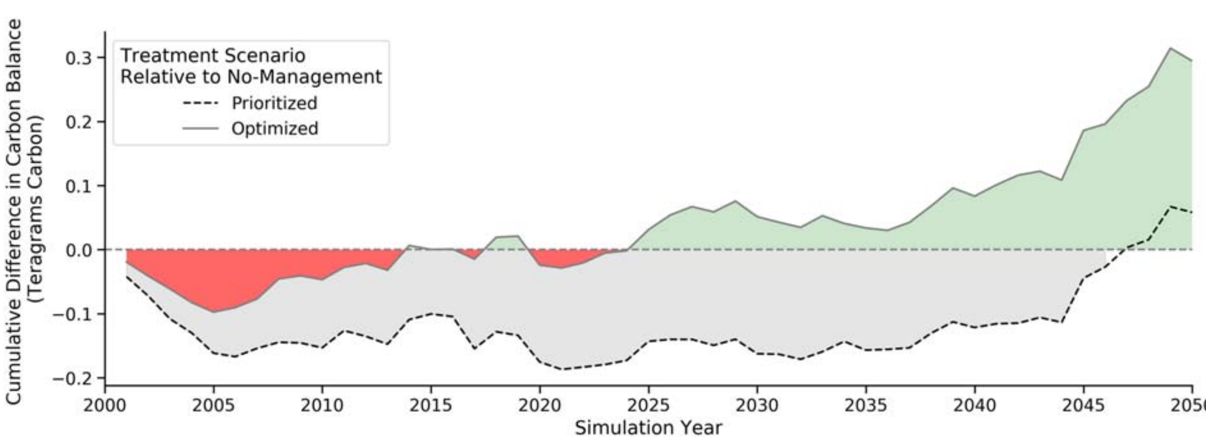

Figure 5. Cumulative net ecosystem carbon balance (NECB) of the prioritized (dashed black) and optimized (solid gray) scenarios, relative to the no-management scenario (0 line), for the entire Santa Fe Fireshed. Positive values indicate the management scenario landscape a had greater NECB relative to the no-management scenario due to the balance of carbon (C) into the ecosystem from photosynthesis and C lost from the system due to thinning, prescribed burning, and wildfires.

(e.g., thinning) will yield the greatest benefit in terms of reducing high-severity wildfire risk, and augmenting these with additional prescribed burning will help reduce the upfront carbon costs of treatment.

Management at local scales is constrained by a range of biotic, abiotic, and human factors and objectives. In our simulations, we used the probability of high-severity fire as the only objective function to minimize, and executed the mechanical thinning of the landscape over the shortest feasible time frame, with regular maintenance using prescribed fire. This rapid transition toward an ecosystem structure resembling historical fire-maintained conditions resulted in increased carbon uptake efficiency and carbon stock accumulations at the scale of the landscape, relative to our no-management scenario (Figures 3 and 5). When operating in our dramatically simplified decision space, we found that optimally placing mechanical treatments to minimize the risk of high-severity wildfires accounted for nearly a three-fold increase in the overall net carbon benefit and cut the time to realize that benefit in half (Figure 5). When optimizing forest management activities to meet a single objective, research in other geographic locations has also demonstrated that fewer management inputs are required when the treatment locations are determined using a quantitative approach (Barros et al., 2019; Chung et al., 2013; Krofcheck et al., 2018, 2019). However, working within place-based abiotic, biotic, and human constraints to achieve societally desirable objectives oftentimes requires balancing competing objectives.

The multivariate decision-making space for forest management in the western United States includes minimizing wildfire hazard for communities, habitat provision for protected species, and water quality and quantity, among others. In the case of the Santa Fe Fireshed and other forested watersheds of the southwestern United States, a century of fire-exclusion, nearly 2 decades of extreme drought, and warming have increased high-severity wildfire risk (Hurteau et al., 2014; Singleton et al., 2019; Swetnam & Brown, 2011). In this water-limited region, streamflow invariably increases following high-severity wildfires due to decreased infiltration and decreased vegetation water use (Bart, 2016; Wine et al., 2018; Wine & Cadol, 2016). However, the measured increase in water yield from severely burned watersheds following precipitation events is paired with a significant detriment to water quality, which has cascading negative impacts on wildlife, riparian biodiversity, and ultimately the provision of municipal water from forested landscapes (Cooper et al., 2015; Jackson et al., 2012; Jones et al., 2016; Murphy et al., 2018).

Thinning treatments and the reintroduction of frequent surface fires help restore a more heterogeneous forest structure and reduce the probability of high-severity wildfires (Figure 2). These forest conditions are correlated broadly with increased forest productivity and biodiversity (Barros et al., 2017; Spies et al., 2017). Yet, a restored forest structure beneficially affects nearly every aspect of ecosystem function and the corresponding services that forests provide. Forests that experience fire on an interval close to the historic norm tend to show increased productivity over time, in part as a result of the increased tolerance to biotic and abiotic disturbance afforded by size, age, and species heterogeneity (Kerhoulas et al., 2013; Voelker et al., 2019). At the scale of the landscape, this can result in greater water use efficiency, increased carbon sequestration, and increased water availability (North & Hurteau, 2011; Roche et al., 2018). Thus, the opportunity exists to manage for a suite of ecosystem services and meet a range of societal objectives by a priori evaluation of the factors that pose the largest risk to ecosystem services in frequent-fire forests across the western United States.

Encouragingly, our simulation results suggest the potential for management to stabilize the provision of ecosystem services even in semiarid landscapes that have an increased likelihood of high-severity fire. Further, when treatments are optimally placed, the carbon losses from treatment can be minimized, and the NECB maximized under projected climate change (Figures 3 and 5). While management decision-making is rarely univariate, understanding the carbon consequences of forest management is important as society seeks to mitigate climate change and begins to price these activities (Fargione et al., 2018; Griscom et al., 2017; Verdone & Seidl, 2017).

The work we present here suggests the potential for collaborative fuels and fire management efforts to leverage simulation modeling to build on or optimize the impact of place-based fuels treatment strategies. Here, we incorporated a modeled probability of high-severity fire risk to both determine the location of treatments and to broaden the extent of prescribed burning to restore ecologically appropriate fire into areas that otherwise were not planned to be treated. Given the increasing use of collaborative planning to implement forest management activities that meet a suite of societal objectives (Schultz et al., 2012), this approach can help inform decision-making by providing insight into the potential for planned activities to meet desired goals.

Our approach can be applied in other ecosystems that have seen a departure from their historic fire regime. Prior research in a Sierran mixed-conifer forest has demonstrated the value of integrating existing management plans with modeling to ask specific questions about the impacts of using mechanical thinning or prescribed burning in isolation or in combination (Krofcheck et al., 2017) and has shown that constant application of prescribed burning is required to maintain the initial gains in reducing high-severity fire risk. Similarly, the utility of using a risk-based approach to efficiently allocate treatments has been demonstrated in a range of forest types, from pine plantations in the southeastern United States to conifer forests in Oregon (Ager et al., 2014; Krofcheck et al., 2018). Consequently, whereas the specific insights from this study broadly relate to southwestern frequent-fire-adapted landscapes, the strategic pairing of proposed management decision-making strategies with simulation modeling efforts can be used to ask specific questions regarding the potential for proposed treatments to interact with future climate, and may shed light on ways to maximize the impact of management while reducing the associated costs.

Our results should be considered in the context of the limitations of our simulation approach. The factors influencing the probability of high-severity fire in our study are ignition locations, fire weather, and vegetation. While we used random ignitions to develop the probability of a high-severity fire layer that informed the optimized scenario, human ignitions are a large contribution to the total number of fires and tend not to occur randomly on the landscape (Balch et al., 2017). Developing the probability surface with local fire start data would likely better inform the result. We developed our fire weather distributions using projected climate data to account for the projected increase in temperature and its effect on fuel moisture. However, extreme weather events (e.g., high winds, severe drought, etc.) can influence fire behavior and spread, and these are unaccounted in our fire weather distributions because of the resolution of the projected climate data and the influence that local topography has on wind. The distribution of vegetation on our simulated landscape is interpolated from remotely sensed and forest inventory data. As a result, the vegetation conditions, which influence fire behavior, at a given location on our simulated landscape likely deviate from reality. Improving the probability of the high-severity fire layer would require a more intensive field plot network in order to identify the exact locations that have the highest risk of high-severity fire. Further, simulated landscapes are much simpler than their natural counterparts and do not incorporate many of the real world and societal complications inherent to natural systems. Our simulation environment operated at the scale of 1 ha, and while this is spatially very highly resolved compared to most land surface modeling studies, the implications for how management activities are planned and executed needs to be considered. As an example, our simulations assumed that specific hectares of the landscape could be treated, either in isolation or in aggregate, and ignored the strategic usage of roads or importance of structures in placement of treatments and management of wildfires. While accounting for these additional factors would likely change the geographic location of some areas with a high probability of high-severity fire within a particular fireshed, the concept of using a risk-based approach to locating forest treatments will retain utility.

5. Conclusions

The current structure of forested landscapes of the southwestern United States have been shaped by a legacy of fire-exclusion, increasing the likelihood that changing climate and wildfires will significantly impact the ecosystem services these forests provide. Management activities to restore forest structural heterogeneity and ecologically appropriate fire regimes can help build forest adaptive capacity for dealing with ongoing climate change and help ensure the continued provision of ecosystem services. A data-informed approach to allocating management activities across a landscape provides the opportunity to minimize the costs and tradeoffs that are inherent in forest management. Further, building adaptive capacity into these systems facilitates their continued contribution to climate regulation through carbon uptake and storage.

Acknowledgments
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Forest restoration as a strategy to mitigate climate impacts on wildfire, vegetation, and water in semiarid forests

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Abstract. Climate change and wildfire are interacting to drive vegetation change and potentially reduce water quantity and quality in the southwestern United States, Forest restoration is a management approach that could mitigate some of these negative outcomes. However, little information exists on how restoration combined with climate change might influence hydrology across large forest landscapes that incorporate multiple vegetation types and complex fire regimes. We combined spatially explicit vegetation and fire modeling with statistical water and sediment yield models for a large forested landscape (335,000 ha) on the Kaibab Plateau in northern Arizona, USA. Our objective was to assess the impacts of climate change and forest restoration on the future fire regime, forest vegetation, and watershed outputs. Our model results predict that the combination of climate change and high-severity fire will drive forest turnover, biomass declines, and compositional change in future forests. Restoration treatments may reduce the area burned in high-severity fires and reduce conversions from forested to non-forested conditions. Even though mid-elevation forests are the targets of restoration, the treatments are expected to delay the decline of high-elevation spruce–fir, aspen, and mixed conifer forests by reducing the occurrence of high-severity fires that may spread across ecoregions. We estimate that climate-induced vegetation changes will result in annual runoff declines of up to 10%, while restoration reduced or reversed this decline. The hydrologic model suggests that mid-elevation forests, which are the targets of restoration treatments, provide around 80% of runoff in this system and the conservation of mid- to high-elevation forests types provides the greatest benefit in terms of water conservation. We also predict that restoration treatments will conserve water quality by reducing patches of high-severity fire that are associated with high sediment yield. Restoration treatments are a management strategy that may reduce undesirable outcomes for multiple ecosystem services.

Key words: climate change; ecological modeling; fire ecology; forest restoration; hydrology; LANDIS-II; sediment.

Introduction

Climate change is altering vegetation distributions and fire regimes in the western United States. Vegetation types are shifting to higher elevations (Allen and Breshears 1998), and wildfires are becoming more frequent and intense (Westerling et al. 2011). Wildfire and vegetation change interact, as forests are commonly replaced by sprouting shrub vegetation that is better adapted to higher temperatures and drier conditions following wildfire (Strom and Fulé 2007, Tarancón et al. 2014). High-intensity wildfires often lead to reductions in water quality from erosion and high sediment loads (Neary et al. 2009, Smith et al. 2011) and vegetation type conversions are expected to influence watershed output (Huxman et al. 2005). With water deficits expected for the western United Sates in the coming century (Woodhouse et al. 2010), it is important to understand the threats to forested watersheds.

Forest managers are attempting to reduce the risk and spread of high-severity wildfires through forest restoration using treatments such as tree thinning, prescribed burning, and managed wildfires to decrease tree density and fuel loads. Restoration treatments have been successful in restoring historical forest attributes and reducing the potential for high-severity fire under contemporary climate conditions (Fulé et al. 2012). However, the outcomes of restoration under future climate conditions are uncertain and it may be difficult to utilize prescribed fire due to climate change effects on fire season windows. Due to uncertainty, there is interest in management that focuses on maintaining ecosystem function and regional native biodiversity (Stephenson 2014, Golladay et al. 2016) rather than recreating a historic condition. The provisioning of plentiful, clean water for both environmental flows and human use is an important ecosystem function for many semiarid forests.

The forests of the United States provide a significant amount of surface water and groundwater supply to the country (Barr 1956), and the connection between watershed land cover and the magnitude and timing of surface water flows has long been recognized (Bosch and Hewlett 1982, Robles et al. 2017). Recent studies have highlighted the importance of ecosystem health in the contributing area of an aquifer for reliable groundwater resources (Scanlon et al. 2005, Wyatt et al. 2015). Wyatt (2013) found, from a systematic global literature review, an average of 0–50% initial increase in water yield in coniferous forests when basal area is reduced by 5–100%. Forest restoration is also expected to maintain water quality by reducing the risk of high-intensity wildfire. Substantial soil loss due to rill and gully formation

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occurs after high-intensity wildfire (Neary et al. 2012), which can increase sediment loads in rivers and streams. Monitoring before and after the Cerro Grande Fire, which burned ponderosa pine and mixed-conifer forest in New Mexico, found that post-fire suspended sediment concentrations in ephemeral streams were more than 100 times higher than pre-fire levels (Malmon et al. 2007). Most measures of water quality, including concentrations of major ions and nutrients, turbidity, and pH, are significantly altered by wildfire for at least four months (Earl and Blinn 2003).

The potential for land cover change to impact water quantity and quality is especially high for karst aquifers. Flow through karst aquifers is characterized by a combination of fast flow traveling through sinkhole and cave networks (Lauber and Goldscheider 2014) and slow flow traveling through porous media. Due to the fast flow component, discharge from karst aquifers is more sensitive to perturbations in water quality (Vesper et al. 2001, Mahler et al. 2004). Localized disturbance around a sinkhole, such as a high-severity wildfire, is likely to degrade the quality of discharge from the connected fast flow karst system, Therefore, management of upland forests to preserve hydrologic function may be a feasible strategy for conservation of spring, aquatic, and riparian habitat that is supported by discharge from a karst aquifer.

The Kaibab Plateau, which forms the North Rim of Grand Canyon National Park (GCNP), is a classic representation of a snowmelt-dominated karst aquifer system (Tobin et al. 2017). Snowmelt runoff and precipitation infiltrates the Kaibab Plateau rapidly via sinkholes, faults, and fractures and slowly through diffuse infiltration. Once in the subsurface, it travels hundreds of meters vertically before moving laterally through the karst system in the North Rim's Redwall-Muav Aquifer (R-aquifer; Brown 2011, Jones et al. 2017). Sinkhole density on the Plateau is 3–5 sinkholes/km^2. Most precipitation (about 60%) falls during the winter (November–March) as snowpack and subsequently melts during spring (March–May), when low temperatures, minimal plant use, and saturated conditions in the vadose zone allow more water to recharge the aquifer system. Roaring Springs, the primary water source for GCNP, requires winter precipitation to sustain perennial flow as little recharge occurs during the summer monsoon (mid-July–September; Ross 2005, Schindel 2015). Most water discharged from the R-aquifer aquifer is relatively young and susceptible to rapid impacts from land-use activities on the Kaibab Plateau (Ross 2005).

We combine spatially explicit vegetation and fire modeling with statistical water and sediment yield models to evaluate the impacts of a range of restoration and climate scenarios on water inputs to a karst system. The study objectives were to (1) predict changes in fire regimes and forest vegetation on the Kaibab Plateau under a range of climate and restoration scenarios; (2) estimate the change in future hydrologic and sediment output due to forest type change and restoration; and (3) identify areas of the Kaibab Plateau that are most likely to experience negative hydrologic impacts.

Methods

Study site

The Kaibab Plateau is a 335,000-ha area of the Colorado Plateau region in Northern Arizona and includes portions of GCNP and the Kaibab National Forest (KNF). Elevation ranges from 1,439 to 2,830 m and climate and vegetation type vary with elevation. At Bright Angel Ranger Station, the only long-term climate monitoring site in the study area, average annual precipitation was 62.7 cm and temperatures ranged from an average July maximum of 25.2°C to an average January minimum of −8.1°C (NOAA NCEI 2011). About 40% of precipitation occurs as high-intensity summer monsoon storms and 60% occurs as low-intensity winter rain or snow. Most runoff and groundwater recharge on the southern Colorado Plateau are generated by winter precipitation (Baker 1986). Soils are primarily alfisols and entisols derived from limestone parent material (USDA NRCS 2013).

Variability of environmental site conditions and corresponding differences in species viability and growth are represented in LANDIS-II by subdividing the modeled landscape into ecoregions. We divided the Kaibab Plateau into four elevation-based ecoregions that align with the major forest types and associated fire regimes (Table 1): high elevation (spruce–fir; 2,675–2,830 m), high-mid elevation (mixed conifer; 2,450–2,675 m), low-mid elevation (ponderosa pine; 2,050–2,450 m), and low elevation (pinyon–juniper; 1,600–2,050 m; Vankat 2011*a*, *b*). We further diveded these elevation-based ecoregions by northeast- and southwest-facing aspects, resulting in a total of eight ecoregions. See Flatley and Fulé (2016) for a detailed description of the vegetation and fire regimes at the study site.

The Kaibab Plateau is uplifted to the East by the structural East Kaibab Monocline. After water infiltrates, dominantly through focused recharge in the over 7,000 sinkholes in the Permian Kaibab Formation, it travels vertically downward for hundreds of meters to the regional R-aquifer. The R-aquifer is composed of the Cambrian Muav Formation, Devonian Temple Butte Formation, and Mississippian Redwall Limestone and is perched on the Cambrian Bright

Table 1. Elevation range, dominant vegetation type, and climate for four ecoregions on the Kaibab Plateau, Arizona, USA.

Ecoregion	Elevation (m)	Dominant vegetation type	Annual precipitation (mm)	Maximum July temperature (°C)	Minimum January temperature (°C)
High	2,675–2,830	Spruce–fir	746	25.4	−9.8
High-mid	2,450–2,675	Mixed conifer	656	26.4	−8.7
Low-mid	2,050–2,675	Ponderosa pine	489	28.8	−6.7
Low	1,600–2,050	Pinyon–juniper	365	32.1	−4.7

Notes: Values are means. Precipitation and temperature values are derived from PRISM 30-yr climate normals for 1981–2010 (PRISM Climate Group 2004).

Angel Shale. North Rim springs are a mix of older water from groundwater storage and younger water from fast karst recharge (Monroe et al. 2004). Although there are over 20 springs, most of the water discharges from Angel Spring, Emmett Spring, Roaring Spring, Abyss Spring, Tapeats Spring, and Thunder River Spring (Jones et al. 2017).

Climate and restoration scenarios

We simulated the response of wildfire, forest dynamics, and hydrologic output to changes in climate and restoration approaches from 2010 to 2110. Each simulation included an initialization run up of 600 yr under the historical fire regime (calendar years 1280–1880), followed by 130 yr of fire exclusion (calendar years 1880–2010), which allowed forest conditions to reach a state that approximates current forest conditions within the study area (see Flatley and Fulé 2016). The impact of 20th century logging within the (KNF) was simulated with two logging treatments implemented with the biomass harvest extension (v2.1; Gustafson et al. 2000). Based on timber records from the forest (Sesnie and Bailey 2003), we applied a selective logging treatment that removed 25% of the biomass from all cohorts across a cumulative 50% of the landscape during 1955–1980. Then we applied a more intensive logging treatment that removed 50–70% of the biomass from mature cohorts (>31 yr), across a total of 24% of the landscape from 1980 to 1990. Logging treatments were not applied to forests in GCNP, reflecting the absence of past logging in these forests. We then modeled the landscape response according to a series of climate and restoration scenarios spanning 2010–2110. We ran 10 replicates for each scenario in order to account for stochasticity associated with individual fire events that vary according to ignition points and fire weather in individual runs.

We modeled nine future change scenarios (3 climate scenarios $\times$ 3 restoration scenarios) designed to assess the outcomes of changing climate and restoration approaches alone and in combination. Future climate projections were based on an ensemble average of 17 general circulation models (GCM) included in the IPCC fifth assessment and available for use with Climate-FVS (Crookston and Rehfeldt 2008). We chose the ensemble GCM outputs from representative concentration pathway (RCP) 4.5 as an assessment of moderate climate change and RCP 8.5 as a high climate change scenario (Meinshausen et al. 2011). We initiated climate-induced growth and establishment changes in 1990 for both the RCP 4.5 and RCP 8.5 climate change regimes, while we held the historical climate conditions constant for the no climate change regime.

We tested three restoration scenarios that differed in terms of the area treated annually: no restoration, low restoration, and high restoration. The no restoration scenario included no thinning or burning. The low and high restoration scenarios implemented thinning treatments for an initial 20 yr (1990–2010), followed by prescribed burning for the remainder of the simulation. The modeled restoration treatments match contemporary restoration practices in southwestern frequent-fire forests in which thinning is used to alter forest composition and structure, followed by prescribed burning for the reduction of fuel loads (Reynolds et al. 2013). We only applied restoration treatments in the low-mid-elevation and high-mid-elevation ecoregions, which are currently occupied by ponderosa pine and dry-mixed conifer. The low restoration scenario treated 1.25% of the target area per year (80-yr rotation) with thinning or prescribed burning and the high restoration scenario treated 5% of the target area per year (20-yr rotation).

Vegetation modeling approach

Climate-FVS and LANDIS-II.—We used Climate-FVS and LANDIS-II to model fire regime and forest response to climate change and restoration treatments. Climate-FVS is a forest growth simulation model that adjusts species viability and growth rates according to site specific, downscaled climate projections (Crookston et al. 2010). We used Climate-FVS to estimate input values for LANDIS-II, which included species establishment probabilities, aboveground net primary productivity, and maximum aboveground live biomass for individual species in response to changing climate conditions. LANDIS-II (v6.0; Scheller et al. 2007) is a spatially interactive forest landscape simulation model that can be used to model spatial processes such as fire spread, forest succession, and species dispersal (Gustafson et al. 2010, Duveneck and Scheller 2015, Hurteau et al. 2016). The core model is compatible with a series of extensions for simulating forest processes. We modeled forest growth, competition, succession, and regeneration using the Biomass Succession extension (v3.1; Scheller and Mladenoff 2004). We chose a 1-ha cell resolution, with each of the extensions operating at a 5-yr time step. Flatley and Fulé (2016) provide a detailed description of the model structure and calibration for the Kaibab Plateau study area (see Appendix A in Flatley and Fulé [2016] for LANDIS-II input parameters).

Fire disturbance.—We used the Dynamic Fire and Fuels System (DFFS) extension for LANDIS-II (v2.0; Sturtevant et al. 2009) to model fire disturbance. DFFS simulates fire occurrence and spread according to inputs of daily fire weather data, ignition rates, and fire duration distributions that vary by ecoregion. We collected daily fire weather data (ca. 1995–2013) for each ecoregion, including temperature, wind speed, wind direction, relative humidity, and precipitation, from seven Remote Automated Weather Stations (RAWS) located within or adjacent to the study area and available for download through the Western Regional Climate Center (available online).[6]

We calibrated the parameters for the historical fire regime, used during the initialization period prior to the future change scenarios, according to historical mean fire intervals from local tree ring reconstructions of fire history. We modeled the baseline (no climate change) future fire regime according to mapped fire perimeters within GCNP from 1990 to 2011. We removed all prescribed fires from this list, then grouped the fires according to the ecoregions in which they occurred. We then used the list of fires to calculate fire size parameters for each ecoregion. We iteratively adjusted the initial fire size parameters according to the results of calibration runs on the full landscape until mean fire size and fire rotations in each ecoregion approximated those

[6] http://www.raws.dri.edu.

calculated from the initial federal fire records. We then used fire durations provided in the DFFS output for each fire to create fire duration distributions for each of the calibrated fire regimes. The use of a fire duration rather than fire size to parameterize the fire regime allows fire sizes to respond to future changes in fire weather resulting from climate change. For example, climate change influences on fire weather may increase the rate of fire spread, allowing a fire to burn more area during the same fire duration period.

We simulated fire regime response to future climate change by adjusting daily fire weather data according to projected shifts in temperature and precipitation for each climate scenario (RCP 4.5 and RCP 8.5) and each time step for which projections were available (2030, 2060, and 2090). We added projected temperature increases directly to daily temperature values and multiplied daily precipitation values by the projected percent change in annual precipitation. We adjusted daily relative humidity values according to increased temperature effects on atmospheric water vapor capacity but did not factor precipitation changes into relative humidity values. Precipitation changes were relatively minor under both climate change scenarios (1–6% percent change). Fire spread rates responded to fire weather changes, resulting in increases or decreases in area burned and fire severity. Fire severity is calculated according to fire spread rate, foliar moisture content, and the fuel type parameters of crown base height and surface fuel consumption (Sturtevant et al. 2009).

Restoration treatments.—We implemented restoration treatments (thinning and prescribed burns) with the Biomass Harvest extension. Restoration treatments were based on thinning and prescribed burn treatment prescriptions obtained from staff with the KNF and GCNP. In the low-mid elevation ecoregion, thinning treatments removed cohorts of all species except *Pinus ponderosa* and *Quercus gambelli*. *P. ponderosa* and *Q. gambelli* cohorts younger than 110 yr (i.e., cohorts that established after fire exclusion) had their biomass reduced by 80–95%. We implemented the prescribed burns in the Biomass Harvest extension, because the DFFS extension is designed to simulate a relatively stochastic wildfire regime. The Biomass Harvest extension enables the user to control the total area impacted and target individual stands as managers would with a prescribed fire. In the low-mid-elevation ecoregion, we implemented prescribed burns to remove cohorts of all species except *P. ponderosa* and *Q. gambelli*. We reduced ponderosa cohorts in biomass according to their age (1–10 [95% biomass removed]; 11–30 [80%]; 31–100 [50%]; 101–1,000 [10%]). *Q. gambelli* cohorts <100 yr old had their biomass reduced by 95%. In the high-mid-elevation, we only applied thinning and prescribed burning treatments to south and west-facing aspects. For thinning treatments, *Abies concolor*, *Pseudotsuga menziesii*, *P. ponderosa*, and *Q. gambelli* cohorts were retained, with biomass reductions matching those in the low-mid-elevation prescribed burns. Prescribed burns retained cohorts of these same species, with the same age related biomass reductions used for the low-mid-elevation prescribed burns. Following a thinning treatment or a prescribed burn, we assigned cells to the post-fire fuel type for the next 20 yr (Yocom 2013).

Vegetation model outputs.—LANDIS-II model runs produced raster maps of individual tree species biomass at 10-yr time steps which we then converted to maps of forest types and basal area for input into the hydrologic model. We created forest type maps with the Biomass Reclass extension, using individual tree species biomass to classify raster cells into the following forest types: spruce–fir (*Picea engelmannii*, *Abies lasiocarpa*, *Picea pungens*), aspen (*Populus tremuloides*), wet mixed conifer (*A. concolor*, *P. menziesii*, *P. engelmannii*, *A. lasiocarpa*, *P. pungens*), dry mixed conifer (*A. concolor*, *P. menziesii*, *P. ponderosa*), ponderosa pine (*P. ponderosa*), Gambel oak (*Q. gambelli*), pinyon–juniper (*Pinus edulis*, *Juniperus osteosperma*), and non-forest (no tree species biomass). Using previously collected, local plot data representing each of the modeled forests types, we developed relationships between individual species biomass and basal area (Fulé et al. 2002, 2003*a*, *b*, Huffman et al. 2008, 2009). We used allometric equations to calculate biomass by species for each plot in the data set (Chojnacky et al. 2014) and developed linear regressions relating plot level biomass to basal area for individual species. We used these regression equations to convert individual tree species biomass outputs from LANDIS-II to total basal area per cell.

The design of LANDIS-II around tree cohorts, rather than individual trees, presented a challenge in assessing the influence of forest structure on hydrologic output. The regression equations used to convert individual species biomass to basal area were robust (r^2 = 0.99–0.97). Yet, we recognize that a single basal area value could represent drastically different structures (e.g., many small diameter trees vs. a few large diameter trees). However, the basal area values were only used to estimate changes in runoff immediately following restoration treatments. Basal area removed during restoration treatments targeted younger cohorts. This would shift biomass and basal area towards older, larger cohorts, which should align well with the structural outcomes of treatments in the paired watershed experiments.

Hydrologic modeling approach

Rainfall–runoff equations.—We developed regression equations for the rainfall–runoff relationship in each of the major vegetation types on the Kaibab Plateau through a reanalysis of data from historic paired watershed studies conducted in Arizona in the 1950s–1980s. The existence of large historical data sets and lack of quality environmental forcing, calibration, and validation data for the site make a statistical modeling approach more appropriate than a process-based approach for surface hydrology on the Kaibab Plateau. Experimental logging treatments were performed on many of the watersheds (Baker 1999). We used pre-treatment and control watershed data to develop the rainfall–runoff relationships so that the relationships are representative of an undisturbed watershed. While the use of historical data does not account for the effects of fire suppression in the second half of the 20th century, an analysis of streamflow, climate, and forest cover from 1914 to 2012 found that the majority of streamflow declines attributable to fire suppression occurred between 1914 and 1963 (Robles et al. 2017). We normalized runoff by area to give units of depth and tested linear and quadratic rainfall–runoff functions for each ecoregion using

r^2 and root mean square error (rmse) to indicate the goodness of fit, and tested both winter (October–May) and total annual precipitation as explanatory variables. We included additional variables in the relationship and used an F test to determine if their coefficient values were significantly different from zero at the 95% confidence level. The additional variables tested included watershed size, slope and aspect, and mean, minimum, and maximum temperature both annually and during the winter. Precipitation was the only significant predictor of runoff. To test for model overfitting, we fit the equations to a random sample of 70% of the original data and tested for goodness of fit with the remaining 30% of the data. We examined model residuals for patterns of dispersion or bias. We conducted an independent validation of our model for runoff in undisturbed watersheds using data from two USGS gauging stations in the region with vegetation types similar to the Kaibab Plateau. We used gridded precipitation and vegetation data sets for model inputs. Modeled runoff provided a good fit ($r^2 > 0.83$) to measured data with no detectable bias. Full validation methods and results are presented in Appendix S1.

We determined the rainfall–runoff relationship for the high-elevation forest types, including wet mixed conifer, spruce–fir, and aspen, using data from the Thomas Creek and Willow Creek experimental watersheds on the Apache-Sitgreaves National Forest in east-central Arizona. The sites support a mix of wet mixed-conifer, spruce–fir, and aspen forest types. Willow Creek has one gauged watershed that ranges in elevation from 2,680 to 2,830 m, and mean annual precipitation is 863 mm (Gottfried 1983). Thomas Creek has one control and one treatment watershed that range in elevation from 2,545 to 2,819 m with an annual precipitation of 768 mm (Gottfried 1991). The two sources provide a total of 58 site-years of data and give a rainfall–runoff relationship of

$$R = 0.000338P^2 + 0.00959P - 2.16, P \geq 67\,\text{mm} \qquad r^2 = 0.85, \text{rmse} = 66.5 \tag{1}$$

where R is annual runoff and P is winter (October–April) precipitation, both expressed in mm.

We used data from the three gauged watersheds at Workman Creek Experimental Watershed to determine the rainfall–runoff relationship for the dry mixed conifer forest type. Workman Creek is located in dry mixed conifer forest in the Sierra Ancha Mountains approximately 100 km northeast of Phoenix at an elevation of 2,010–2,356 m with a mean annual precipitation of 835 mm (Rich and Gottfried 1976). The instrumentation consists of a main dam weir just below the confluence of the north, middle, and south forks of Workman Creek with weirs on the north and south forks just above the confluence that can be subtracted from the main dam flow to determine flow in the middle fork. Twenty-eight site-years of data are available and provide the relationship

$$R = 0.295P - 80.3, P \geq 272\,\text{mm} \qquad r^2 = 0.89, \text{rmse} = 26. \tag{2}$$

The Beaver Creek Experimental Watershed on the Coconino National Forest included 20 small, gauged catchments, six in the pinyon–juniper vegetation type and 14 in the ponderosa pine forest type. The catchments in the ponderosa pine type range in elevation from 2,054 to 2,225 m, and mean annual precipitation, measured by a network of gauges, ranges from 550 to 785 mm (Baker 1986). The pinyon–juniper catchments range in elevation from 1,580 to 1,950 m with mean annual precipitation of 304 to 685 mm (Clary et al. 1974). We developed the rainfall–runoff relationship for the ponderosa pine and oak forest types using data from ponderosa pine catchments at Beaver Creek and the Castle Creek Experimental Watershed in ponderosa pine forest in eastern Arizona. Castle Creek had a treatment and control pair of gauged watersheds at elevations of 2,390–2,600 m with a mean annual precipitation of 635 mm (Rich 1972). The 78 site-years of data for ponderosa pine give the following relationship:

$$R = 0.591P - 139.8, P \geq 236\,\text{mm} \qquad r^2 = 0.85, \text{rmse} = 52. \tag{3}$$

We used data from Corduroy Creek in eastern Arizona in addition to the pinyon–juniper catchments at Beaver Creek to develop a rainfall–runoff relationship for the vegetation type. Two branches of Corduroy Creek were gauged and range in elevation from 1,580 to 2,250 m with a mean annual precipitation of 508 mm (Collings and Myrick 1966). Based on 110 site-years of data, the rainfall–runoff relationship is

$$R = 0.000425P^2 - 9.46, P \geq 149\,\text{mm} \qquad r^2 = 0.82, \text{rmse} = 18.2. \tag{4}$$

While vegetation types characteristic of lower elevations than pinyon–juniper are not common on the Kaibab Plateau under current conditions, it is likely that non-forest vegetation types will become more common in the future due to climate change and fire. We developed a rainfall–runoff relationship to represent these vegetation types using data from two experimental watersheds in the chaparral vegetation type. The two gauged Whitespar watersheds near Prescott, Arizona, range between 1,770 and 2,135 m elevation and have a mean annual precipitation of 600 mm. The Three Bar experimental site on the Tonto National Forest includes three gauged watersheds ranging in elevation between 1,000 and 1,600 m with mean annual precipitation of 620 mm (Hibbert et al. 1982). The two sites provide 42 site-years of data and give the following rainfall–runoff relationship:

$$R = 0.000419P^2 - 0.241P + 30.714, P \geq 385\,\text{mm} \qquad r^2 = 0.83, \text{rmse} = 14.8. \tag{5}$$

To predict the baseline runoff (not accounting for the effects of restoration or fire) in a given cell of the vegetation model output, we input the precipitation for the climate scenario and year, determined as described in *Precipitation inputs*, into the equation for the forest type of the cell assigned by the vegetation model.

Equations for restoration impacts on runoff.—Forest thinning has been shown through numerous studies to increase runoff (Bosch and Hewlett 1982). To account for this, we developed forest type-specific multiple regression equations to describe the change in runoff over baseline levels due to restoration. We used data from paired watershed thinning experiments conducted at the same sites described in the previous section. Robles et al. (2014) developed the following equation for runoff increase due to restoration in ponderosa pine forest using 57 site-years of data from Beaver and Castle Creeks

$$\begin{aligned}\Delta R = &-28.464 + 0.148P - 0.015PY \\ &- 0.092P[\exp(-\mathrm{BA}_1/10.33) \\ &- \exp(-\mathrm{BA}_2/10.33)], \qquad (6)\\ P &\geq 230\,\mathrm{mm} \\ r^2 &= 0.67, \mathrm{rmse} = 25.4\end{aligned}$$

where ΔR is the increase in annual runoff attributed to forest thinning in mm, P is total winter precipitation (October–April) in mm, Y is years since treatment, BA_1 and BA_2 are basal area before and after treatment, respectively, in m^2/ha. No increase in runoff due to thinning is predicted in years with winter precipitation below 230 mm or more than 10 yr after the thinning.

There are several assumptions inherent in this modeling approach. First, the thinning treatment conducted in the historic paired watershed studies, such as strip thinning and patch clearing, reduced basal area by a similar amount but in a different spatial pattern than modern restoration treatments. Second, it does not directly model watershed processes such as evapotranspiration and snowmelt that influence runoff. A full discussion of the model assumptions and their potential impact on results can be found in Appendix S3 of Robles et al. (2014). Process-based modeling addresses these issues, but has data input requirements and computing requirements that make it impractical for coupling with the vegetation modeling in this study. Moreno et al. (2015) used a process-based ecohydrologic model to simulate the effects of the proposed Four Forest Restoration Initiative (4FRI) on the Tonto Creek watershed in Arizona and predicted a 1–4% increase in streamflow. Robles et al. (2014) also modeled the potential effects of 4FRI using the regression approach presented here (Eq. 6) and predicted a 2% increase in streamflow. In the absence of streamflow data from restored watersheds, the agreement between these models provides converging lines of evidence that the impact of restoration on streamflow is small and positive.

Following the approach used by Robles et al. (2014), we developed an equation for change in runoff due to restoration in mixed conifer forests. We tested equations for runoff increase in mixed conifer forests with data from wet and dry mixed conifer combined and separated. The equation for combined data provided a good fit to the data, so we used the same equation for runoff increase in wet and dry mixed conifer following thinning. We fit the following equation to 22 site-years of data from Thomas and Workman Creeks:

$$\begin{aligned}\Delta R = &-16.996 + 0.0967P \\ &P[\exp(-\mathrm{BA}_1/10.33) - \exp(-\mathrm{BA}_2/10.33)], \qquad (7)\\ r^2 &= 0.86, \mathrm{rmse} = 27.9.\end{aligned}$$

We found that time since treatment was not a significant predictor of runoff increase. At the Thomas and Workman Creek sites, which were monitored for 8 and 12 yr following thinning, respectively, increased runoff was observed in thinned catchments through the duration of the study period. However, caution should be taken in applying this equation to systems more than 12 yr past thinning and as a conservative estimate we do not apply it more than 10 yr after restoration in this study.

We calculated the basal area values before and after thinning from the vegetation model as described in *Vegetation model outputs.* To predict the runoff from a ponderosa pine or mixed conifer cell in the vegetation model output that was restored within the past 10 yr, we calculated the baseline runoff with Eq. 1, 2, or 3 and added the runoff increase, calculated with Eq. 6 or 7, to the baseline.

Precipitation inputs.—We based the precipitation inputs for the equations described in the previous sections on the distribution of precipitation in the historic record to represent the high inter-annual variability that is characteristic of precipitation in the southwestern United States. We assigned precipitation inputs to vegetation model cells based on ecoregion and kept them consistent throughout model runs. For example, if a cell in the low-mid-elevation ecoregion shifted from ponderosa pine to pinyon–juniper, runoff would be calculated with the equation for pinyon–juniper (Eq. 4) and the precipitation input for the low-mid-elevation ecoregion. We used maximum likelihood estimation to fit a lognormal distribution to annual winter (October–May) precipitation data recorded at the historic paired watershed sites described in the previous sections that are representative of each ecoregion: Thomas Creek and Willow Creek for the high-elevation ecoregion, Workman Creek for the high-mid-elevation ecoregion, Beaver Creek and Castle Creek for the low-mid-elevation ecoregion, and Beaver Creek and Corduroy Creek for the low-elevation ecoregion. The two parameters of the lognormal distribution, log mean (μ) and log standard deviation (σ), for each of the ecoregions are given in Table 2. In each model run, we calculated precipitation corresponding to a given annual percentile, such as the 50th percentile to represent a median year or the 10th percentile to represent a 10-yr drought, using the cumulative distribution function of the lognormal distribution for input into the runoff equations.

We conducted runoff modeling with and without considering the effect of climate change on precipitation. This makes it possible to separate the direct effect of climate change on runoff via altered precipitation and the indirect effects of changing vegetation. The ensemble model predictions for the RCP 4.5 and 8.5 scenarios are not consistent in

Table 2. Parameters of the lognormal distribution, log mean (μ) and log standard deviation (σ), for winter (October–May) precipitation in each ecoregion and the number of site years (N) used to fit the distribution.

Ecoregion	μ	σ	N
High	6.322	0.537	52
High-mid	6.177	0.459	26
Low-mid	6.046	0.473	255
Low	5.551	0.416	69

Table 3. Change in winter precipitation (October–May) over 1990 baseline predicted by the ensemble model average under the RCP 4.5 and RCP 8.5 scenarios for the ecoregions in the study area.

	Change in winter precipitation (mm)					
	RCP 4.5			RCP 8.5		
Ecoregion	2030	2060	2090	2030	2060	2090
High	−6.7	−17.6	−16.3	0.9	−12.8	7.1
High-mid	−5.9	−15.7	−14.7	0.3	−11.5	6.4
Low-mid	−4.0	−11.7	−11.2	−0.5	−8.8	4.8
Low	−2.5	−8.0	−7.8	−0.7	−6.4	2.8

Notes: Values are an average of northeast- and southwest-facing aspects. Negative values indicate a decrease in precipitation.

their predicted trajectories for winter precipitation in the study area ecoregions (Table 3). Under the RCP 4.5 scenario, a gradual decrease in winter precipitation that stabilizes after 2060 is predicted. Very little change is predicted before 2030 for the RCP 8.5 scenario followed by a decrease up to 2060. A sharp increase between 2060 and 2090 results in 2090 values above the 1990 baseline. In cases where climate change is included in the runoff modeling, we adjusted the parameters of the lognormal distribution such that the mean of the distribution increases or decreases by the predicted change from the 1990 baseline and we do not change the standard deviation of the distribution.

Effects of fire on runoff.—High-intensity wildfire has a substantial effect on the hydrologic cycle. A number of gauged catchments in Arizona have experienced large wildfires and the records from these events suggest short-term increases in runoff (Hallema et al. 2017). Moderate to severe wildfires are also associated with substantial reductions in water quality due to increased sediment mobilization (Campbell et al. 1977, Malmon et al. 2007), so it is unlikely that runoff increases from wildfire would be beneficial to habitat or suitable for human use. Therefore, we do not model wildfire-related changes in runoff in this study. We conducted an assessment of water quality vulnerability to wildfire as described in the following section.

Sediment yield vulnerability assessment

Pelletier and Orem (2014) assessed wildfire effects on sediment yield using airborne LIDAR measurements before and one year after a major wildfire in a region of New Mexico with the same vegetation types as the Kaibab Plateau. Slope and burn severity were the main determinants of sediment yield and the following relationship was determined for sediment yield (normalized by contributing area) over contributing areas >0.1 ha:

$$Y(S,B) = 1.53 S^{1.6} B^{1.7} \quad (8)$$

where Y is sediment yield (mm), S is slope (per mm), and B is equal to 1, 2, or 3 to represent the U.S. Forest Service's Burned Area Reflectance Classification (BARC) low, moderate, and high burn severities, respectively.

We applied the relationship from Pelletier and Orem (2014) to the Kaibab Plateau to identify areas that are vulnerable to water quality reductions due to wildfire. It should be noted that actual sediment yield following a wildfire depends on the frequency and intensity of rain events. Thus, the sediment yield calculations should be treated as relative values used to quantify vulnerability. We converted the burn severity estimates produced by LANDIS-II to the BARC scale as follows: (1) LANDIS-II outputs of 3 are BARC low severity, (2) LANDIS-II outputs of 4 and 5 are BARC moderate severity, and (3) LANDIS-II output 6 and 7 are BARC high severity. We calculated slope for each 1 ha vegetation model cell from the USGS National Elevation Dataset 2013 1/3 arc-second product using the ArcMap 10.3.1 Spatial Analyst Package (ESRI, Redlands, California, USA).

To quantify the impacts of stochastic fire occurrence in the LANDIS-II outputs, we calculated an expected value of annual sediment yield for each 1 ha vegetation model cell

$$\begin{aligned} E[Y_n] = {} & P_n(1) \cdot Y(S_n,1) + P_n(2) \cdot Y(S_n,2) \\ & + P_n(3) \cdot Y(S_n,3) \end{aligned} \quad (9)$$

where $E[\,\cdot\,]$ is the expected value operator; Y_n is sediment yield from the nth model cell; $P_n(1)$, $P_n(2)$, and $P_n(3)$ are the annual probability of low-, moderate-, and high-severity fire, respectively, in the nth model cell; and S_n is the slope of the nth model cell. We calculated the fire probabilities using the LANDIS-II outputs

$$P_n(B) = \frac{1}{N}\sum_{i=1}^{N}\frac{F_{B,n,i}}{L} \quad (10)$$

where N is the number of model runs, $F_{B,n,i}$ is the number of fires of severity B that occur in the nth model cell during the ith model run, and L is the length of a model run. We calculated sediment yield for the 10 model runs for the period of 1990–2060.

Results

Fire and forest modeling

Restoration treatments greatly reduced future wildfire impacts on the Kaibab Plateau under all climate scenarios. Restoration treatments decreased area burned in wildfires, with the high restoration rate nearly tripling the mean wildfire rotation (Table 4). Similarly, mean area burned in high-severity fires was greatly reduced in response to restoration treatments under all climate scenarios (Table 5). The influence of climate change on the fire regime was less pronounced, with only minor changes in fire rotation and high-severity area burned under the different climate scenarios.

Climate change resulted in marked declines in aboveground biomass (AGB). For all scenarios, mean AGB was high in 1990 due to the effects of fire exclusion during the 20th century (Fig. 1). Under the no climate change scenarios, wildfires and restoration treatments reduced biomass steadily during the 21st century to levels that approximated the historic mean exhibited during the frequent fire period. Climate change drove steeper declines in biomass beginning in the year 2030, resulting in considerable reductions in

Table 4. Wildfire rotation in years for Kaibab Plateau from 2010 to 2110 under potential future climate conditions and restoration rates.

Climate condition	Restoration rate: No restoration	Low restoration	High restoration
No change	45.5 (3.7)	56.4 (6.2)	123.7 (11.7)
RCP 4.5	48.1 (3.6)	63.7 (6.1)	130.8 (16.6)
RCP 8.5	41.0 (3.5)	53.3 (5.4)	127.8 (15.1)

Note: Values are means with SD in parentheses.

Table 5. High-severity area burned in thousands of hectares for Kaibab Plateau from 2010 to 2110 for potential future climate conditions and restoration rates.

Climate condition	Restoration rate: No restoration	Low restoration	High restoration
No change	289.0 (25.4)	207.2 (32.9)	51.6 (16.0)
RCP 4.5	229.0 (30.5)	155.2 (28.4)	45.7 (22.4)
RCP 8.5	275.1 (34.1)	187.9 (28.6)	46.8 (17.8)

Notes: Values are means with SD in parentheses. High-severity fires were fires of severity 4–5 on a scale of 1 (low-severity, surface fire) to 5 (high-severity, stand-replacing fire).

biomass by the end of the century (approximately 43–58% reduction from the historical mean). Biomass totals at the end of the climate change scenarios in 2110 were similar regardless of restoration. However, the restoration treatments did preserve biomass during the middle years of the simulation. The positive influence of restoration treatments on biomass decline was most apparent in the high climate change scenario.

The percent cover of different forests types also shifted in response to climate change (Fig. 2). Higher elevation spruce–fir, wet mixed conifer, and aspen declined under the two climate change scenarios. The high restoration scenario was most effective in retaining a higher percentage of the landscape in spruce–fir, mixed conifer, and aspen forest cover (13.5%; 13.6%) compared to low restoration (6.5%; 5.5%) and no restoration (3.8%, 3.3%), for the RCP 4.5 and RCP 8.5 climate scenarios, respectively. Non-forest area consistently increased in response to climate change. The application of restoration treatments limited this trend, with the high treatment rate most effectively reducing increases in non-forest area under both climate change scenarios.

Hydrologic modeling

In the absence of restoration, runoff in a year with median precipitation is expected to decrease by 2100 in the study area by 0.5%, 1.3%, and 10.0% for the no climate change, RCP 4.5, and RCP 8.5 scenarios, respectively, (Fig. 3) due solely to shifts in vegetation type (i.e., precipitation inputs to the hydrologic model were not adjusted to account for climate change). Restoration ameliorated the effects of runoff change due to vegetation shifts across the climate scenarios

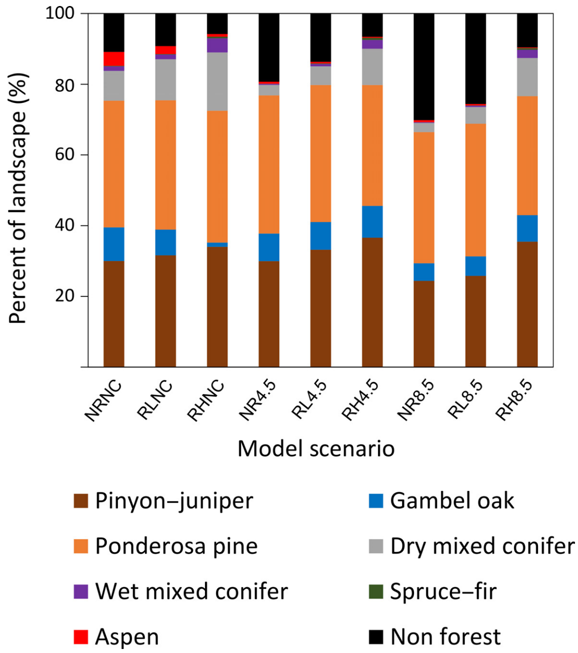

Fig. 2. Bar plot of the percentage of the study landscape in different forest types in the year 2110 under modeled climate conditions and restoration approaches (NR, no restoration; RL, low restoration; RH, high restoration; NC, no climate change; 4.5, RCP 4.5; 8.5, RCP 8.5).

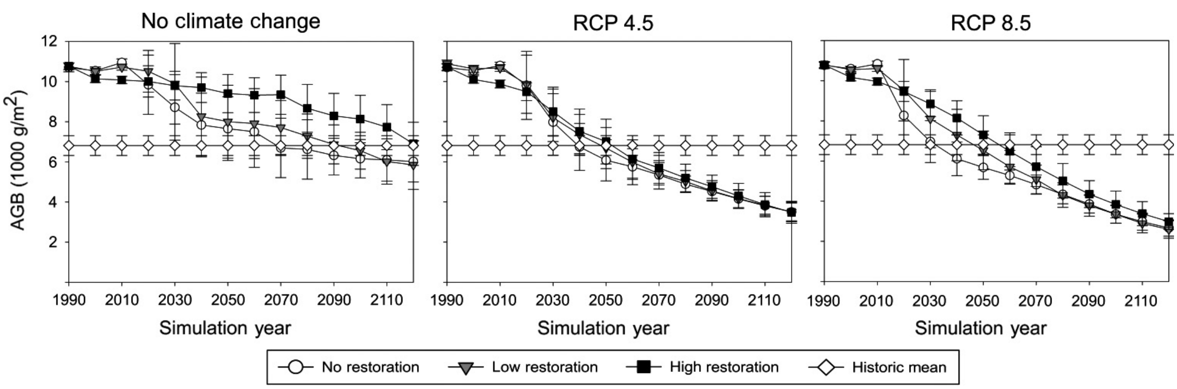

Fig. 1. Aboveground live biomass (AGB) for the Kaibab Plateau, Arizona, USA, from 1990 to 2110 under modeled future climate conditions and restoration rates. Values are mean ± SD across model runs.

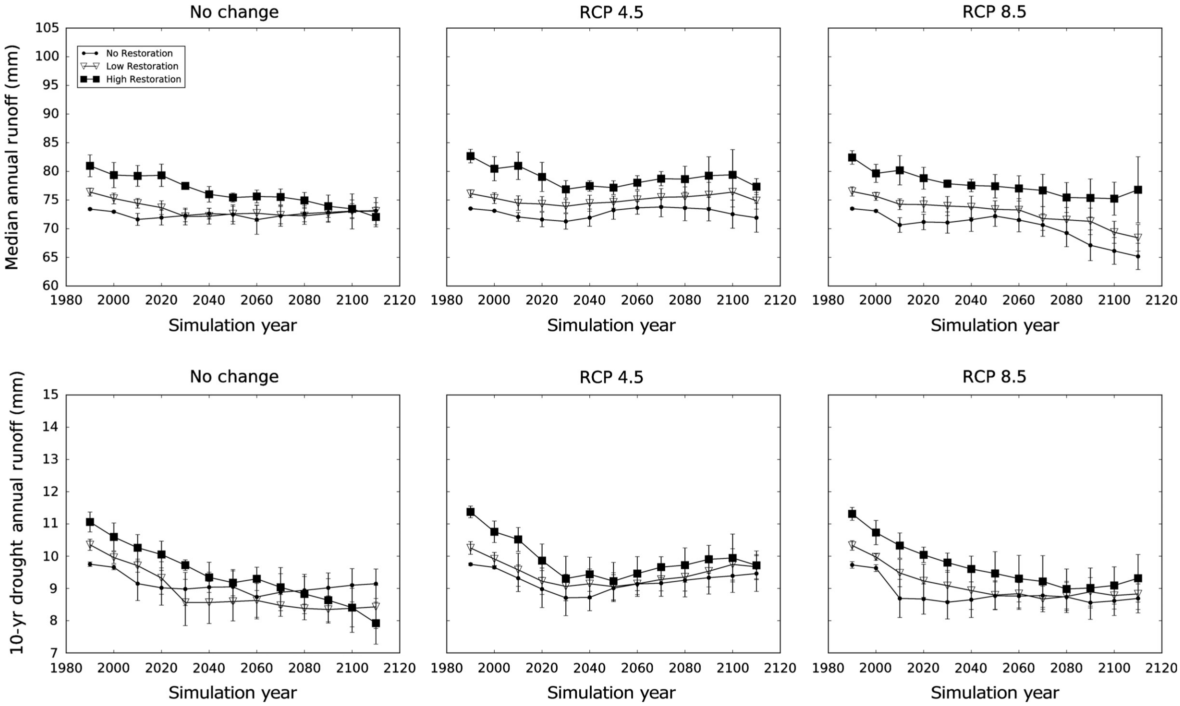

FIG. 3. Predicted total runoff from the study area, normalized by area, from 1990 to 2110 under future vegetation distributions and restoration rates. Precipitation inputs are not adjusted to account for the effects of climate change. The top row of panels shows runoff for a median (50th percentile) annual precipitation and the bottom row of panels shows runoff for a 10-yr drought (10th percentile) annual precipitation scenario. Values are means ± SD across model runs.

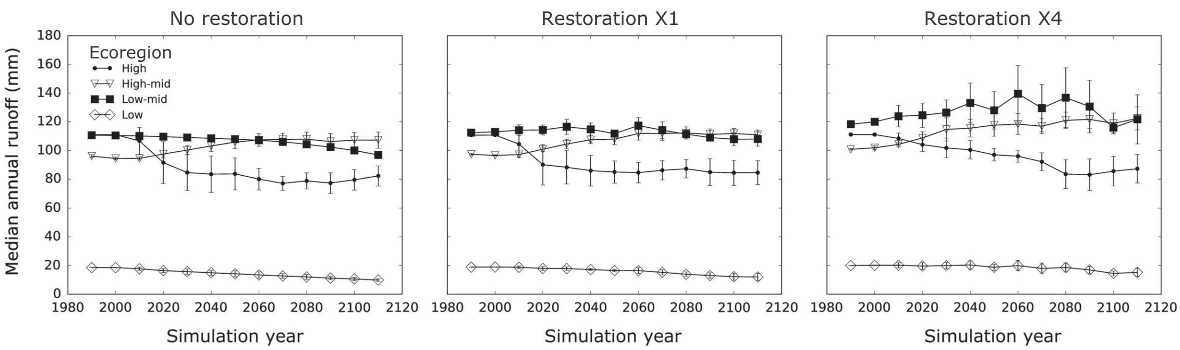

FIG. 4. Predicted runoff from each ecoregion, normalized by the area of the ecoregion, from 1990 to 2110 under the RCP 8.5 climate scenario and varying restoration rates. Precipitation inputs are not adjusted to account for the effects of climate change. Runoff is given for a median (50th percentile) annual precipitation. Values are means ± SD across model runs.

and is even expected to result in small increases (<5%) in some cases. Under drought conditions, runoff is consistently low across scenarios and is expected to decline across all climate change scenarios despite restoration treatments.

Runoff normalized by area is much higher for the forested ecoregions than for the low-elevation ecoregion that is mostly pinyon–juniper (Fig. 4). The decline in spruce–fir and wet mixed conifer forest types (Fig. 2) drives a decline in runoff in the high-elevation ecoregion by mid-century. Runoff from the high-mid-elevation ecoregion is more reliable as dry mixed conifer forests are maintained or transition to ponderosa, which has minimal consequences for runoff. Runoff from the low-elevation ecoregion declines in the RCP 4.5 and 8.5 scenarios because most low-elevation ponderosa transitions to pinyon–juniper and some pinyon–juniper transitions to non-forest. Both transitions have negative consequences for runoff.

The model estimates that under contemporary conditions, the high-mid- and low-mid-elevation ecoregions generate 81% of total runoff on the Kaibab Plateau in a median precipitation year. Though the low-elevation ecoregion is the largest by area (36% of the study area) it only contributes 9% of the total runoff from the Kaibab Plateau. The decline in runoff from high-elevation forests is driven by an increase in the frequency of years with low runoff years and a decrease in the frequency of years with moderate runoff (Fig. 5). However, years with high runoff do occur even in future scenarios under climate change.

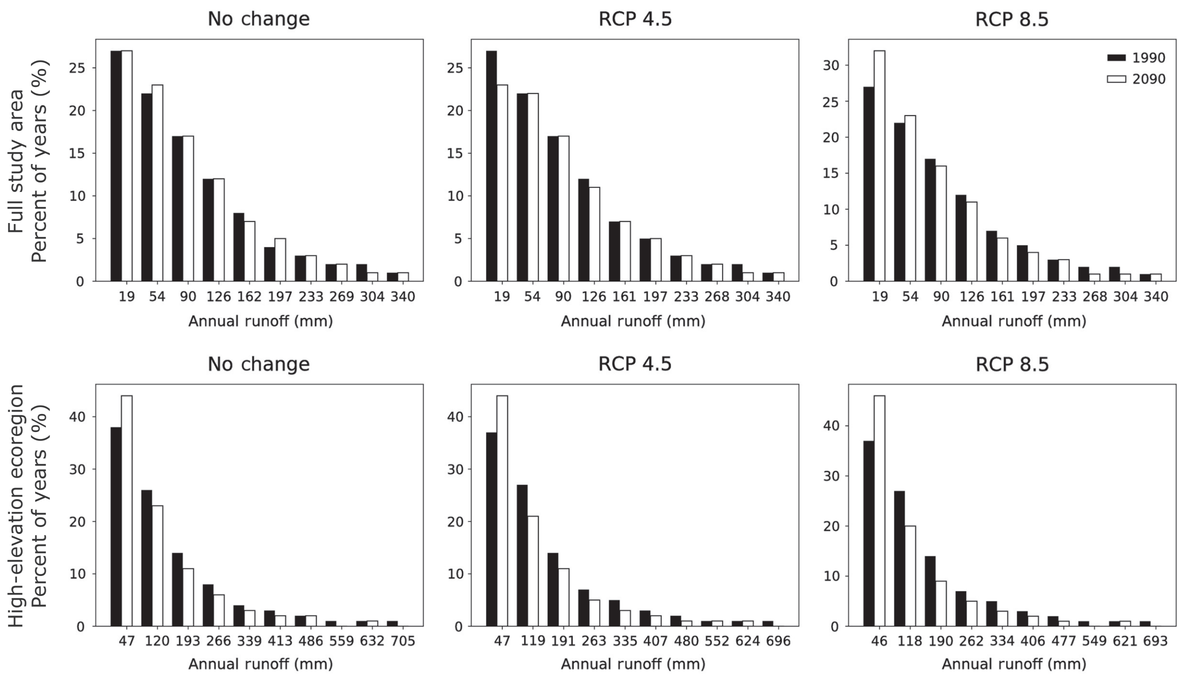

Fig. 5. Distribution of annual runoff values as the percentage of years falling in a bin centered on the given value in 1990 and 2060 under future vegetation distributions in the absence of restoration. The top panel shows averages for the entire study area and bottom panels show average values for the high-elevation ecoregion. Precipitation inputs are adjusted to account for the effects of climate change.

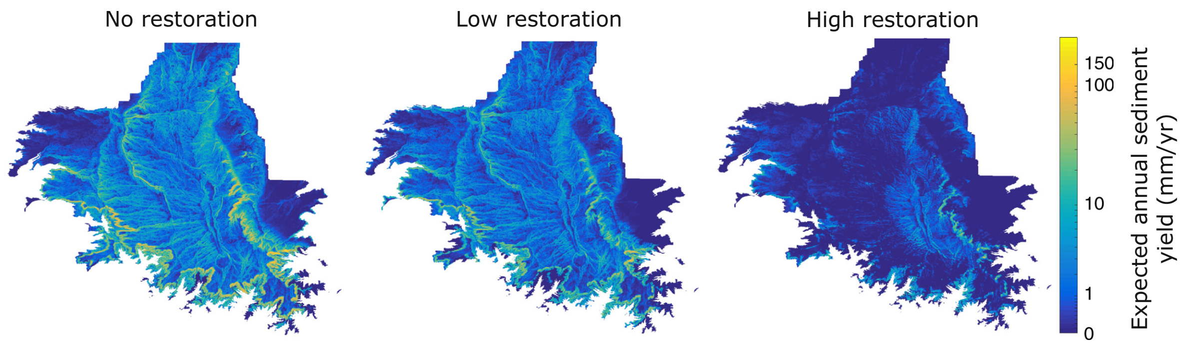

Fig. 6. Expected value of annual sediment yield between 1990 and 2060 modeled at a 1-ha scale using the annual probability of low-, moderate-, and high-severity wildfire predicted by Climate-FVS and LANDIS; slope; and the relationship between burn severity, slope, and sediment yield developed by Pelletier and Orem (2014).

Sediment yield vulnerability

Expected annual sediment yield was highest in the high-slope areas around the canyon rim and at mid elevations where fire severity was highest (Fig. 6). Sediment yield was reduced in the restoration scenarios, particularly in the mid-elevation ecoregions where most thinning activity was concentrated. Across all restoration scenarios, the low-elevation ecoregion had the highest per area sediment yield (Fig. 7). Restoration was most effective at reducing sediment yield in the low-mid- and high-mid-elevation ecoregions, where restoration treatments were applied, which had a 94% and 85% reduction, respectively, for the high restoration scenario. Even though restoration treatments were not applied in the high- and low-elevation ecoregions, there was a reduction in sediment yield of around 56% and 85%, respectively, in the high restoration scenario.

Discussion

Fire regimes and forest vegetation

Climate change drove declines in AGB and shifts in forest composition; particularly the loss of higher-elevation mixed conifer, aspen, and spruce–fir forest types. In our model, forest change was primarily driven by two processes: (1) wildfire driven mortality and (2) tree regeneration failure. High-severity fire initiates change by removing AGB and necessitating forest recovery through regeneration. Under contemporary climate conditions the forest recovers relatively quickly as adjacent, unburned forests provide viable propagules that enable regeneration, biomass recovery, and compositional stability. In the case of very large patches of high-severity fire, LANDIS-II simulated regeneration delays due to the dispersal limitations of individual species propagules. However, our

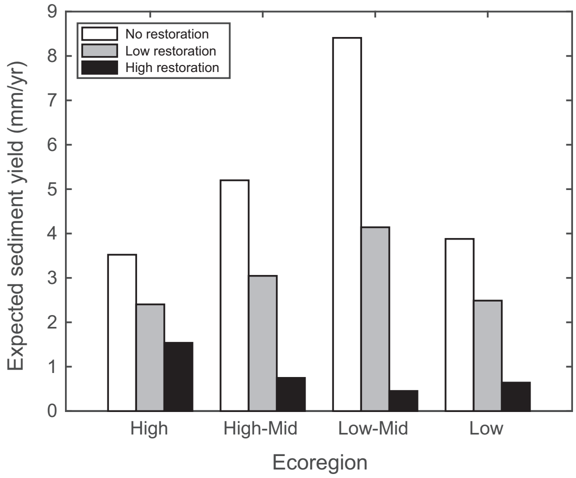

Fig. 7. Average expected annual sediment yield between 1990 and 2060 by ecoregion and restoration scenario.

implementation of LANDIS-II did not incorporate changes in soil conditions or competition with herbaceous vegetation, which can result in longer term regeneration failure following high-severity fire in southwestern forests under contemporary climate (Savage and Mast 2005, Roccaforte et al. 2012). In the climate change scenarios, the regeneration probability of adjacent species approaches zero by the middle of this century, resulting in regeneration failure and driving compositional changes. Fire disturbed sites may remain unforested for long periods until viable lower-elevation species become available for colonization through uphill migration.

Biomass declines and compositional change were greater in our study compared to recent LANDIS-II simulations of climate change in the Sierra Nevada Mountains of California (Liang et al. 2016). This may be partly due to differences in the tree species–climate relationships that drive regeneration in each study: Climate-FVS (Crookston et al. 2010) vs. Century Succession extension (Scheller et al. 2011). However, the Kaibab Plateau may be particularly vulnerable to climate induced vegetation change. The upper elevations of the plateau represent the lower end of the mesic conifer climate niche in the southwestern United States. The Kaibab Plateau does not provide cooler, higher-elevation habitat where these species might be less vulnerable to climate change. Our results are similar to other bioclimatic models that project the decline of *P. engelmannii* and *P. menziesii* on the Kaibab Plateau (Notaro et al. 2012, Truettner 2013, Rehfeldt et al. 2014). The Sierra Nevada Mountains or the more southerly Pinaleño Mountains in Arizona and Sangre de Cristo Mountains in New Mexico may provide higher-elevation habitat that supports greater retention or uphill migration of spruce–fir, mixed conifer, and aspen.

Restoration treatments, through their effects on the fire regime, mediated climate-driven changes in vegetation. Previous empirical and modeling studies have shown that landscape scale restoration can have a significant impact on area burned and fire severity in southwestern forests (Finney et al. 2005, Fulé et al. 2012, Hurteau 2017). In our simulations, restoration treatments effectively reduced area burned regardless of climate scenario. Indeed the climate condition had limited influence on the fire regime, suggesting that in our model fire was driven more by fuel condition, rather than fire weather. Reductions in high-severity area burned due to the restoration treatments reduced turnover of high-elevation forest types and reduced non-forest area. While the loss of climate conditions conducive to the regeneration of mesic conifers and aspen indicates that they will eventually be lost from the plateau (Flatley and Fulé 2016), in the absence of stand replacing disturbances, tree longevity enables overstory forest vegetation change to lag behind climate change (Svenning and Sandel 2013). Therefore wildfire, in addition to insect, disease, and drought mortality, will modify the timing of forest turnover and consequent climate-induced vegetation change. Our models suggest that forest restoration can delay vegetation change, reducing the steepness of biomass declines and providing opportunities for uphill movement of lower-elevation species.

The hydrologic modeling suggests that a decrease in total runoff from the Kaibab Plateau of up to 10% could be possible without restoration. Even though conservative assumptions were used with regards to runoff increases, restoration resulted in small increases in runoff in most cases. The increases were not large enough to plan for increased runoff following restoration. This is consistent with results from other landscape-scale modeling studies of restoration impacts on hydrology (Robles et al. 2014, Moreno et al. 2015). However, larger decreases in runoff are expected for areas in the high- and low-elevation ecoregions under all scenarios, though the declines are greatest without restoration. This poses a particular concern for a karst system such as the Kaibab Plateau, because the source area of a spring may be localized within one ecoregion. Flow reductions at high elevation are of greater concern for springs, because sinkhole density is positively correlated with elevation and with geologic structure (Jones et al. 2017). Flow in Roaring Spring, the water supply for GCNP, is a combination of rapid flow through conduits in the Karst geology and slow flow through a low-permeability matrix. Rapid flow travels 2,000 m vertically and over 40 km horizontally in less than six weeks (Jones et al. 2017). Because the water from rapid flow is so young, increases in sediment yield on the Kaibab Plateau are likely to increase turbidity in Roaring Spring.

The model results for the high-elevation ecoregion should be interpreted cautiously. Data on rainfall–runoff relationships for non-forested areas, which account for a significant portion of the ecoregion by the end of the simulation, are limited in high-elevation regions, so we applied a relationship for non-forested areas at lower elevations. Historical studies showing runoff increases following clearcutting (Baker 1986) suggest that runoff may increase following forest canopy loss due to successional changes, which is opposite of what is predicted by our modeling framework. Data from high-elevation forests in Wyoming affected by Mountain Pine Beetle found that runoff decreased substantially relative to a control site when forest canopy was lost (Biederman et al. 2014), and a broader analysis of sites affected by tree die-off found no change or a decrease in runoff (Biederman et al. 2015). This suggests that forest loss due to die-off and successional change, which is what we predict will happen on the Kaibab Plateau, has a fundamentally different impact on the hydrologic cycle than logging.

Restoration was highly effective in reducing the vulnerability of the entire study area to sediment yield following wildfire. Restoration treatments impacted sediment yield most clearly in the mid-elevation zones where treatments were carried out. However, it also reduced sediment yield in the more vulnerable low- and high-elevation ecoregions, presumably by reducing the likelihood of high-severity fire spreading into these untreated forest types. The impact of restoration on sediment yield was much greater than the impact on runoff, suggesting that the primary hydrologic benefit of restoration projects is to reduce the vulnerability of the water supply to increased turbidity following wildfire.

Conclusions

Our results indicated that a high restoration rate (20-yr prescribed burning rotation) was the most beneficial in terms of reducing high-severity fire, slowing forest composition change, maintaining runoff, and reducing sediment yield. The lower restoration rate (80-yr prescribed burning rotation) provided some positive benefits, which supports the implementation of more limited restoration projects, when funding for more extensive or frequent treatments is not feasible. Prescribed burning rotations shorter than 20 yr may be inadvisable, driving more rapid declines of contemporary forests and preventing uphill migration of species adapted to the new climate regime (Diggins et al. 2010, Flatley and Fulé 2016). High-elevation forests were most vulnerable to reductions in water yield due to climate change. Consistent with other landscape-scale studies, restoration resulted in only small increases in runoff but was effective in minimizing reductions in runoff due to climate change. Our simulations indicate that restoration is an effective tool for preventing erosion and water quality issues associated with high-severity wildfire.

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1746/full

LANDSCAPE RESTORATION STRATEGY FOR THE FIRST ANALYSIS AREA

REPORT

FROM THE FOUR FOREST RESTORATION INITIATIVE STAKEHOLDER GROUP TO THE USFS 4FRI PLANNING TEAM

OCTOBER 1, 2010

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The October 1st, 2010, version of the Four Forest Restoration Initiative Landscape Strategy document is intended to be a first draft product to assist the Forest Service as it moves closer to developing a proposed action in late 2010. The 4FRI stakeholder group fully intends that this document will be meaningfully considered and integrated within the 4FRI NEPA process. Equally importantly, however, the 4FRI stakeholder group considers this document to be a starting set of recommendations to be substantially built upon throughout the NEPA process. The stakeholder group intends to build out the Landscape Strategy and provide more explicit guidance, including that outlined in Recommendation 4 of this document. The group intends that its work will be closely coordinated with the Forest Service, such that recommendations can be meaningfully integrated throughout the NEPA process.

Contents

I. EXECUTIVE SUMMARY

The 4FRI landscape restoration strategy is a planning effort designed to develop a comprehensive, ponderosa pine forest restoration strategy for a 2.4 million acre assessment area. To achieve desired outcomes, the 4FRI Stakeholder Group, in cooperation with the U.S. Forest Service (USFS), is preparing a 4FRI Landscape Restoration Strategy (FLRS) to contribute information, analysis outputs, and guidance for forest restoration implementation planning at the programmatic and project levels.

In order to fulfill a collective desire to conduct landscape level forest restoration, a group of stakeholders and the USFS created the Four Forest Restoration Initiative (4FRI) to address ponderosa pine forest restoration across 2.4 million acres on four National Forests in northern Arizona: the Apache-Sitgreaves, Coconino, Kaibab, and Tonto National Forests. The Landscape Strategy Working Group (LSWG), a sub-group of the 4FRI Stakeholder Group, was tasked to work with an integrated USFS team of specialists, the USFS 4FRI Team to develop a comprehensive restoration strategy for the entire 4FRI area. Specifically, by October 1, 2010, the USFS requested information regarding existing conditions, identification and prioritization of treatment areas, descriptions of desired post-treatment conditions, ranges of treatment types, best management practices/sideboards, and a monitoring framework. This information is needed in order to provide recommendations to the USFS as they develop a proposed action under the National Environmental Policy Act (NEPA) for the first restoration analysis area. Additional time is required for the collaborative group to complete the comprehensive landscape strategy.

To develop a landscape strategy for locating forest restoration treatment areas, the LSWG developed a "Firescape" approach. We identified firescapes as sub-landscapes within the analysis area where treatments were further defined and mechanical thinning and prescribed fire treatments could be applied to implement forest restoration. We used spatial data layers the LSWG developed which identified candidate treatment areas within the ponderosa pine forest type most likely available for mechanical thinning treatments. Areas defined as "excluded" have low-potential for receiving mechanical thinning treatments. These areas may still benefit from forest restoration activities, and may be identified for treatment during site-specific restoration planning. These techniques were applied to the first analysis area to provide a set of recommendations that can aid the USFS 4FRI Team with development of proposed forest restoration actions. This document provides a proof-of-concept for using a systematic approach to stratify a large analysis area into strategic areas for treatment area identification and description of existing and desired conditions within the first analysis area on Coconino and Kaibab National Forest System Lands. From this process, six working group recommendations were developed which specified how forest restoration could be strategically applied within the 4FRI landscape.

1. Three scales at which landscape-level forest restoration planning should be conducted.
2. A process for identifying and delineating firescapes and treatment areas
3. A set of desired conditions for ponderosa pine restoration at three scales
4. A desired context within which to proceed with collaborative planning
5. A monitoring framework from which to implement adaptive management
6. A request that the USFS work with the 4FRI stakeholders to identify and use appropriate decision support and forest modeling tools

The Science and Monitoring Working Group (SMWG) developed the monitoring framework and will deliver this document to the USFS under separate cover. The 4FRI stakeholder group is continuing to develop ranges of treatment types, best management practices/sideboards, prioritized monitoring indicators, and address outstanding issues within the collaborative. This information will be included in the comprehensive landscape strategy to be delivered to the USFS.

Implementation of the 4FRI should be ecologically and economically sustainable. Although these two distinct goals can be at odds, the 4FRI stakeholders believe they can work together to accomplish landscape-scale forest restoration in northern Arizona. Through the utilization of restoration byproducts by appropriately scaled industry, 4FRI aspires to implement ecologically sustainable restoration treatments in an economically sustainable manner.

Wood utilization provides one approach to offset treatment costs. However, the current state of the economy and the volatility of wood products markets suggest that we should consider other means to offset treatment costs as well. In addition to relying on industry investment, other funding possibilities include the monetization of ecosystem services, development of cost-share agreements, and if necessary, direct financing of treatment activities.

The Economic and Utilization analysis of the landscape strategy identifies issues and solutions to the barriers that undermine wood utilization. It also examines policy changes that may be required for stewardship contracting. Finally, it explores the desired and emerging opportunities to capture the value of ecosystem services so that they can be used to support ecological restoration. A fuller discussion can be found in Appendix A.

II. STUDY AREA DESCRIPTION

The first analysis area of the 4 Forest Restoration Initiative lies primarily within the "Western Mogollon Plateau" forested landscape outlined in the *Statewide Strategy for Restoring Arizona's Forests.* Located in north-central Arizona, between the Grand Canyon and Mogollon Rim, this area encompasses numerous communities including those of Flagstaff, Williams, Payson, and Strawberry. US Forest Service (USFS) lands dominate the area of ponderosa pine with private, state and military lands interspersed. All of the Coconino and two-thirds of the Kaibab national forests with Williams and Tusayan ranger districts are represented in this first EIS area. Elevation ranges from 935-3800 meters where areas above 1400 meters are dominated by overstory vegetation comprised of ponderosa pine and adjacent mixed conifer at higher elevations and pinyon-juniper woodlands at lower elevations, with diverse and abundant grass and forb community understory. Large areas of small, dense thickets of ponderosa pine are a common condition responding to

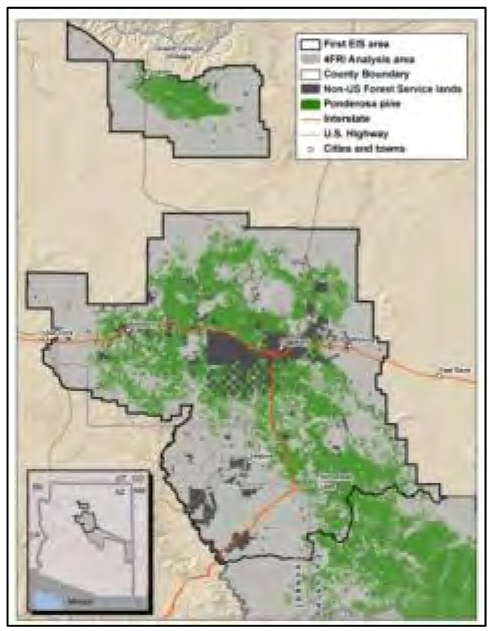

Figure 1. Study area and geographic location for the first 4FRI Analysis Area.

land management practices of fire suppression for many years in the southwest. From 2000-2010 56 wildfires greater than 100 acres have occurred with one of the largest in Coconino National Forest history in 2010 of over 15,000 acres.

III. EXISTING PONDEROSA PINE FOREST CONDITIONS

Knowledge of existing ecological conditions within southwestern ponderosa pine (*Pinus ponderosa*) forest is needed as a basis for land management planning, decision-making and identifying steps toward desired conditions. Ponderosa pine forests in northern Arizona have shifted from naturally open conditions to high densities of small diameter trees in the last century (Covington and Moore 1994), dramatically increasing the size and severity of wildland fires (Swetnam and Betancourt 1998). These circumstances represent a loss of ecosystem services such as biodiversity and watershed health, climate change mitigation, and recreation and scenic values that are tied to Arizona's economy and quality of life.

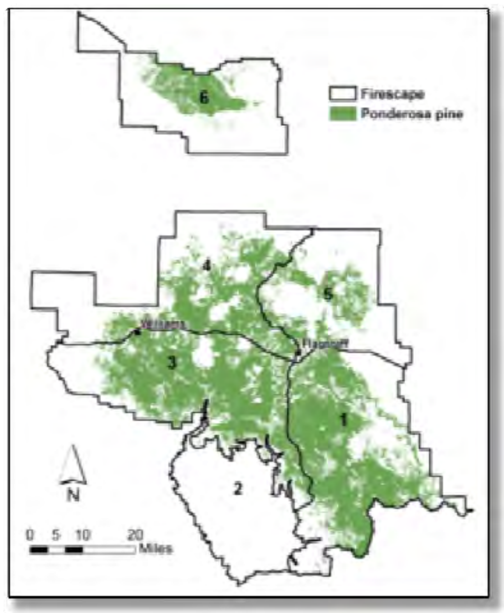

Figure 2. Six firescapes delineated within the first 4FRI EIS area.

For this assessment, we synthesized data and information at multiple spatial scales to identify restoration strategies that can reduce high fire hazard and maintain or enhance ecosystem values. Existing ponderosa pine landscape conditions were described according to forest structure, composition, potential fire behavior and focal wildlife species habitat such as the Mexican spotted owl (*Strix occidentalis lucida*). Available forest inventories and geospatial information were combined to estimate forest conditions and provide landscape planning and forest restoration recommendations to the USFS.

We assessed existing conditions for the first analysis area within the 4FRI area at three separate spatial scales (**Table 1**). The analysis area scale comprised the full spatial extent of the ponderosa pine type within the first analysis area (**Figure 1**). Outlined below is the approach used to map and analyze "firescapes" as strategic locations for landscape planning and implementing ponderosa pine restoration treatment within the first analysis area. A firescape scale was used to subdivide the analysis area into geographic areas where forest treatments can be implemented in a step-wise fashion to restore fire adapted conditions. Analyses at the smallest spatial extent used 6th code watersheds that were aggregated according to similar ecological[1] values and risks posed by extreme wildland fire danger. To inform the development of a Proposed Action, an analytical process was used to map "treatment areas" within firescapes and describe current and desired conditions in section VII of this report. Treatment areas were defined as forest which contain 5,000 to 50,000 acres of ponderosa pine that can potentially be treated with mechanical thinning and prescribe burning.

Table 1. Three spatial scales at which existing ponderosa pine forest conditions were described.

Analysis scale	Extent (acres)	Definition
Analysis Area	~875,000	First NEPA analysis area
Firescape	≥200,000	Firescapes w/in 1st analysis area
6th-code watershed	≤50,000	Individual watershed or sub-basins within 1st analysis area

Mapping Firescapes

To develop a landscape strategy for locating forest restoration treatment areas, a "Firescape" approach was developed. Firescapes are roughly synonymous to "firesheds" following Bahro et al. (2007). Firescapes were identified as sub-landscapes within the analysis area which encompass >200,000 acres and where mechanical thinning and prescribe burning treatments can be applied in a strategic and systematic manner for restoring fire adapted ponderosa pine conditions at a landscape scale. Therefore, a firescape was defined as a contiguous geographic area where endemic levels of fire and other disturbances can be safely restored over time-periods of approximately 5 to 20 years. A time period of up to 20 years was assumed necessary for completing forest restoration treatments and reintroducing the role of fire to an individual firescape.

[1] The term ecological is defined here as including ecosystem processes, biological attributes and human livelihoods as listed under 2007 forest conservation and sustainability Criterion 1 thru 6 of the 1993 Montréal Process**.**

Within the analysis area, six firescapes were mapped (**Figure 2, Table 2**) based on a combination of the following criteria:

1. The area is sufficiently large (≥200,000 acres) to encompass extensive and contiguous ponderosa pine forest and contain wildland fires of greater than average size and severity.
2. Area is generally oriented southwest to northeast to accommodate natural burn paths of large wildland fires.
3. Perimeters are delineated along or near level 3 or better roadways (e.g., state highways and other paved roads) to facilitate fire management access and operations.
4. Perimeters were also delineated along or near ecological and topographic boundaries such as ponderosa pine vegetation, watersheds, and other prominent terrain features.

Table 2. Criteria used to map each firescape within the first analysis area and the total number of ponderosa pine acres (PIPO) within each firescape. Firescape 2 contains less than 1000 acres of ponderosa pine and was not considered in further analyses.

Firescape No.	Total acres	Total PIPO acres[1]	Description
1	526,542	285,117	Area east of I-17 and south of I-40 following PIPO and watershed boundary along eastern border.
2	283,571	930	Area below the Mogollon Rim, west of I-17 and along watershed boundaries.
3	494,630	291,385	Area above the Mogollon Rim, west of I-17 and south of I-40.
4	462,026	159,737	Area west of Hwy 180 and northI-40 following the watershed boundary and PIPO type north of the San Francisco peaks.
5	307,422	73,154	Area containing the San Francisco Peaks and PIPO type east of Hwy 180and north of I-40
6	331,403	65,302	Kaibab NF, Tusayan Range District and PIPO type
Sum	2,405,593	875,625	

[1]Ponderosa pine (PIPO) forest acres excluding areas with a high level of disturbance occurring between 1999 and 2010. Disturbance was calculated as Landsat TM ΔNDVI values < 1 standard deviation from the mean change value (ΔNDVI< -0.05).

Analyzing firescapes

Firescapes provide a unit of analysis with which to compare and contrast current forest structure, canopy fuel and modeled fire behavior conditions across the analysis area. These data provide baseline information for:

1. Developing proposed actions to restore fire adapted conditions in a strategic and systematic fashion.

2. Identifying and describing candidate treatment areas which contain 5,000 to 50,000 acres of ponderosa pine that could be treated with mechanical thinning and prescribe burning.
3. Monitoring progress towards achieving desired conditions at both analysis area and fireshed scales.
4. Identifying adaptive strategies for refining restoration treatments that are transferable to other firescapes and subsequent analysis and implementation areas.

In addition, Finney (2007) suggested that spatial fuel treatment patterns over a sub-set of areas across a landscape can be optimized to influence the movement of large fires and reduce the threat of severe crown fire behavior. The firescape concept lends itself to an iterative fire modeling and a Strategic Placement of Treatments (SPOTS) approach that can be modeled with Treatment Optimization Model (TOM) functions in the FlamMap fire modeling software package (Collins et al. 2010). LSWG participants anticipate that a SPOTS modeling approach could be used to model potential areas for mechanical thinning within a firescape and treatment area, which over time would facilitate the safe operational management of planned and unplanned fire ignitions.

Existing Ponderosa Pine Composition and Structure

Forest land within the analysis area form contiguous acres of tree cover that is dominated by ponderosa pine. Plant species diversity within the ponderosa pine forest type is typically comprised of annual and perennial grasses, forbs and other woody plants. As many as 20 plant associations exist within the ponderosa pine type (USDA Forest Service 1997), that are distinguished from one another on the basis of other low stature trees and understory plants. In light of these attributes, detailed and up-to-date landscape-scale data describing ponderosa pine forest composition is limited. Vegetation information collected with the USFS Terrestrial Ecosystem Survey (TES) can afford general information on percent cover of understory species within TES polygons circa 1980. However, these data were not analyzed due to time constraints and desire to focus on existing forest conditions. An exception was ponderosa pine and oak species (*Quercus spp.*) associations. Given the importance of pine-oak vegetation to multiple wildlife species (Abella 2008), particularly the threatened Mexican spotted owl (USDI FWS

1995), we used available and land cover data developed by the ForestERA project and LANDFIRE program to estimate the amount of pine-oak vegetation across the analysis area and within each firescape (**Figure 3**). Firescapes 1 and 3 have the greatest proportion of pine-oak vegetation.

We estimated ponderosa pine forest structural conditions using tree data collected between 1995 and 2005 from the USFS Forest Inventory and Analysis (FIA) plots. FIA tree data were summarized with the Forest Vegetation Simulator (FVS) for all ponderosa pine dominated plots[2]. We only used plots without a record of disturbance post-dating the inventory date (*n* = 277). Disturbance on a plot was estimated using Normalized Difference Vegetation Index (NDVI) values derived from Landsat Thematic Mapper (TM) imagery taken between the dates of 1999, 2004 and 2006. All plots with negative NDVI change values, indicating a potential disturbance, were eliminated from the analysis.

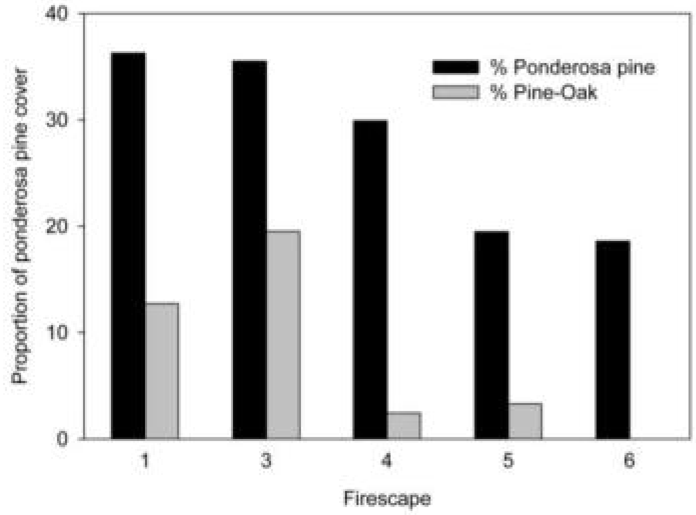

Figure 3. Proportion of ponderosa pine and pine-oak vegetation within each firescape.

Modeled forest structure layers for 2009 were derived by combining FIA permanent plots and remotely sensed data. FIA forest plots and coordinates were used as ground reference data to generate a set of forest structural parameters at each plot location. Plots measured between 1995 and 2005 were imported to the Forest Vegetation Simulator (FVS) and Central Rockies variant and initially grown forward to 2007 to match TM imagery from the end of 2006 growing season[3]. Therefore, structural parameters for all trees ≥1” diameter-at-breast height (dbh) on FIA

[2] For this analysis, we used previously summarized FIA plots in the ponderosa pine type and the entire 2.4 million acre 4FRI area. This had little impact on forest structure values summarized at a large spatial scale.

[3] Forest structure models constructed from 2006 Landsat TM images and FIA plots were applied to 2009 Landsat TM images. The 2009 images were radiometrically calibrated to 2006 image dates using pseudo invariant targets and an empirical line image normalization technique.

plots were estimated using FVS sub-models (e.g., tree growth, wood volume, tree biomass and percent canopy cover) and projected to 2007. Change detection with previous Landsat image dates was used to eliminate FIA plots showing disturbance after tree measurements were taken. A total of 781 undisturbed FIA plots representing all major forest types were used to develop predictive models of forest structure using Random Forest regression trees (Brieman 2001). An additional 579 non-forest points were also included in the reference dataset generated from high resolution digital orthophotos (1-m pixels) as FIA plots did not represent non-forest spectral conditions across TM images. A best model selection process, bootstrapped error estimates and variance explained by each model were used to evaluate forest structure model outputs.

Summarized Data

Forest structural attributes summarized from FIA plots and digital data were used to estimate overall ponderosa pine conditions across the analysis area and firescapes. All ponderosa pine areas with a moderate to high level of disturbance using TM image-based change detection methods between1999 to 2010 (~89,000 ac) were removed from digital grids for characterizing existing conditions. Moderate to high level disturbance was considered <1 standard deviation from the mean ΔNDVI value, (ΔNDVI< -0.05; *see* also Beck and Gessler 2008). Disturbance areas post-dating 2006 and 2009 were not sufficiently represented in forest structure data layers (e.g., 2010 Schultz Fire). In addition, ponderosa pine forests with a high level of disturbance from 1999 to 2010 were not considered candidate areas for restoration treatments (**Figure 4**).

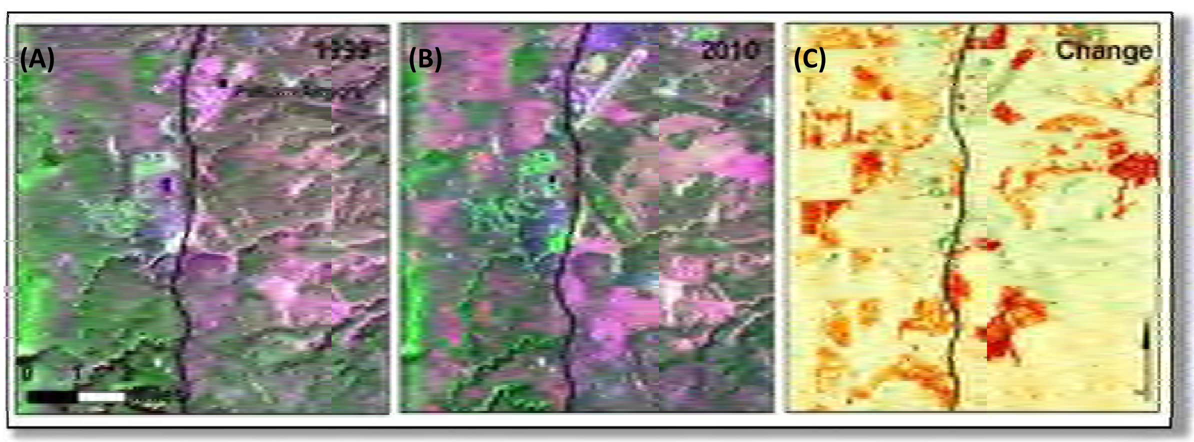

Figure 4. Change detection using ΔNDVI values from a (**A**) 1999 TM images and (**B**) 2010 TM images to identify (**C**) areas of moderate to high disturbance (orange to red) resulting from

activities in the analysis area such as forest thinning treatments, urban development, and wildland fires.

Digital forest structure data matched closely with FIA plot summaries (**Table 3A, B**). Most of the forest structure data layers were derived with 65% or more of the variance explained from validation statistics. Exceptions were variables such as tree density, canopy base height and quadratic mean diameter which were below 50%, which translates to higher levels of uncertainty for these forest structure data layers.

On average, ponderosa pine forest show high stem densities and stem biomass **(Table 3A, B)** relative to historical forest conditions (Covington and Moore 1994, Covington et al. 1997). At the turn of the century, an average of 47 trees per acre (TPA) and 58 ft^2/ac of basal area (BA) were measured in 15 permanent plots from Arizona and New Mexico (Moore et al. 2004). Conditions summarized from FIA plots and digital forest structure data layers indicate that lower 25th percentile forest conditions are close to or exceed tree basal area and density estimated from these historical plots. Uncertainty exists about historical forest plots and reconstruction data and their representation of prior forest conditions (Bell et al. 2009), particularly with respect to the spatial heterogeneity and structural conditions across large landscapes. However, strong evidence suggests that widespread forest change has occurred during the last century such as increased tree densities as a result of reduced fire activity for most Southwest forest types, greatly increasing forest vulnerability to large scale disturbances and climate change (Fule et al. 2010).

Table 3. Ponderosa pine forest structure conditions summarized by (**A)** FIA permanent plots (*n* = 277) and (**B**) newly developed digital data layers from 2009 satellite data.

A. Forest structure variable[1]	**Max**	**Median**	**Min**	**Mean**	**Std. Dev**	**25%**	**75%**
Trees per acre	4124	327	6	562	675	161	619
Canopy cover (%)	83	42	7	41	14	32	51
Basal area (ft^2/ac)	237	114	13	117	48	81	153
Stand density index	523	241	29	247	107	162	322
Quadratic mean diameter (in.)	27.0	7.9	1.9	8.6	3.9	6.1	10.5
Cubic foot volume (ft^3/ac)	6834	2048	270	2275	1170	1449	3064
Crown bulk density (kg/m^3)	0.20	0.05	0	0.06	0.03	0.04	0.07
Canopy base height (ft)	94	14	2	16.5	11.3	9	21

[1]Values derived from summarized FIA plots which provide a rough estimate how forest structure conditions are distributed across the 4FRI landscape.

Table 3 (cont.). Ponderosa pine forest structure conditions summarized by (**A)** FIA permanent plots (*n* = 277) and (**B**) newly developed digital data layers from 2009 satellite data.

B. Forest structure variable[1]	**Max**	**Median**	**Min**	**Mean**	**Std. Dev**	**25%**	**75%**
Trees per acre[2]	2989	530	0	563	282	280	941
Canopy cover (%)	69	38	0	37	11	28	42
Basal area (ft^2/ac)	224	112	0	109	35	74	125
Stand density index	538	238	0	232	77	151	267
Cubic foot volume (ft^2/ac)	5995	1934	0	1875	845	916	2266
Crown bulk density (kg/m^3)	0.122	na	0	0.043	0.018	0.023	0.051
Canopy base height (ft)	40	na	0	13	4.7	8.1	15

[1]Values derived from digital data layers and 30m grid cells which provide a detailed estimate of forest structural conditions and distributions across the first 4FRI analysis area.
[2]Trees per acre were summarized from available 2006 digital data, also removing recent disturbance areas.

Digital maps of forest structure visually identified large-scale differences in ponderosa pine conditions such as areas of high or low canopy fuels and basal area among firescapes (**Figure 5A, B**). Areas of high canopy fuel conditions and basal area were observed in three large contiguous areas within firescapes 1, 3, and 4. A large portion of ponderosa pine forest was excluded from forest structure variables mapped in firescape 5 as a result of the high severity 2010 Schultz Fire and our change detection analysis.

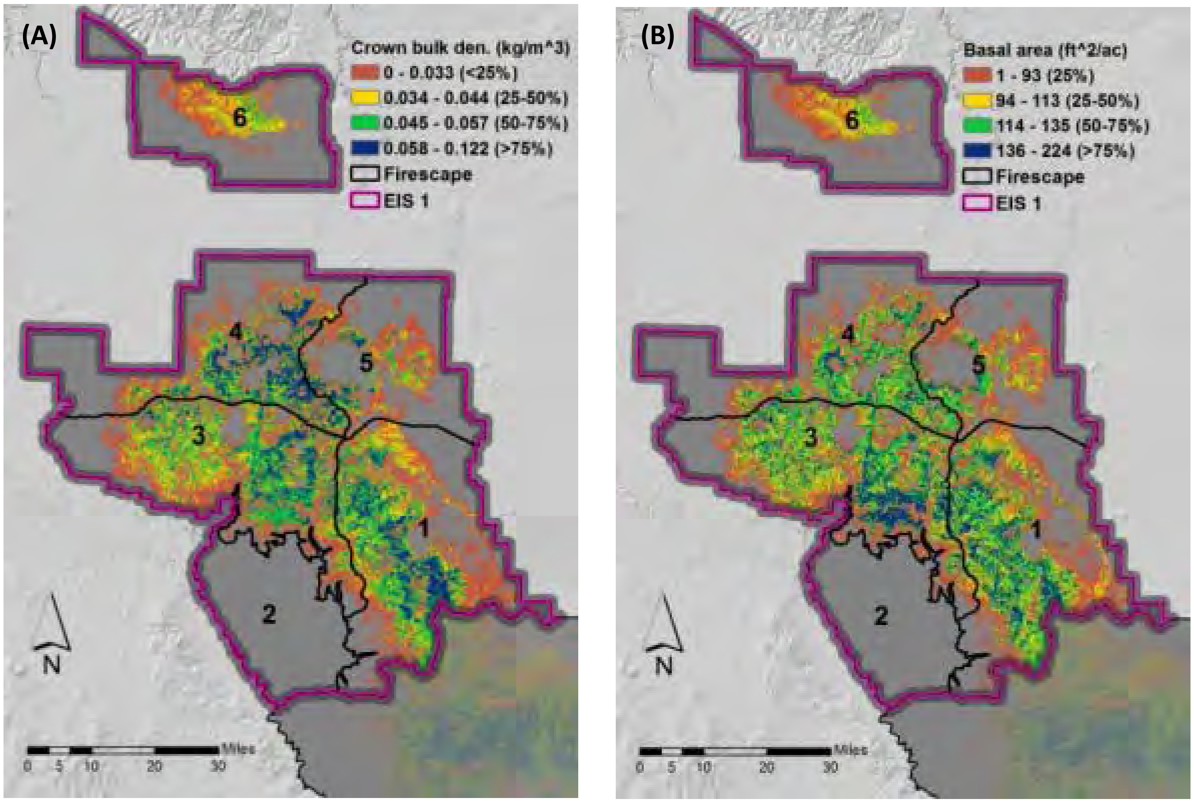

Figure 5. Updated 2009 ponderosa pine forest structure data layers for (**A**) crown bulk density and (**B**) basal area across the analysis area and firescapes.

Mapped forest structure conditions (2009) for ponderosa pine basal area, tree density and canopy fuels and cover were also summarized in each firescape to compare and contrast existing conditions between areas (**Figure 6A-D**). Firescapes 5 and 6 were lower in all forest structure categories in comparison with the other three firescapes. As noted above, firescapes 1, 3 and 4 have more contiguous areas of ponderosa pine and showed consistently greater canopy fuels, basal area, canopy cover and tree density than the other two firescapes. Nevertheless, synthesis methods were needed to more comprehensively evaluate existing forest conditions and estimate the potential for high-severity wildland fires. In the following section fire behavior models were used to assess the interaction between forest structure parameters, topography, fuel moisture, and fire weather conditions.

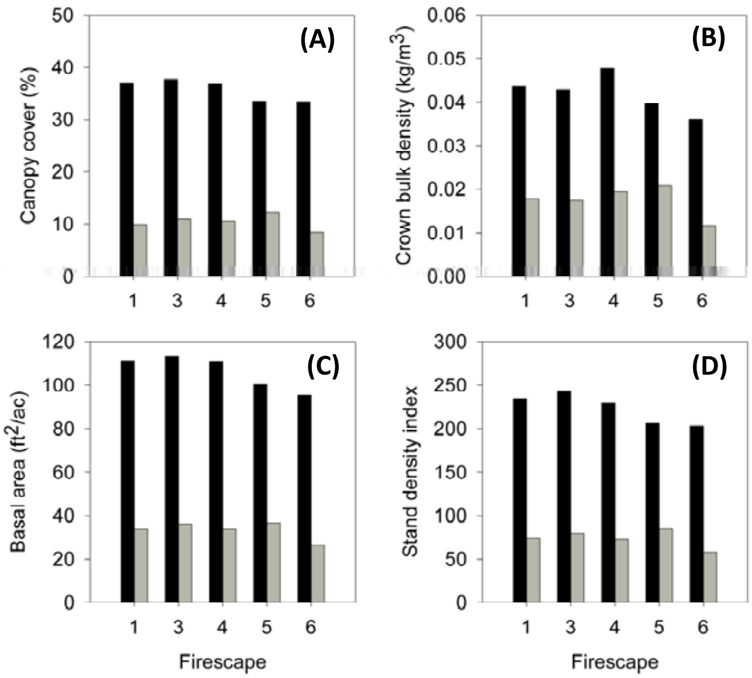

Figure 6. Ponderosa pine forest (**A**) canopy cover, (**B**) crown bulk density (canopy fuels), (**C**) basal area and (**D**) stand density index summarized by firescape using digital data layers. Black bars are average values are and grey bars standard deviation.

Predicted Fire Behavior

In southwestern ponderosa pine ecosystems, high-severity fires currently burn across areas many times larger than they did less than a century ago (Swetnam and Betancourt 1998, Westerling et al. 2006). Ponderosa pine ecosystems were historically shaped by a variety of natural processes, including a fire regime characterized by predominantly frequent, low-intensity surface fires (Covington and Moore 1994). Current fire behavior is a result of the shift in forest structure from low tree densities and open conditions toward more contiguous canopy fuels with high crown fire potential (**Figure 5A**). An increased number, size, and severity of stand-replacing fires continues to pose a threat to human communities and infrastructure, in addition to a potential loss of ecosystem services such as forest carbon storage and climate mitigation, and biodiversity and watershed protection. Uncharacteristic fire behavior can also alter successional patterns within burned areas, leading to novel post-fire plant communities further perpetuating unnatural fire regimes (Savage and Mast 2005, Kuenzi et al. 2008).

An important theme articulated by the LSWG was to develop strategic approaches to reducing the threat of large and severe wildland fires, while restoring fire as an ecosystem process which plays a vital role in developing desired forest conditions. Reestablishing ecosystem resilience to wildland fire events will require the safe reestablishment of natural fire regimes, which can allow for changing climate conditions (Fulé, 2008). When coupled with the re-establishment of landscape-scale fire processes over time, the strategic implementation of thinning and burning treatments in parts of the study area is anticipated to create forest conditions that are less prone to shifts in native plant community structure and composition (Allen et al. 2002, Falk et al. 2006).

Current fire conditions within the analysis area were estimated using the FlamMap fire behavior model and LANDFIRE refreshed digital data layers (http://www.landfire.gov/). Remote Automated Weather Station (RAWS) data from the analysis area were used to parameterize the model based on 85th and 97th percentile fire weather conditions. Eighty-fifth percentile conditions were characterized as average fire season conditions and 97th percentile conditions were identified as extreme fire weather conditions associated with intense fire behavior in northern Arizona. Low fuel moisture conditions and higher sustained wind speeds (18 miles per hour) at or close to the 97th percentile are consistent with fire weather conditions for several large fires that burned on the Kaibab National Forest since 1992 (Kleindienst 2009, unpublished report). Kleindienst (2009, unpublished report) also noted that 98% of all fires are contained with initial attach efforts and nearly all large fires have occurred under 90th percentile or greater fire weather conditions.

The LANDFIRE refresh process updates forest structure data layers in locations with wildland fire or other disturbances >1000 acres in size[4]. Therefore, smaller fires and thinned areas are not accounted for in these updates. LANDFIRE data layers have also been adjusted for Southwest forest condition and improve forest structure model estimates of crown bulk density and canopy cover important to fire mode runs. As a post processing step, areas moderate to high disturbance according to 2010 - 1999 ΔNDVI values were assumed to be reduced to surface fire only to

[4] LANDFIRE forest structure data layers are derived from 1999-2001 Landsat TM images which predate numerous large and small disturbance areas within the analysis area.

better incorporate recently thinned areas and other disturbances <1000 acres. In addition, fire model outputs and predicted fire behavior categories were rescaled to a 50 acre minimum mapping unit.

Fire model outputs indicated potential fire behavior categorized as surface fire, passive crown fire and active crown fire for the two fire weather scenarios across all vegetation types. Areas of no prediction were urban areas or other barren lands with no vegetation. Model outputs estimated for 85th percentile conditions showed notably less area predicted as active crown fire behavior than under 97th percentile conditions (**Figure 7A, B**). These predictions appear consistent with known fire behavior under moderate versus extreme fire weather conditions in the analysis area. All further analysis was performed on 97th percentile fire model runs to characterize current conditions within firescapes that that could potentially result in large scale, high-severity wildland fires.

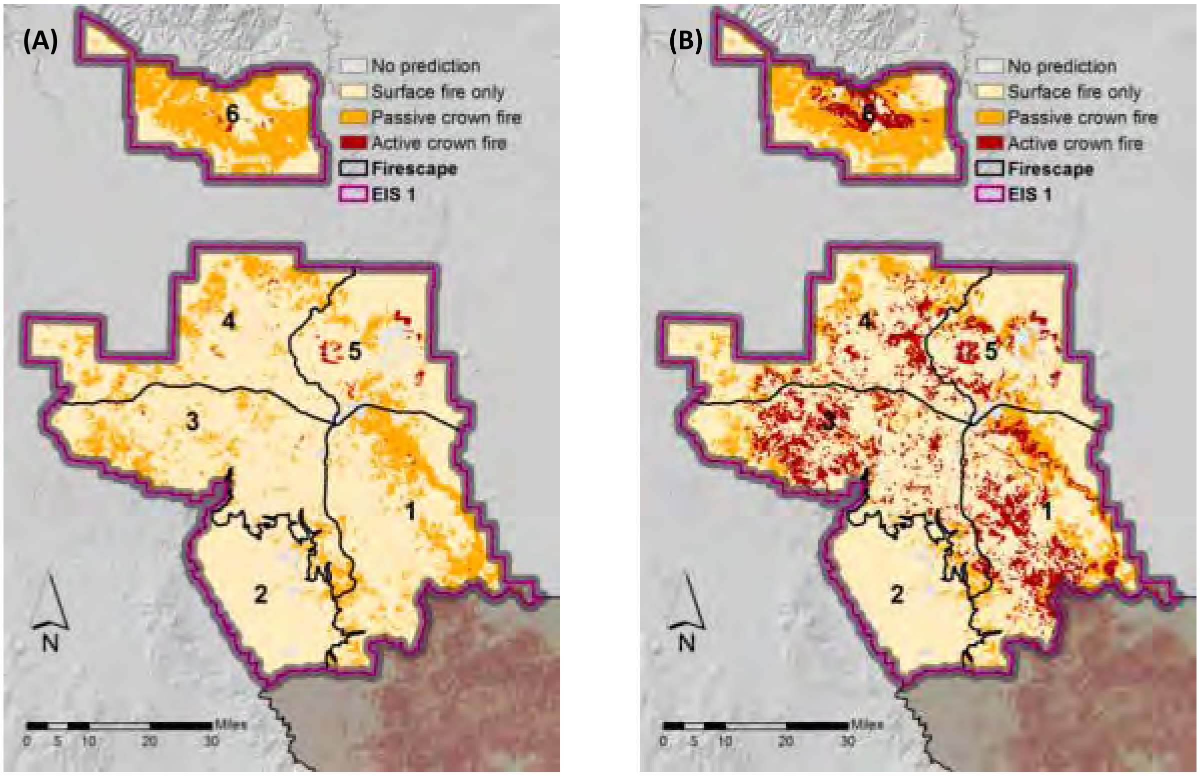

Figure 7. FlamMap fire behavior model outputs from model runs at the (**A**) 85th percentile fire weather conditions and (**B**) 97th percentile fire weather conditions. Model outputs have been rescaled to a 50 acre minimum mapping unit.

Comparisons of 97th percentile fire behavior for ponderosa pine forest among firescapes showed that firescapes 6, 1 and 3 had the greatest proportion of area predicted to achieve active crown fire (**Figure 8**). Result from all but firescape 6 appear consistent with forest structure data summarized for each firescape. Firescapes 6 which covers the Tusayan Ranger District on the Kaibab National Forest was lowest, on average, for all forest structure attributes compared (**Figure 6A-D**), but showed the greatest proportion of predicted and contiguous areas in passive and crown fire categories. Fire model outputs for the Tusayan Ranger District warrant further evaluation as several planned and unplanned natural ignition fires have been implemented for this area in recent years, likely to reduce crown bulk density and other forest structure parameters related to fire behavior (personal observation). These changes may not have been registered in LANDFIRE refreshed data, or less severe fire behavior during burning activities may also have produced lower levels of change levels than the ΔNDVI threhold used (1 standard deviation) to post-process fire model outputs. Regardless, additional information is needed for this area to accurately portray current fire risk.

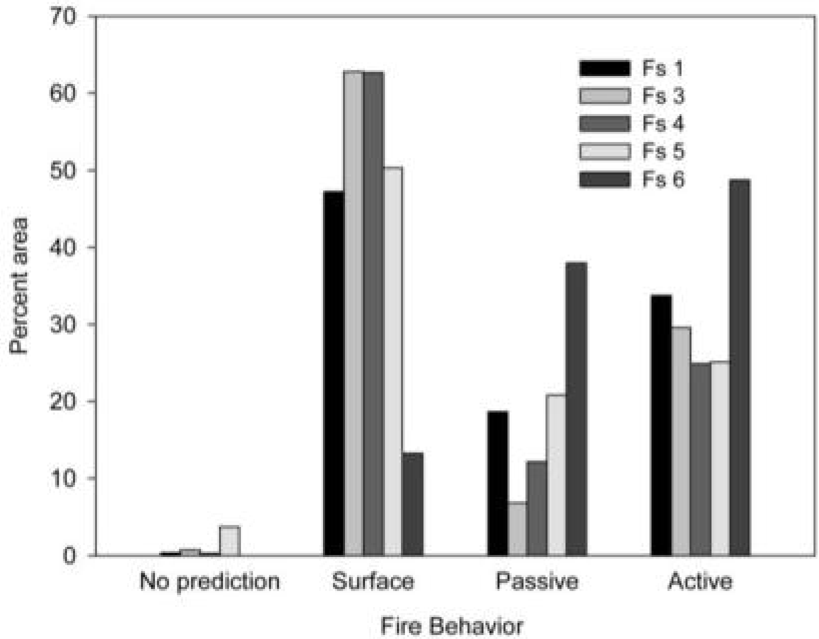

Figure 8. 97th percentile FlamMap fire behavior predictions for the ponderosa pine forest type and five principal firescapes covering the analysis area. Fire behavior categories include 1) areas with no prediction (e.g., urban areas), 2) surface fire conditions, 3) passive crown fire and 4) active crown fire.

IV. TREATMENT AREA IDENTIFICATION

Mechanical thinning and burning treatments should occur in a configuration which meets objectives to restore ponderosa pine forest structure and fire adapted conditions within the analysis area. The LSWG recommends that a standardized and repeatable method be used for subdividing firescapes into treatment areas that encompass 5,000 to 50,000 acres of ponderosa pine forest where mechanical thinning and prescribed fire can potentially be applied. Proposed actions and treatment strategies for each of these areas can be developed and allow for multi-scaled and spatially explicit descriptions of existing conditions, desired post-treatment and future conditions, and treatment options. An example of the process developed by the LSWG is described in detail below.

Treatment Area Identification and Mapping

Analyses were conducted using 6th code watershed boundaries that are based on terrain features and hydrologic function. Treatment areas were necessarily identified within firescape boundaries to facilitate the spatial and temporal sequencing of treatments and enhance opportunities to restore fire adapted conditions in a stepwise fashion. To develop a standard process for identifying treatment areas within a firescape, three types of ponderosa pine conditions were defined:

1. **Candidate treatment areas** are ponderosa pine forest where mechanical thinning treatments could likely occur first.
2. **Excluded areas** are ponderosa pine forest where mechanical thinning was unlikely to occur.
3. **Matrix areas** are ponderosa pine forest not represented by the candidate or exclusion areas/categories (**Tables 4, 5**). We defined these areas as ponderosa pine forests that were not identified for initial treatments, but may be treated based upon additional analyses.

More specifically, candidate ponderosa pine forest were defined as areas most likely to receive mechanical thinning and burning treatments according to digital data layers representing social and ecological values and risks to values posed by potential fire behavior (**Table 4**). Exclusion areas were defined as locations within the ponderosa pine type where mechanical thinning was unlikely to be implemented as a restoration approach according to digital data layers (**Table 5**). However, mechanical, other non-mechanical, or low impact restoration approaches may potentially be applied to exclusion areas to enhance habitat conditions and reduce the threat of wildland fire or other severe disturbance events. These exceptions should be identified during the site-specific treatment identification process the USFS will conduct. In addition, matrix areas may also be given preference for mechanical thinning and prescribe burning over candidate ponderosa pine depending on the spatial context of these areas and restoration objectives.

To develop a systematic process for identifying important differences between treatment areas (e.g., areas where community protection may be the focus versus an area where other resource values would guide treatment), we developed two different scenarios. Each scenario estimated a numerical value representing the level of intersection between candidate area data layers and individual 6th-code watersheds (*n* = 144) in the analysis area. For Scenario I, each candidate data layer was given a possible classification score of at least 1 if it occurred in a non-overlapping pixel with other layers. However, an increased classification score of 4 was given to the intersection of community protection areas and areas of active crown fire predicted using 97th percentile fire weather conditions. Community protection and active crown fire areas occurring independent of one another were given an increased clarification score of 3 and 2, respectively. This process allowed us to spatially identify community protection areas, locations with active crown fire, and other high-value resources within wildlands to aid the USFS in developing treatment scenarios for these important areas. The intersection of layers could have a maximum classification score of 10, as any other candidate layer was counted only once. Although these areas do receive more points than others, this process was not meant to rank communities above wildland areas for treatment, but to provide a means of classifying and identifying different forest management settings within firescapes. Below are all of the steps used to process data layers in Scenario I:

Step I. Watershed classification score (for each pixel in watershed)

1. Intersection of community protection & active crown fire = 4
2. Community protection = 3
3. Active crown fire = 2
4. Any other candidate area = 1
5. Maximum weight = 10
6. Calculate the average pixel classification score within a watershed

Step II. Proportion of candidate areas

1. Calculate the proportion of area occupied by each candidate treatment area in a watershed
2. Calculate the average proportion of all candidate treatment areas

Step III. Watershed similarity value

1. Multiply the average watershed classification score by the average proportion of candidate treatment areas in a watershed

Step IV. Group similar watersheds as treatment areas

1. Combine 6th code watersheds with similar watershed classification scores
2. Contain treatment areas within 5th code watersheds, when possible

Scenario II used a different set of watershed classification scores giving active crown fire a 3 and all other layers a score of one (**Table 4**). For this scenario, the additive value of all overlapping candidate area data layers was summed on each pixel in a watershed which also resulted in a maximum classification score of 10. For example, areas of 97th percentile passive and active crown fire do not overlap and can be counted only once in a given area. All other processing steps were equal between the two scenarios.

The above scenarios and set of analysis steps provided four principal outputs:

1. A method to group 6th code watersheds into treatment areas ranging in size from 5,000 to 50,000 acres.
2. The total number of acres of ponderosa pine forest within candidate treatment areas for each watershed, firescape and the analysis area.
3. The total number of acres of ponderosa pine forest excluded from mechanical treatment within a watershed, firescape and the analysis area (i.e., analysis area).
4. The total number of "matrix" acres that are not within either of the excluded or candidate treatment area categories.

The total number of non-overlapping candidate, excluded and matrix ponderosa pine forest acres for the analysis area were 557,713, 208,562, and 109,054 acres respectively (**Tables 4, 5**). An example of these calculations by firescape and treatment area is given below with results from the treatment identification scenarios.

Table 4. Digital data layers representing candidate areas for treatments areas within the ponderosa pine forest type.

Layer	Candidate treatment areas	Description	# Acres	Scenario I[4]	Scenario II[5]
na	Active crown fire 97^{th} and community protection	Intersection between active crown fire and community protection data layers	na	4	na
1	Active crown fire 97^{th}	97^{th} percentile w/50 acre filter	271,454	3	3
2	Municipal + aquatic species watersheds[1] + Flagstaff CWPP watersheds	Community Wildfire Protection Plan watersheds/flood protection	264,341	1	1
3	Community protection areas[1]		188,348	2	1
4	MSO restricted habitat[2]	Mexican Spotted Owl restricted habitat	177,062	1	1
5	Passive crown fire 97^{th}	97^{th} percentile w/50 acre filter	132,117	1	1
6	NEPA completed acres	Areas USFS has completed NEPA analysis and compliance; Areas where specified treatment can happen more readily	120,359	1	1
7	Major roads buffer (USFS level 3-5)	0.5 mile upwind	92,243	1	1
8	Mountain top buffer[3]	1 mile from derived mountain top	27,969	1	1
9	NOGO PFAs minus nest cores	Northern Goshawk post-fledging areas	26,107	1	1
					1
10	MSO PAC buffer[3]	0.5 mile upwind in restricted habitat	19,992	1	1
11	Active crown fire 85^{th}	85^{th} percentile w/50 acre filter	6,440	1	1
12	Recreation areas w/ infrastructure + named campgrounds	Point locations buffered 1/8 mile	597	1	1
	OVERLAP	Subtract areas of overlap, no double counting of acres	769,318		
		Total Acres	**557,712**	**10**	**10**

[1]Estimated from the Small Diameter Wood Supply Assessment (www.forestera.nau.edu)
[2]Model derived during Western Mogollon Plateau Adaptive Landscape Assessment (www.forestera.nau.edu)
[3]High value buffer areas are derived from buffering selected landscape features. These may depict priority areas for treatment
[4]Senario I had a maximum classification score of 10, as only 1 point is added for another candidate area apart from 97^{th} percentile active crown fire and community protection areas.
[5]Senario II also had a maximum classification score of 10, as some layers do not overlap such as active and passive crown fire.

Table 5. Digital data layers representing exclusion areas within the ponderosa pine forest type

Layer No.	Exclusion areas	Description	No. of Acres
1	Non-NFS lands	Private, state, and other lands not managed by the USFS	81,955
2	MSO protected activity centers	Occupied MSO sites, approximately 600 acres in size	56,914
3	Sensitive soils[1]	Soils with mechanical treatment limitations due to compaction, etc.	34,646
4	Specially designated areas	Inventoried roadless areas, research natural areas, wilderness, special management areas	31,483
5	Steep slopes[1]	Slopes greater than forty percent	27,601
6	NOGO nest core areas[1]	Consist of 3, 30-acre nest areas, for a total of 90-acres	25,681
7	Mountain tops	Elevation and vegetation thresholds, areas greater than 1000 acres	2,797
8	Stream buffers[1]	100 foot buffers on either side of perennial streams	450
9	Areas of significant change	Landsat derived change detection 1999-2010 capturing all types of disturbance (e.g. treatments, fire, etc.)	
	OVERLAP	Subtract areas of overlap, no double counting of acres	-52,965
		Total Acres	**208,562**

[1]Estimated from the Small Diameter Wood Supply Assessment (www.forestera.nau.edu)

Treatment Area Results

Outcomes between Scenarios I and II were not extremely different given that many of the conditions represented by candidate data layers are spatially autocorrelated (**Figures 10A; 11A**). Therefore, watersheds with similar values and fire behavior conditions tended to be grouped rather than widely dispersed. Firescape 3 was used as an example to compare and contrast the two scenarios for grouping watersheds and create treatment areas. In each case, the resulting fire treatment areas were similar in size, extent and location (**Figures 10B, C; 11 B, C**). To process the two outputs in a similar manner, treatment areas were generally defined by similar groups of watersheds along 5^{th} code watershed boundaries. Fifth code watersheds provided a second level of organization with which to cluster similar 6^{th} code watershed groups. Highly aggregated watersheds close to Flagstaff, AZ formed relatively straight forward treatment areas. Other watersheds such as those close to the town of Williams, AZ contrasted more highly with surrounding watersheds. These watersheds were grouped with several other watersheds up-wind of this location. The rational used was that ponderosa pine forest up-wind of Williams contained a large number of areas categorized as active crown fire from 97^{th} percentile fire behavior model runs (**Figure 7B**). In addition, the two watersheds surrounding Williams are bisected by firescape 3 and contain a low number of candidate ponderosa pine when delineated as a separate treatment area (data not shown).

Candidate, excluded and matrix areas were summarized for Scenario I and II resulting in 162,500 total candidate acres and 27,642 total matrix acres within firescape 3 (**Table 6**). For scenario I candidate ponderosa pine acres within each treatment area ranged in size from 6,500 ac to 47,000 ac, in addition to matrix areas not accounted for in candidate and exclusion digital data layers. Scenario II resulted in a similar distribution of ponderosa pine forest categories within firescape 3 (**Table 7).** These data indicate that relatively large treatment areas are needed to encompass candidate areas for treatments between 5,000 ac and 50,000 ac.

Each of the two scenarios presents a process for grouping watershed areas into meaningful treatment areas. Additional steps are likely needed to prioritize and sequence firescapes and treatment areas to receive initial forest restoration projects. Nevertheless, results suggest that

~20 treatment areas will potentially be defined in the first analysis area using these methods. The group selected Scenario 2 as the recommended process for selecting treatment areas.

Scenario I

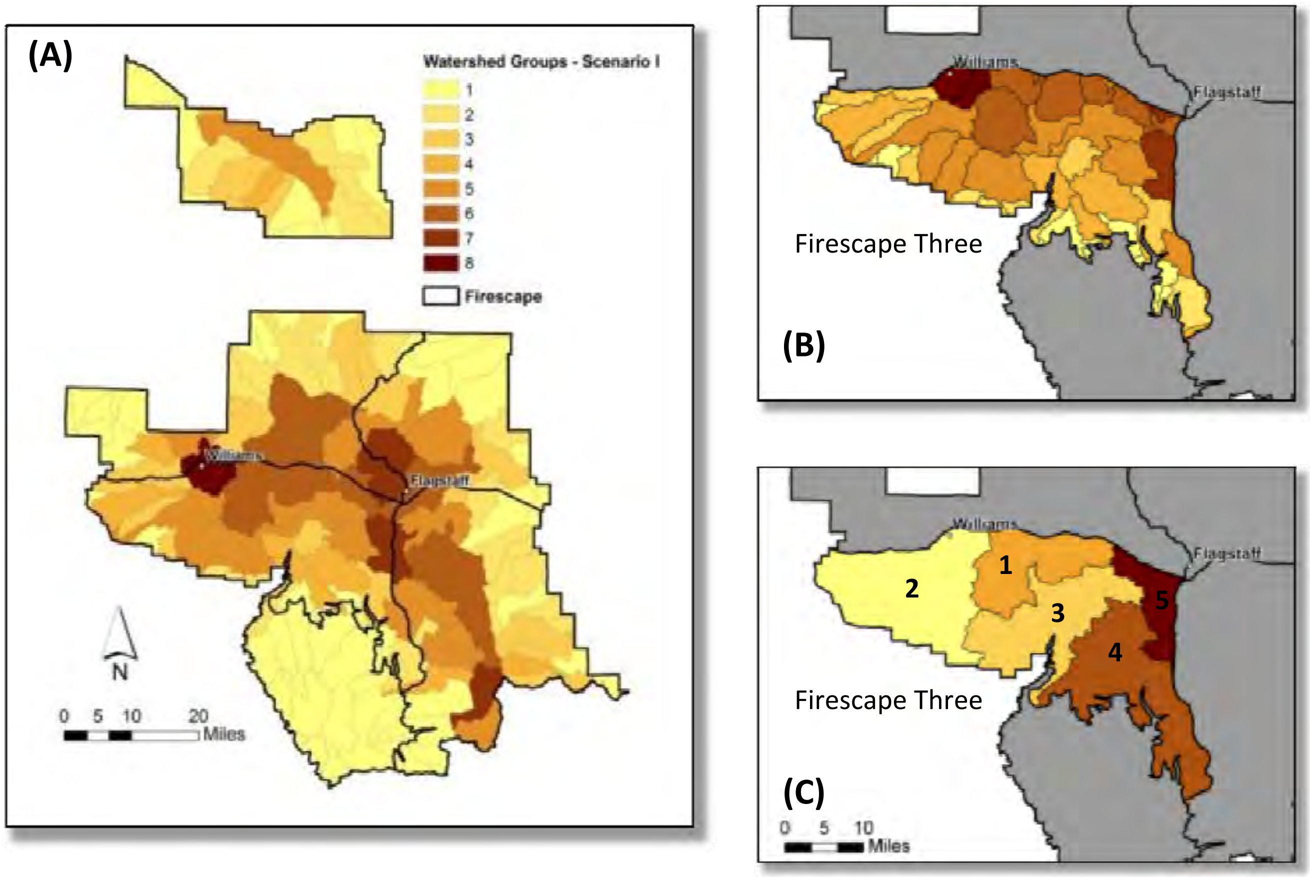

Figure 10. Scenario I treatment area identification that is defined according to (**A**) weighted candidate areas for treatment at the 6th code watershed scale, (**B**) firescape boundary, and (**C**) selected watershed groups.

Table 6. The number of ponderosa pine acres in the three categories (candidate, excluded and matrix) from Scenario I, firescape three.

	Ponderosa pine acres			
Treatment area	**Candidate**	**Excluded**	**Matrix**	**Total**
1	32,701	12,294	4,875	49,870
2	43,830	11,940	4,800	60,569
3	32,324	30,052	14,728	77,104
4	47,206	28,884	3,241	79,331
5	6,523	17,942	0	24,465
Total acres	162,583	101,112	27,643	291,339

Scenario II

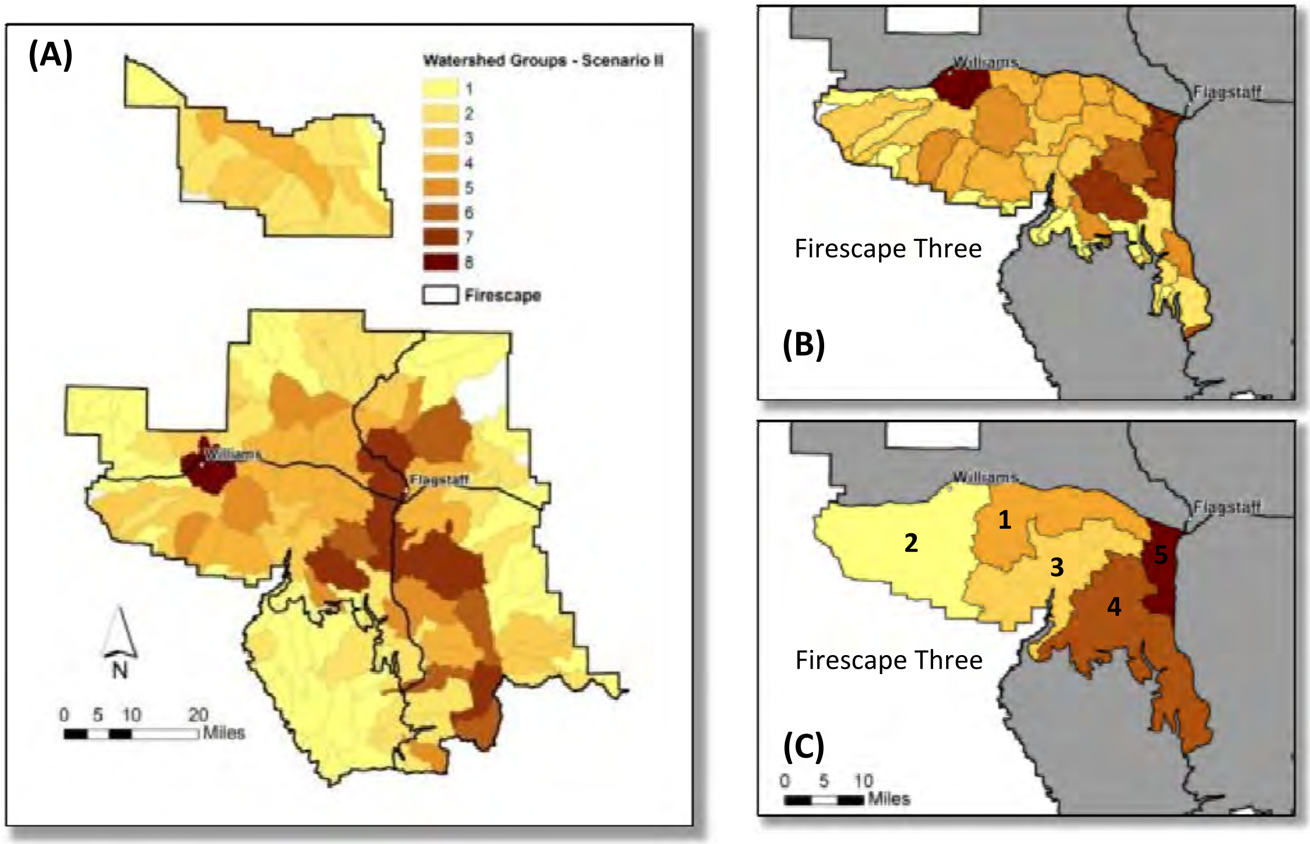

Figure 11. Scenario II treatment area identification that is defined according to (**A**) weighted candidate areas for treatment at the 6th code watershed scale, (**B**) firescape boundary, and (**C**) selected watershed groups.

Table 7. The number of ponderosa pine acres in the three categories (candidate, excluded and matrix) from Scenario II, firescape three.

	Ponderosa pine acres			
Treatment area	**Candidate**	**Excluded**	**Matrix**	**Total**
1	32,856	18,871	4,875	49,870
2	43,830	11,940	4,800	60,569
3	32,324	30,052	14,728	77,104
4	47,206	28,884	3,241	79,331
5	6,267	11,365	0	24,465
Total acres	162,482	101,112	27,644	291,339

V. EXAMPLE TREATMENT AREA DESCRIPTION

The following process used to describe treatment areas can serve as a template for developing area specific current conditions, proposed actions and desired post-treatment and future conditions for each treatment area. For a few locations in the example below, text remains highlighted where data and information can be inserted when data layers and other ongoing work is finalized, such as revision and consolidation of TES units.

Firescape 3 - Garland Prairie Treatment Area Example

As part of the treatment area identification process, an individual treatment area was selected and characterized using derived datasets (**Table 4, 5)**, in addition to spatial data representing current forest conditions. The Garland Prairie Treatment Area (herein called the 'Garland Area') (**Figure 12**) was chosen as an example because of its moderate to high weighted value from the analyses above. It is an area with high potential for active crown fire under extreme fire weather conditions, but has low overlap with community protection areas.

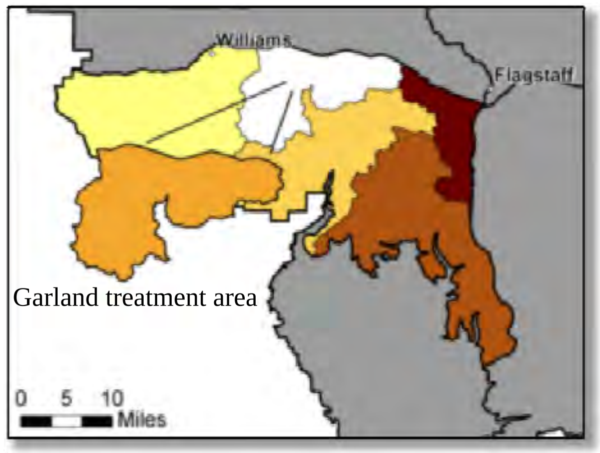

Figure 12. Garland prairie treatment area.

Treatment Area Description

The Garland Area encompasses a total of 73,998 acres, 49,870 acres of which are dominated by the ponderosa pine forest type (**Figure 13A**). Candidate and matrix ponderosa pine areas comprised 32,701 and 12,294 acres of the treatment area and 4,875 acres were excluded (**Figure 13B**). The Garland Area contains portions of six, 6th code watersheds. It is located in Firescape 3 and includes the upper portion of Big Spring Canyon, a primary contributing watershed basin of the Sycamore Canyon watershed, approximately 10 miles west of Flagstaff, Arizona. The town of Bellemont, Arizona is at the eastern edge of the treatment area which includes national forest lands to the west of Camp Navajo and forest surrounding Garland Prairie. The Garland Area also provides an excellent opportunity to demonstrate 4FRI approaches to forest restoration and easy access to the project area from Interstate Highway 40. The Garland Area is considered to have a moderate to high level of priority treatment area due to its contiguous areas predicted to be susceptible to active crown fire, but lower concentration of community protection areas.

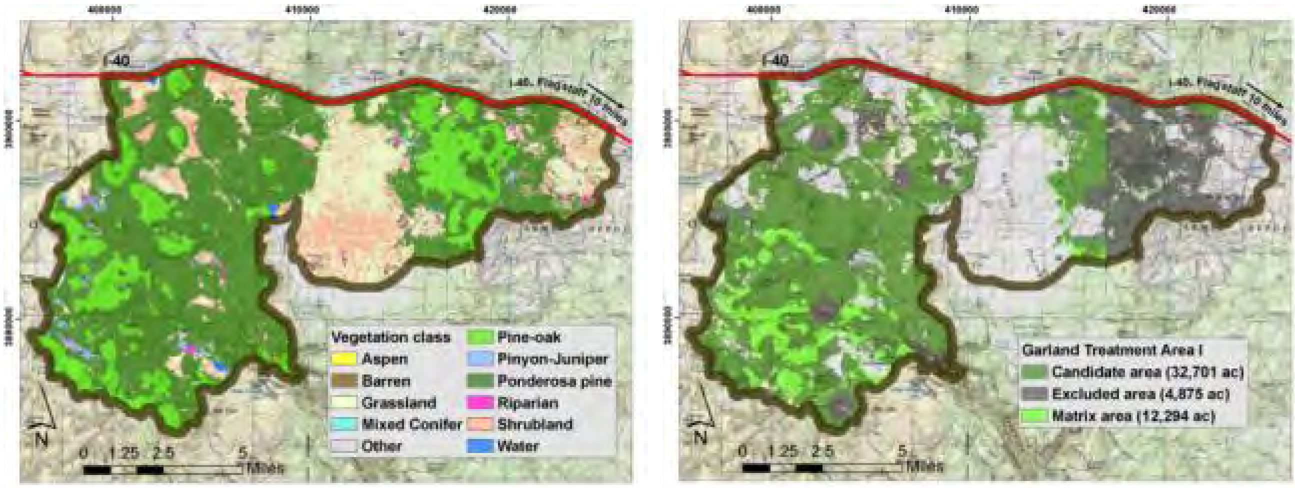

Figure 13. Garland Area west of Flagstaff, Arizona (A) forest composition and (B) spatial data representing candidate treatment, matrix and excluded ponderosa pine forest areas.

Site Characteristics

Abiotic Characteristics – From available Stand Exam forest inventory data, ponderosa pine forests within the Garland Treatment Area are located on moderate productivity sites with an average site index of 71 (SD ± 10) using a base age of 100 years (**Figure 14A**). The ponderosa pine forests within the Garland Area are located on Terrestrial Ecosystem Survey (TES) strata [## (## acres), ## (## acres), and ## (## acres]. Based on TES soil data, the area is predominately characterized by only slight erosion potential (**Figure 14B**).

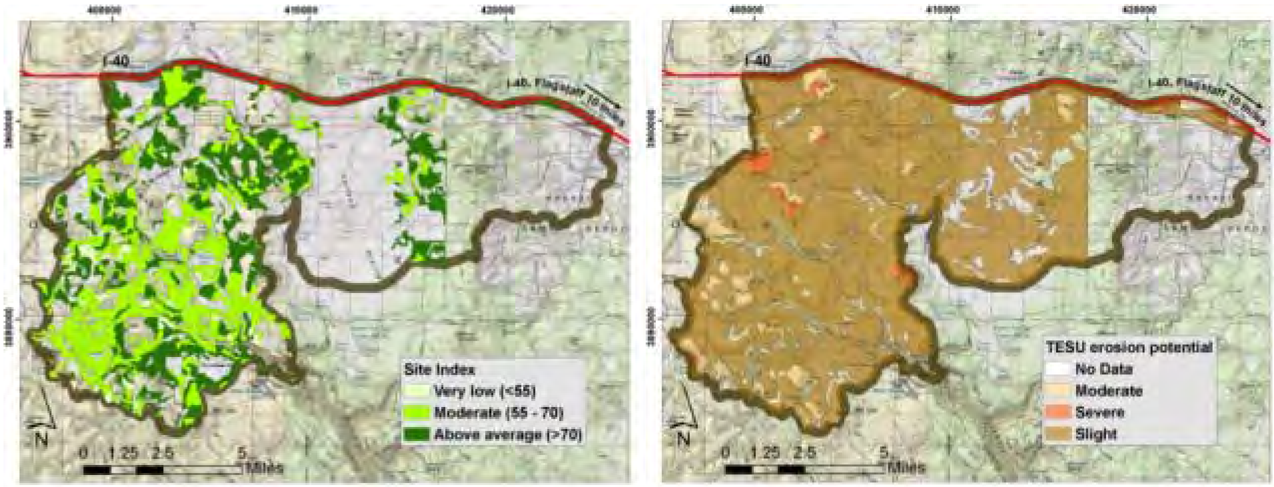

Figure 14. Garland treatment area (**A**) available stand exam site index values and (**B**) TES unit erosion potential data.

<u>**Forest Composition and Structure**</u> - The ponderosa pine forests within the Garland Area are characterized by dense forest conditions dominated by small diameter trees. According to existing USFS stand inventory data (n=319 stands) grown forward to 2007[5], ponderosa pine forest averages 156 (SD±20) trees per acre (tpa) for trees <5 inches dbh and 109 (SD±4) tpa for trees 5 to 16 inches dbh. Larger diameter trees >16 inches average 24 (SD±0.6) tpa. Average stand basal area (BA) and stand density index (SDI) are 120 ft^2/ac (SD±2.3) and 221(SD±5), respectively. These estimates are similar to ponderosa pine estimates from gridded data that showed an average BA of 114 ft^2/ac (SD±27) and SDI of 243 (SD±60) (Figure 15 A,B). Differences in standard deviation among the two estimates are due to sampling differences between forest inventory and gridded data. (PLACE SUMMARY DATA IN TABLE) Within the ponderosa pine forest type, 24% (12,614 acres) is characterized as pine-oak vegetation (i.e., ~20

[5] These data were previously processed during the 2008 Small Diameter Wood Supply Assessment and have not been evaluated for disturbance post-dating forest inventory dates.

ft^2/ac of Gambel oak) across all land ownerships in the Garland Area. Areas comprised of pine-oak within candidate and matrix ponderosa pine forest on USFS lands accounted for 23% (8,478 acres) of these areas (Figure 13A).

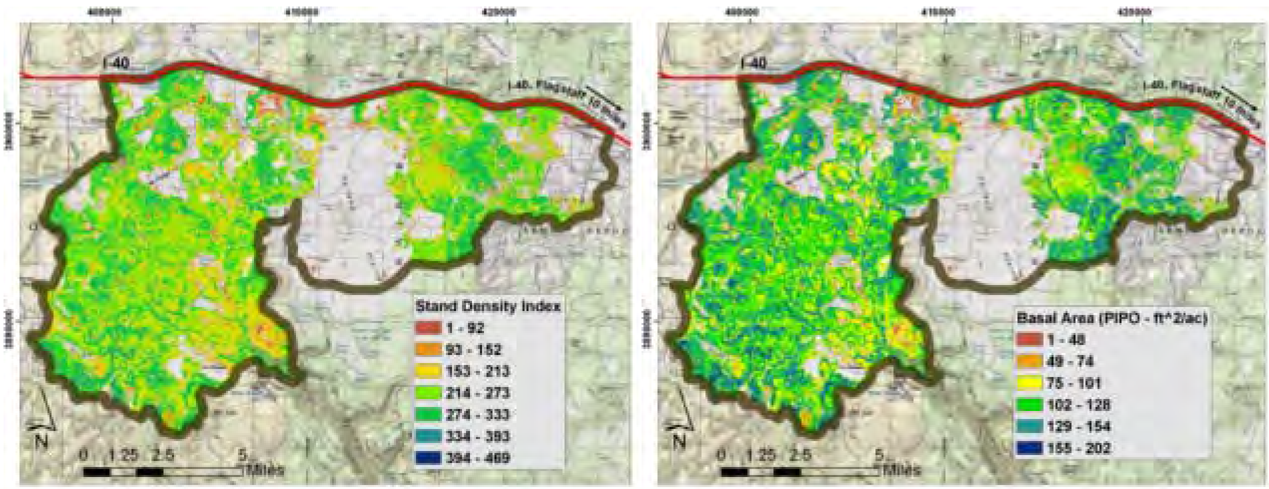

Figure 15. Digital forest structure layers for (**A**) SDI and (**B**) basal area.

Fire Behavior/Risk

Based on existing forest structure and fire behavior models, the Garland Area contains 180 acres of ponderosa pine forest that could potentially support active crown fires at 85th percentile conditions and 20,792 acres of ponderosa pine forest that could potentially support active crown fires at 97th percentile conditions (**Figure 14A, B**). Passive crown fire conditions in ponderosa pine forest accounted for 7,603 acres and 3,791 for 85th and 97th percentile fire weather categories, respectively.

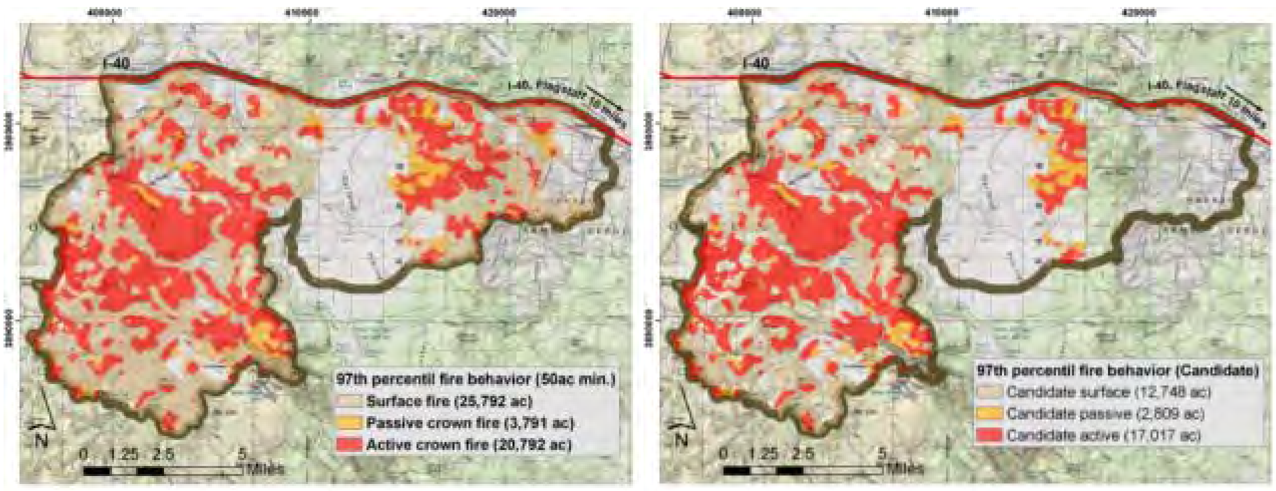

Figure 14. Predicted 97th percentile fire behavior for (**A**) ponderosa pine forest and (**B**) candidate ponderosa pine forest areas only.

Specific Management Criteria

The Garland Area contains areas that require specific management consideration in terms of treatment or fire protection:

17,018 acres of [TYPE OF TREATMENT] within areas of predicted active crown fire behavior within candidate areas

2,810 acres of [TYPE OF TREATMENT] within areas of predicted passive crown fire behavior that are typically adjacent to areas of active crown fire within candidate areas

4,875 acres of excluded areas [LIST TYPE OF ALL EXCLUDED ACRES]

8,382 acres of Pine-oak Mexican spotted owl restricted habitat

18,614 acres of grass and shrub dominated meadows to consider potential conifer encroachment.

Landscape Context

Treatment Area [##] is adjacent to Treatment Areas [#,#,#,# and #]. It is upwind from Treatment Areas [# and #], which contain relatively [DESCRIPTION OF AMOUNT OF "VALUABLE AREAS"], and downwind from Treatment Areas [# and #], which have [DESCRIPTION OF POTENTIAL FIRE BEHAVIOR IN DOWNWIND TREATMENT AREAS]. Additionally, Treatment Area [#] is bordered by [DESCRIPTION OF AREAS THAT REQUIRE SPECIFIC MANAGEMENT CONSIDERATION CONTAINED IN ADJACENT TREATMENT AREAS] that is contained in Treatment Areas [# and #].

VI. DESIRED CONDITIONS FOR PONDEROSA PINE FORESTS IN ARIZONA

The ponderosa pine forest type occurs in the Lower Montane Coniferous Forest. Within the Four Forest Restoration Initiative (4FRI) area, the ponderosa pine ecosystem is dominated by *Pinus ponderosa* var. *scopulorum*, which occurs in pure stands and may also occur with oaks, junipers, pinyon pine, and aspen. In addition, there are transition or ecotone areas where ponderosa pine may be the dominant species, but is intermingled with juniper on drier sites, and white fir and Douglas-fir on more moist sites. Plant associations include numerous grass, forbs, and shrub species, which enhance native plant diversity within the ponderosa pine type.

The natural variability of ponderosa pine forests in northern Arizona includes predominantly frequent surface fire regimes, robust and diverse understory communities and more open, variable forest structures dominated by large, old trees often growing in groups. Fires naturally occur in late spring and summer and their frequency, extent and severity vary with climate, topography and elevation. The variability of forest productivity and structure supports diverse wildlife and facilitates natural trophic interactions. Our understanding of natural variability derives from converging lines of evidence. Those include surveys, photographs and written accounts of pre-settlement forest conditions; research reconstructing pre-settlement forest structure, function, and dynamics; and research studying contemporary relict forests not subject to industrial logging, fire suppression and livestock grazing. Reference conditions help to describe the evolutionary context of ecological systems and identify major determinants of self-regulating ecosystem structure and function.

Desired Conditions

Desired conditions (DCs) are defined for the 4FRI area as a set of ecological, social, and economic objectives established as both qualitative aspirations and measureable outcomes of forest restoration activities. The DCs are long-term goals and are different from post-treatment conditions and near-term plant community responses, which are regarded as milestones toward meeting landscape-scale forest restoration objectives. Restoration treatments should put forest ecosystems on a trend toward their natural structure, composition and patterns and facilitate the re-establishment of self-regulating processes consistent with reference conditions. An adaptive management approach would be implemented to promote flexible decision-making that can be adjusted in the face of uncertainty as outcomes from management actions and other events become better understood.

a. Spatial Scale

   DCs for ponderosa pine forests are identified within the 4FRI area at three spatial scales and extents:

   i. *Landscape*– 2.4 million acres in size, encompasses the entire 4FRI project area
   ii. *Analysis area*– ~750,000 acres in size, encompasses the entire analysis area contained in 4FRI's first Environmental Impact Statement (EIS)
   iii. *Firescapes* [6] -(≥200,000 acres) are a unit of analysis for comparing current base-line forest conditions and desired future conditions as a result of strategic forest restoration activities.

b. Thematic Areas

   Within each spatial scale, DCs are categorized by five thematic areas: 1) conservation of biological diversity, 2) ecosystem resilience, 3) conservation and maintenance of soil, water and air resources, 4) economics, and 5) social systems. The specificity and nature of DCs within these thematic areas differs depending on the particular spatial scale at which they are addressed.

[6] Firescapes are landscapes where fire is an important part of ecosystem processes. They are ≥200,000 ac in size and broadly delineated by terrain features, watershed boundaries, the spatial extent of ponderosa pine forest, contemporary wildland fire patterns, and infrastructure such as major roads. For purposes of the 4FRI they provide a framework to support managing fire across large landscapes in order to achieve sustainable, resilient ecosystems.

Landscape Desired Conditions

At the landscape scale, DCs are described as qualitative goals that should be achieved through the restoration of ponderosa pine forest types within the entire 4FRI area.

a. Conservation of biological diversity
    i. Ponderosa pine ecosystems provide the necessary composition, structure, abundance, distribution, and processes that contribute to the diversity of native plant and animal species across the 2.4 million acre 4FRI landscape
    ii. Viable, ecologically functional populations of native species that include common, listed rare and sensitive species persist in natural patterns of distribution and abundance.
    iii. Natural disturbance processes (e.g., fire, drought-mortality, endemic levels of forest pests and pathogens) are the primary agents shaping forest ecosystem structure, dynamics, habitats, and diversity over time.
    iv. Where fire use is not possible, mechanical treatments are designed to restore and/or maintain forest structure over time.

b. Ecosystem resilience
    i. Ponderosa pine ecosystems in the 4FRI are capable of adapting to or persisting with climate change without rapid, large scale type shifts.
    ii. There is reduced potential for introduction, establishment, and spread of invasive species and the reduction of existing infestations.
    iii. Low intensity frequent fire operates as the primary natural process maintaining forest structure and function.
    iv. Mixed severity fire is sometimes used as a restoration tool in appropriate ecological and social settings (e.g., non-WUI areas) to restore and maintain natural forest types
    v. Forest insects and pathogens occur and operate at endemic levels.
    vi. Ponderosa pine ecosystems in the 4FRI are capable of regeneration and recovery following natural disturbance (e.g., fire, outbreaks of insects and pathogens).

c. <u>Conservation and maintenance of soil, water and air resources</u>

   i. Soil productivity, watershed function, and air quality are not at risk of being degraded by uncharacteristically severe disturbances (e.g., landscape level high-severity fire).

   ii. Sensitive soils are protected through use of appropriate timber harvesting equipment and techniques to reduce erosion and sedimentation that could otherwise damage aquatic life, increase flooding, reduce reservoir capacity, and increase costs of maintaining infrastructure in the vicinity of waterways.

   iii. Forest structure supports a variety of natural resource values and processes, including hydrologic function, which meets ecological and human needs.

   iv. Fire is used as a management tool to support hydrologic function while minimizing impacts to soils and other natural resource values.

   v. Rare and ecologically valuable springs and wet meadows are protected and enhanced through appropriate restoration treatments where needed.

d. <u>Economics</u>

   i. The byproducts of mechanical forest restoration offset the costs of treatment implementation.

   ii. The economic value of ecosystem services provided by restored forests (such as the value of recreation or water) are captured and re-invested to support forest restoration and ecosystem management.

   iii. Rural communities receive direct and indirect economic benefits and ecosystem services as a result of forest restoration and resilient forests.

e. <u>Social systems</u>

   i. There is broad public awareness, understanding/knowledge and support for collaboratively based forest restoration decisions, processes, and outcomes, including the use of fire as a management tool.

   ii. Social values and recreational opportunities are protected and/or enhanced through forest restoration activities.

   iii. Rural communities are protected from high-severity fire and their quality of life is enhanced through forest restoration.

iv. Rural communities play an active part in reducing fire risk by implementing FIREWISE actions and creating defensible space around their property.
v. There is broad public support for the 4FRI collaborative as forest restoration activities are implemented.

Analysis Area Desired Conditions

At the analysis-area scale, DCs are described as qualitative and functional goals that are tailored to address the specific ponderosa pine forest types and other ecological, social, and economic issues within the identified EIS analysis area.

a. Conservation of biological diversity
   i. Ponderosa pine ecosystems provide the necessary composition, structure, abundance, distribution, and disturbance processes that contribute to the diversity of native plant and animal species across the analysis area.
   ii. Viable, ecologically functional populations of native species that include common, listed rare and sensitive species persist in natural patterns of distribution and abundance.
   iii. Natural disturbance processes (e.g., fire, drought-mortality) are the primary agents shaping forest structure dynamics, habitats, and species diversity over time.
   iv. Ponderosa pine ecosystems are composed of all age and size classes within the analysis area and are distributed in patterns more consistent with reference conditions.
   v. Ponderosa pine ecosystems are heterogeneous in structure and distribution at the analysis area. Openings and densities vary within the analysis area to maintain a mosaic appropriate to support resilience of individual trees and groups of trees.
   vi. Ponderosa pine vegetation supporting listed, rare, and declining species and surrounding vegetation is strategically managed to be resilient to uncharacteristic disturbances.
   vii. All pre-settlement trees are retained.
   viii. Understory vegetation composition and abundance are consistent with the natural range of variability.

b. Ecosystem resilience

  i. A majority of the ponderosa pine ecosystems supports frequent, low-intensity fire.
  ii. Mixed severity fire is sometimes used as a restoration tool in appropriate ecological and social settings (e.g., non-WUI areas) to restore and maintain natural forest types
  iii. Ponderosa pine ecosystems are restored to more natural tree densities in order to maintain availability of moisture and nutrients to support adaptation to climate change without rapid, large scale type shifts.
  iv. There is reduced potential for introduction, establishment, and spread of invasive species and the reduction of existing infestations.
  v. Vegetation treatments in ponderosa pine ecosystems are designed and implemented to prevent the spread of invasive species. Ponderosa pine treatments are designed to protect soil and increase understory biodiversity and productivity to improve their resilience to invasive species.
  vi. Natural disturbance processes (e.g., fire, endemic pests, and pathogens) are within the natural range of variability.

c. Conservation and maintenance of soil, water and air resources

  i. Ponderosa pine vegetation treatments are implemented so as to minimize negative impacts to water quality, soil productivity, and air quality. Short-term impacts are minimized through the implementation of best management practices and strategies.
  ii. Restored ponderosa pine ecosystems accommodate natural and other fires without uncharacteristic impacts to soil productivity and or watershed resources.
  iii. Ponderosa pine vegetation within the analysis area is managed strategically and at a level appropriate to prevent degradation of air quality beyond regulatory standards (through wildland fire or managed fire).
  iv. Forest openings are designed to improve snow accumulation and subsequent soil moisture and surface water yield.
  v. Hydrologic processes are re-established to restore springs and wet meadow ecosystems.

d. Economics

i. The average net cost of treatment per acre for all treatments in the analysis area over a ten year period is reduced significantly.

ii. Sufficient harvest and manufacturing capacity exists to achieve restoration of at least 300,000 acres in the next ten years.

iii. Rural communities in the analysis area experience economic benefits and improved ecosystem services associated with a restored forest and reduced high-severity fire risk.

e. Social systems

i. A majority of the general public is aware, knowledgeable and supportive of 4FRI related plans and implemented treatments within the analysis area.

ii. The general public is aware of 4FRI educational and outreach programs and has the opportunity to participate in the 4FRI effort.

iii. Treatments within the analysis area minimize short-term impacts and enhance vegetation characteristics valued by Forest users over the long-term.

iv. 4FRI restoration efforts maintain and/or enhance the quality of life of residents in the analysis area.

Firescapes

Firescapes are sub-landscapes within the analysis area which encompass >200,000 acres and where mechanical thinning and fire can be applied in a strategic and systematic manner for restoring fire adapted ponderosa pine conditions. The goal is to create a contiguous geographic area where natural fire and other disturbances can be safely restored over a time-period of approximately 5 to 20 years, depending upon existing conditions.

a. Conservation of biological diversity

i. There is low potential for unnaturally severe fire to spread across the firescape.

ii. Protect old-growth forest structure during planned and unplanned natural ignition fires.

iii. Natural and prescribed fires maintain and enhance, but do not degrade habitat for listed, rare and sensitive species.

iv. Habitat management is contributing to the recovery of listed species.

v. Wherever practicable, natural fire regimes regulate forest structure and composition.
vi. Planned and unplanned fires support diverse native understory communities and their associated biodiversity.
vii. Populations of native species occur in natural patterns of distribution and abundance.
viii. Forest conditions facilitate species' movement to and from adjacent landscapes, ecosystems or habitats.

b. Ecosystem resilience

i. There is low potential for unnaturally severe fires to spread across the firescape.
ii. Strategically placed treatments allow fire managers to safely manage planned and unplanned natural ignitions fires in a way that benefits and enhances the resilience of forest ecosystems.
iii. Restoration results in forests that are trending toward natural variability, self-regulating, and positioned to adapt to climate change without large, rapid type shifts.
iv. Where possible, natural fire regimes regulate forest structure and composition and align forest changes with climate changes.
v. Natural disturbance processes (e.g., fire, endemic pests and pathogens) occur at endemic levels.
vi. Exotic species are rare or absent and do not create novel ecological communities following disturbance.

c. Conservation and maintenance of soil, water and air resources

i. Strategically placed treatments allow fire managers to manage planned and unplanned fires in locations, seasons and conditions that maximize smoke dispersion and minimize smoke impacts.
ii. Emissions factors, smoldering, and smoke residence time are reduced as fires burn more grass and less green or woody biomass over time.
iii. Stable, restored ecosystems foster watersheds that yield enhanced water quantity and quality and are resilient to climatic variability.

d. Economics

i. Fire management costs are reduced; aggressive fire suppression is unneeded or rare.

ii. Mechanical treatment costs are reduced.

e. Social Systems

i. There is low potential for fires to enter communities.

ii. Rural communities play an active part in reducing fire risk by implementing FIREWISE actions and creating defensible space around their property.

iii. Strategically placed treatments allow fire managers to safely manage planned and unplanned natural ignition fires without loss of human life and property, or severe environmental impacts.

iv. Strategically placed treatments allow fire managers to manage planned and unplanned natural ignition fires in locations, seasons, and conditions that maximize smoke dispersion and minimize smoke impacts.

v. Emissions factors are reduced as fires burn more grass and less green or woody biomass over time.

vi. The public understands, accepts, and supports fire's natural role in forest ecosystems.

VII. RECOMMENDATIONS

The above process provides a proof-of-concept for using a systematic approach to stratify a large analysis area into strategic areas for treatment area identification and description of existing and desired conditions within current and future analysis areas. From this process, the following six working group recommendations specify how forest restoration could be strategically applied within the 4FRI landscape:

1. We recommend that forest restoration proposed actions be described at three scales of analysis: the analysis area, the firescape, and the treatment area.
2. We recommend that the USFS use the process described for identifying and delineating firescapes and treatment areas as a consistent method to conduct landscape scale forest restoration and meet desired conditions. Firescapes provide a systematic process of

characterizing current forest conditions and allows managers to compare and contrast landscape differences.

3. We recommend that desired conditions for conservation of biodiversity, conservation of soil, air, and water resources, ecosystem resiliency, economics, and social systems are acknowledged at each of the three defined scales. These desired conditions should be carried forward into project-level planning and decision-making.
4. We recommend that the USFS continue to collaborate with the 4FRI stakeholder group throughout all phases of the planning process and as the LSWG and stakeholder group completes the comprehensive landscape strategy for the entire 4FRI area. This collaboration should continue to have a high-level of transparency and development of analysis milestones. The following recommended next steps would occur in collaboration with USFS and coincident with USFS planning:
    - Treatment Area Descriptions for treatment areas in the first EIS analysis area, which shall include a description of treatment area-specific site characteristics, desired future conditions, and management options for achieving comprehensive ecosystem restoration (e.g., thinning, fire management, wildlife habitat improvement, watershed management, riparian restoration).
    - A comprehensive landscape strategy report for the entire 2.4 million acres
    - Treatment Area Descriptions for the remaining 2.4 million acres that were not included in the first EIS analysis area
5. We continue to recommend that the USFS implement a monitoring program consistent with the framework and recommendations developed by the SMWG as a necessary step in the adaptive management process.
6. We recommend that the USFS work with the 4FRI stakeholder group to use available decision-support and forest modeling tools, where appropriate, to develop proposed actions, potential treatment alternatives, and to aid with post-treatment monitoring.

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APPENDIX A. The Economics of Forest Restoration.

The Economic and Utilization analysis of the landscape strategy identifies issues and solutions to the barriers that undermine wood utilization. It also examines policy changes that may be required for stewardship contracting. Finally, it explores the desired and emerging opportunities to capture the value of ecosystem services so that they can be used to support ecological restoration. A fuller discussion will be provided in the comprehensive landscape strategy report. A summary of the key elements of the strategy are included below.

Wood Utilization

⇒ ***Issue:*** **Administrative costs of treatment preparation are too high**. Administrative costs to the Forest Service for treatment preparation include: project preparation, task order/contract administration, planning required under NEPA and NFMA, and project management.
Solution: **Strive for greater efficiency by qualifying more acres per treatment per dollar spent.**
- Where appropriate use task orders rather than contracts to save overhead cost. Although still untested, working at the landscape scale and qualifying more acres under one EIS will hopefully reduce the cost of NEPA.

⇒ ***Issue:*** **It is difficult to profitably utilize large volumes of small-diameter wood**. In order for the private sector to make a profit there must be a market place for small diameter wood products.
Solution: **Where appropriate use federal and state policies to influence markets for wood products.**
- From an energy perspective maintain and/or increase renewable energy standards to increase demand for biomass generated electricity and thermal energy
- Define biomass-generated electricity and thermal energy as a “renewable energy”
- Provide a definition of biomass that is inclusive of products harvested from federal lands during forest restoration activities
- Encourage the state to purchase wood products that are manufactured from wood in Arizona
- Generally and specifically support the use of Arizona-grown, ponderosa pine-derived products (e.g., modify building codes to allow for the use of pine lumber)
- Develop financial incentive programs that support Arizona’s existing and future wood products industry.

⇒ ***Issue*:** **There is uneven harvest, milling and manufacturing capacity across the 4FRI region.** On the western side of the Mogollon rim infrastructure is limited; on the eastern side capacity has developed as a result of the stewardship contract.

***Solutions*:** **Infrastructure should be supported where it exists and encouraged where none exists but is needed.**
- Existing infrastructure that is capable of utilizing sufficient quantities of restoration byproducts and supporting 4FRI’s restoration efforts should be sustained and supported. It may be necessary in these places to subsidize treatments. The value of

restoration combined with the value of avoiding severe fire and associated damage justifies this investment.
  - Where infrastructure capable of supporting forest restoration does not exist, or where exiting industry is struggling, actions should be taken that support a favorable investment climate. The Forest Service can encourage investment by configuring contracts and structuring task orders to ensure wood supply and economically viable harvest regimes over time periods that are long enough to recover costs and provide a return on investment.

⇒ ***Issue*:** **Wood supply can be unpredictable and therefore undermine private investment.** Predictability of wood supply from federal land is a key issue to investors. Decreasing wood supply from federal land during the late 1980s and 1990s contributed to the closing of wood-based industries in the Southwest. Several factors influence the flow of wood from federal land: (1) the capacity of the federal government to complete administrative tasks and (2) disruptions due to legal challenges.

Solution: **To ensure a predictable wood supply**:
  - The 4FRI will collaboratively plan management in order to build stakeholder support. The goal is to create a plan that is broadly supported, thereby lowering the risk of administrative and legal challenges.
  - The NEPA documents will unfold at a large scale to achieve administrative efficiency, improve cumulative effects analysis, and improve the strategic timing and placement of treatments.
  - The Forest Service and Congress will need to invest in the recruitment and training of sufficient personnel to accelerate administrative planning and deliver 50,000 acres of mechanical treatments per year.

⇒ ***Issue:*** **The contracting instrument chosen to implement treatments will influence private investment and business sustainability.**
Solution: In order to sustain or attract business the contract instrument should be flexible and should:
  - Support actions that are needed to perform ecological restoration
  - Span a sufficient time period to provide an adequate return on private investment
  - Provide a guarantee of annual acres of treatments
  - Allow the exchange of goods for services

Stewardship Contracting

⇒ ***Issue:*** There are two significant challenges associated with using stewardship contracts to accomplish the 4FRI's goals: (1) stewardship contracts have a statutory 10-year limit on contract duration and (2) stewardship contracts generally require a cancellation ceiling. Additionally, the Forest Service's authority to execute Stewardship Contracts is scheduled to expire in 2013 and uncertainty remains regarding a legislative extension.
Solutions: In order to overcome the challenges associated with using a stewardship contract the industry representatives in the 4FRI stakeholders collaborative have identified the following questions:
With regard to the contract duration:
  - Can the Forest Service develop and implement a long-term strategy to sequence/phase contract issuance, within the confines of its stewardship contracting authority, to provide a contract commitment to industry that is greater than 10 years?

- Can the Forest Service immediately follow issuance of a 10-year stewardship contract with a second, prospective stewardship contract?
- Are there other options for extending the term of a stewardship contract?
- Is a statutory extension of the stewardship contract term limit feasible?

With regard to the contract cancellation ceiling policy:

- Can the Forest Service waive or negotiate the amount of the cancellation ceiling requirement for contracts that require significant investment in new infrastructure? Are funds available at the department or agency level to support the cancellation ceiling? Could such funds be guaranteed for the necessary length of time?

- Are there alternative mechanisms that would allow the Forest Service to comply with stewardship contracting cancellation ceiling requirements without creating undue financial burdens for the department, agency, or contracting entity?

With regards to the contracting authority:

- Will the Forest Service or Congress be renewing the Stewardship Contracting Authority?

The Economic Benefits of Restored Forests: Wood Utilization and Ecosystem Services

The strategy identifies numerous economic benefits provided during and after restoration in a restored forest. These include:

- Significant economic benefit for local and regional economies due to businesses and jobs created.
- Reduced wildfire costs both in terms of the cost of wildfire suppression and potential losses due to severe fire.
- Enhanced economic activity associated with recreation, wildlife viewing and hunting
- Protection and conservation of watersheds that support water quality and quantity
- Carbon Sequestration and uncharacteristic loss of carbon due to severe wildfire in overstocked forests.

APPENDIX B. List of analyses identified as important for landscape level restoration planning by the LSWG.

Biodiversity

1. Model wildlife habitat corridors for focal species.
2. Incorporate existing species richness models (for both wildlife and plants).
3. Incorporate the characteristics of fire refugia into decision criteria for prioritizing treatments (e.g., identify areas that would have a higher probability containing naturally dense canopy conditions).
4. Incorporate existing and future recovery plan actions and recommendations into treatment design.
5. Identify habitat requirements necessary to maintain viable populations of focal species.
6. Map current distribution of invasive plant focal species and invasive vertebrate species.

Fire

1. Map natural fire regimes; analysis to be designed with fire-researchers.
2. Map firescapes – discrete geographic areas, or Fire Management Units/Zones, within which strategically placed and sequenced treatments facilitate safely managing planned and unplanned ignitions for resource benefit.
3. Model maximally efficient configurations of ecological restoration treatments that would slow the spread of large scale crown fire under 97th percentile conditions.
4. Identify area where ecological restoration treatments would reduce crown fire behavior under the 97th percentile fire weather conditions.
5. Identify areas where ecological restoration treatments would reduce crown fire behavior under moderate (85th percentile) fire weather conditions.
6. Identify areas where ecological restoration treatments would facilitate the operational management of planned and unplanned ignitions.
7. Plan wildland fire suppression tactics that are operationally effective to protect life and property and community infrastructure.
8. Update CWPPs to identify co-operative funding options, jurisdictions, and responsibilities to fund implementation strategies outside of Federal and State jurisdictions.
9. Evaluate utilization of all policies, authorities and outcome objectives, to meet desired protection outcomes

Restoration

1. Develop landscape scale forests consisting of a range of size and age classes dominated by larger, older trees. Use forest and remote sensing data to characterize and plan treatment areas.
2. Develop forest structure that reestablishes natural range of variability, maintains/enhances heterogeneity, and consists of groups and clumps defined by openings. Use forest and remote sensing data to characterize and plan treatment areas.
3. Develop understory habitat that includes native shrubs, grasses and forbs. Plan overstory treatments to release understory vegetation.
4. Restore micro-habitat features. Account for specific habitat features (e.g., springs, grasslands, late-successional conditions) while planning overstory treatments.
5. Identify areas potentially impacted by terrestrial operations or areas benefiting from treatments.

6. Use climate change models and forest and remote sensing data to characterize vulnerable areas, identify snow retention areas, etc.

Utilization/Economics

1. Understand existing and innovative tree harvest, wood and biomass utilization. Refresh analyses of products and markets and enlist the assistance of the Forest Products Lab.
2. Identify and provide support for federal contracting approaches that encourage investment with a focus on longer contract lengths.
3. Identify current infrastructure, businesses and markets that support wood harvest.
4. Identify areas available for mechanical harvest.
5. Analyze different contract tools and approaches to achieve DCs.
6. Work with the USFS to identify key places where administrative efficiency can be achieved.
7. Explore partnership opportunities with utilities or other entities that benefit from healthy forests.
8. Quantify the number and economic importance of non-wood based businesses.
9. Understand the economic value of water derived from northern Arizona forests and map watersheds and municipalities using the water. Attach economic value to the water
10. Consider the value of sequestering and off-setting carbon emissions.

4FRI Planning Workgroup

Wednesday August 9, 2017 Meeting Minutes
10:00 am to 12:00 pm
Coconino National Forest Supervisor Office – Flagstaff
Conference Call (877) 820-7831, access code 691102#

1) **Welcome and introductions / additions to agenda - Pascal Berlioux.**

   See sign-in attendance sheet attached.

2) **Approval July 5, 2017 meeting minutes - Pascal Berlioux / All.**

   The July 5, 2017 meeting minutes were circulated electronically prior to the meeting. The minutes were approved as circulated.

3) **Approval of final SPLYT language - All.**

   The draft final SPLYT language was circulated electronically prior to the meeting. The workgroup discussed two modifications:
   - Replace "(e.g., UAE 20, upper end of NRV for BA and TPA)" with "For example, a stand identified with the flexible toolbox to receive a UEA 10-25 treatment, would be treated to 10% interspace and to the upper end of NRV for TPA and BA;"
   - Replace "upon site visit" with "upon field verification."

   The workgroup reached unanimous consensus, shared by the Forest Service, on the following final language:

   > The iterative spatial analysis and field validation effort undertaken by the 4FRI Team and stakeholders yielded an initial filter for SPLYT stands located outside of Mexican Spotted Owl (MSO) Protected Activity Centers, MSO Recovery Habitat, and wildland urban interfaces (WUI), SPLYT criteria are: a) Site Class 1; b) Quadratic Mean Diameter (QMD) of the largest 20 trees is >15", and c) there is >50 square feet/acre of basal area in trees >16" diameter at breast height (DBH). All stands will be field-verified prior to mechanical thinning. Stands (or portions thereof) meeting SPLYT criteria, including those not captured by the data filter, will be treated at the lowest range of intensity. For example, a stand identified with the flexible toolbox to receive a UEA 10-25 treatment, would be treated to 10% interspace and to the upper end of NRV for TPA and BA, in order to maintain large tree dominance and conditions favorable to canopy-dependent species. Stands (or portions thereof) that are captured by the SPLYT criteria data filter but upon field verification are determined not to meet the SPLYT criteria will be treated within the range of intensities applied to other non-SPLYT stands.

   The Planning Workgroup agreed to recommend at the August 23 Stakeholders meeting that the language be formally adopted by the Stakeholders Group as the official 4FRI Stakeholders Group language.

4) Fire Treatments in MSO PACs - USFS / All.

The Forest Service gave a presentation on proposed fire treatments in some MSO PACs located in the 1st EIS footprint. This presentation will also be given to the Stakeholders Group at the August 23 Stakeholders meeting.

The Planning Workgroup agreed to recommend at the August 23 Stakeholders meeting that the proposed fire treatments be formally endorsed by the Stakeholders Group.

5) Recommendation on Rim Country NEPA Alternatives to Stakeholders Group - USFS / All.

The Planning Workgroup discussed extensively whether to make the recommendation to the Stakeholders Group that the Stakeholders Group request that the Forest Service re-instate the original Alternative 3.

The Planning Workgroup could not reach consensus, as members answered the question as follows:

- Ecological Restoration Institute: yes
- Grand Canyon Trust: no
- Arizona Game & Fish Department: no
- Center for Biological Diversity: no
- Eastern Arizona Counties Organization: no
- Nature Conservancy: pass
- Trout Unlimited: pass

Although the Forest Service was not invited to participate in the stakeholders' recommendation decision, the position of the Forest Service was stated as Alternative 3 having been removed from the NEPA analysis.

The Planning Workgroup agreed to report to the Stakeholders Group that it was not able to reach consensus, and that it would therefore not make the recommendation to the Stakeholders Group that the Stakeholders Group request that the Forest Service re-instate the original Alternative 3.

6) Action items / Next meeting .

For lack of agenda item, the Planning Workgroup agreed to cancel the regularly scheduled August 17 conference call.

The next Planning Workgroup meeting will be held on Wednesday September 6, 10:00 am to noon, at the Coconino SO. USFS will provide agenda items.

Planning Committee 8/9/17

Wendy Jo Haskins	USFS
Randy Fuller	USFS
Jamie Clark	AZ G&F
Todd Schulke	CBD
Amy Waltz	ERI
Neil Chapman	TNC
CARY THOMPSON	USFS
Steve Rosenstock	AZGFD
John Souther	USFS
Debra Mollet	USFS
Pascal Berlioux	ECO
Mary Lata	USFS
Patrick Moore	USFS
Mike Dechter	USFS
Joe Miller	TU
Annette Fredette	FS
Matt Cole	USFS
Travis Bruner	GCT
[illegible]	USFS
Scott Russell	USFS

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silviculture

Decoupling the Diameter–Age Debate: The Boise National Forest's Legacy Tree Guide

John Riling, Kathleen Geier-Hayes, and Theresa Jain

As trees age, they develop discernible attributes (legacy characteristics), that provide critical wildlife habitat. An arbitrary diameter cap is often used in planning to ensure old trees remain on the landscape. Although a relation exists between tree age and diameter, several environmental factors also influence growth; consequently, not all large trees are old and not all small trees are young. Personnel on the Boise National Forest questioned the efficacy of using a diameter cap of 20 in. (51 cm) as a method for conserving old trees because it prevented the ability to meet other Forest Plan desired conditions associated with restoring ecosystems. To address this concern, Forest personnel conducted an administrative study within four project areas. Data were collected on trees ≥20 in. (51 cm) dbh—primarily ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*). Results from this study provided the data used to refine a locally relevant legacy tree field guide, built trust among stakeholders, and improved the environmental planning process.

Keywords: old trees, ponderosa pine, diameter limit, stakeholder collaboration, restoration

Both large and old trees serve a variety of structural and functional roles within forested ecosystems. Old trees are unique because they display distinguishable characteristics from younger trees. Perry and Amaranthus (1997)and Franklin et al. (2007) describe these old trees and other survivors of disturbance as "biological legacies." Kaufmann et al. (2007) and Van Pelt (2008) labeled these types of trees "legacy trees." The bole of legacy trees, by nature of the structural complexity of their bark surface, can provide numerous microhabitat sites supporting abundant and diverse insect communities, which in turn support large varieties of wildlife species and enhanced species diversity (Lindenmayer and Laurance 2017). Legacy trees and trees with legacy characteristics contribute to functional old forest habitat and can serve as ecological "stepping stones" for plant and animal species across a landscape (D'Amato and Catanzaro 2009). When dead, they provide a unique snag habitat compared to younger dead trees because they have a greater surface area of loose bark, more stem and branch decay, and larger cavities (Mannan et al. 1980). Trees with legacy characteristics generally provide a greater dead wood medium for arthropods, crevices, or cavities for roosting bats, perching sites for raptors and other birds, excavation opportunities for cavity nest or den sites, and a growth substrate for fungi, moss, and lichens than dead trees with less surface area or less structurally complex bark and limbs. These large dead trees also tend to remain upright longer than younger snags because they have more extensively developed root systems and a higher proportion of heartwood that decays slower than sapwood (Morrison and Raphael 1993, Bull et al. 1997). Generally, these trees are survivors of past disturbances, from either one previous stand initiation event or numerous low- to moderate-intensity disturbance events (Figure 1). These survivors act as a sanctuary in disturbance-driven ecosystems by preserving biological diversity through seeds, maintaining certain types of habitat and microclimates, and helping preserve connectivity within and across landscapes.

Legacy trees typically grow in openings and generally occur in dominant or co-dominant crown classes, which favor large crown development (Figure 2). They can be a single isolated tree or grow together in clumps and groups. In addition, older trees have deep bark fissures, wide bark plates, greater variation in bark color, flattened or rounded crowns, dead or epicormic branches on the lower bole, possibly dead tops, and a complex crown form. Van Pelt

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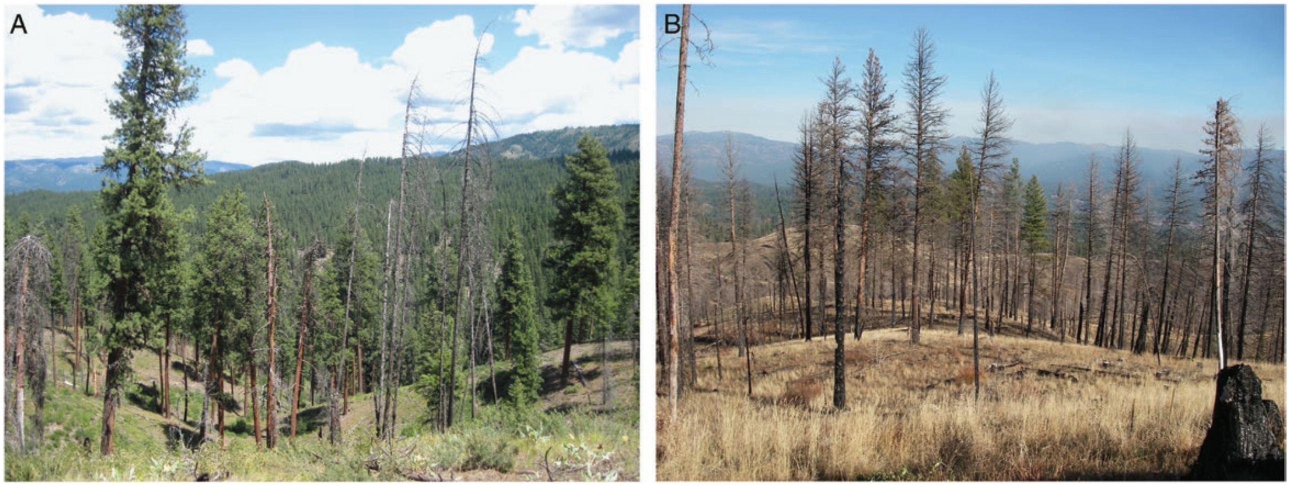

Figure 1. Trees that survive disturbance may become legacy trees. Particularly trees that live through numerous disturbances (A) or survive high intensity wildfires (B) develop legacy characteristics.

Figure 2. Legacy ponderosa pine, known as the Holbrook tree, located on the Boise National Forest.

(2008) suggested that these characteristics generally start to develop in trees older than 150 years. When managing for old forest conditions in drier forest types, legacy trees provide the foundation from which to build restoration actions (Van Pelt 2008); therefore, it is imperative to be able to recognize and include them during project planning and implementation.

A popular method to maintain these trees on the landscape is to apply an arbitrary diameter cap (all trees above a particular dbh are retained) (USDA Forest Service 2013); however, Van Pelt (2008) noted that although there is a linear relation between diameter and age, tree diameter is more a function of environmental conditions than time. He found that not all old trees were large, and not all large trees were old, and subsequently not all large trees were legacies. He concluded that older trees with legacy characteristics are not necessarily the largest trees.

The Boise National Forest (BNF) Plan, as amended in 2010, emphasizes a wildlife conservation strategy, which focuses management objectives toward restoring, recruiting, and fostering resilient old forest habitat and large tree stand conditions. Long-lived shade-intolerant species such as ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*) are prioritized for conservation, but other species, such as Douglas-fir (*Pseudotsuga menziesii*) or grand fir (*Abies grandis*), have similar legacy characteristics important for old forest habitat (Franklin et al. 2008). In response to public concerns focused on retaining old trees, projects on the BNF started including diameter cap design features/elements (specific means,

Management and Policy Implications

This study addressed three management goals. The first was to adapt the Van Pelt (2008) old tree identification guide for tree species on the Boise National Forest (BNF) to quickly and consistently address management objectives. Field crews were able to use the BNF legacy tree guide to identify old trees efficiently and accurately based on legacy characteristics. The second was to quantify large tree (≥20 in. dbh) abundance and tree diameter–age relations to inform and improve efficiencies in planning. We determine that not all large trees were old, and not all old trees were large, but trees larger than 27.5 in. (69.49 cm) dbh tended to be over 150 years old, which provided a good modeling threshold. Retaining all large trees would result in a large tree size class dominated by young-to-mature, shade-tolerant grand fir. The third goal was to build stakeholder trust and support by illustrating that the forest can conserve old trees using methods other than diameter caps. The local collaborative group expressed support for the legacy tree guide, which helped streamline the National Environmental Policy Act of 1969 planning process. This science-based management approach provides an easily replicated framework for validating tree-age relations in other forests as well as an efficient and effective method to conserve old trees.

measures, or practices that make up aspects of the proposed action and alternatives). The BNF has included different diameter caps, particularly 20.0 in. dbh (50.8 cm), as this corresponds with the Forest's large tree size class. However, consistent with findings of Abella et al. (2006), Triepke et al. (2011), and Sanchez-Meador et al. (2015), managing with diameter caps results in tradeoffs that have been shown to limit the BNF's ability to restore desired species composition and structural conditions (USDA Forest Service 2013). To address these challenges, an administrative study was conducted to answer the following questions: (1) Using an administrative study, did the developed BNF legacy tree guide that used concepts from Van Pelt (2008) provide consistent and reliable identification of legacy trees? (2) Could we identify a diameter–age relation for non-legacy and legacy trees, and if so, was there a diameter threshold that could be used in forest planning to represent trees ≥150 years old?

Methods

Administrative Study Area

Four landscapes were selected in ponderosa pine, Douglas-fir, and grand fir habitat types (Steele 1981) on the BNF, north of Boise, Idaho (Figure 3). These are the dominant habitat types where active management occurs on the forest. In addition, these locations represent moderate growing conditions on the BNF and consequently ideal environments where soil moisture and growing season length should not constrain plant growth. Furthermore, three of the four project areas involved a collaborative process with the Boise Forest Coalition, a citizen-led collaborative group composed of stakeholders from a broad range of outside interests including the environmental community, timber industry, recreational groups, and State and County government, which allowed for direct application of results and collaborative feedback through a consensus decision process (http://boiseforestcoalition.org/main_page.html). The four landscapes occurred within the Scriver Integrated Restoration Project (2013), Williams Creek Project (2015), High Valley Integrated Restoration Project (2016), and French Hazard WUI Project (2018) (Figure 3).

Legacy Tree Rating

Van Pelt's (2008) system rates individual trees into four categories: (1) young tree; (2) mature tree <150 years old; (3) mature tree

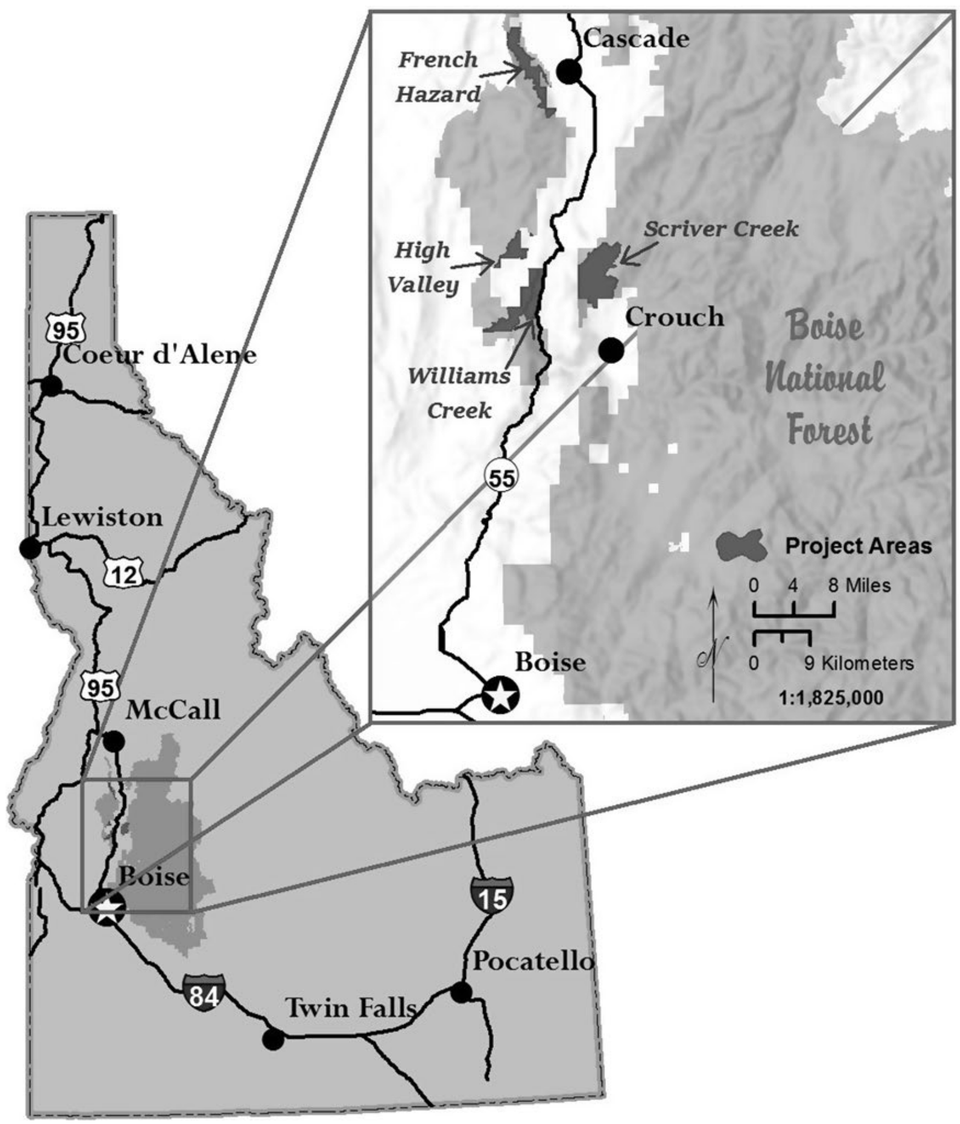

Figure 3. Vicinity map displaying four sampling locations (project areas) on the Boise National Forest.

≥150 years old; and (4) old tree ≥250 years old. The crews assigned each tree a category using three to four groups of criteria specific to each tree species, including bark condition, evidence of knots, crown indicators, and crown vigor. Descriptive criteria within the groups include color, bark plate/fissure size, presence and location of dead branches, branch stubs and knots, epicormic branching characteristics, crown profile, and crown vigor (Van Pelt 2008) (Figure 4, Table 1). Each group is assigned a score ranging from 0 to 5 based on what criteria best fit the tree. For example, the criteria for the bark condition group for ponderosa pine are 0 (dark bark with small fissures), 1 (outermost bark ridge flakes reddish, fissures small), 2 (colorful plates, plate width about equal to fissure width), 3 (maximum plate width between fissures ≥6 in. (15.2 cm) and <10 in. (25 cm), and 5 (maximum plate width between fissures ≥10 in.). The scores for the criteria groups are added together to determine the overall rating for the tree, which then determines assignment to one of the four age categories. Van Pelt (2008) provided a rating system for ponderosa pine, western larch, and Douglas-fir trees.

Van Pelt's (2008) legacy tree rating system provided basic concepts that were used to develop the BNF's legacy tree guide with some modifications. Van Pelt (2008) did not develop a rating system for grand fir, but did provide examples of old tree form, bark characteristics (transitioning from smooth to finely dissected fissures), and attributes that result from multiple disturbances (e.g., fire scars, Indian paint fungus, epicormic branch formation). These indicators were used to classify legacy status for grand fir, but not to determine general age, as Van Pelt (2008) did for other species. In addition, based on forest inventory data and professional judgement, and to reflect differences in growing conditions, forest personnel adjusted tree heights to reflect the shorter trees found on the BNF compared to areas sampled by Van Pelt (2008). Furthermore, the four age categories described in Van Pelt (2008) were collapsed into three:

Figure 4. Photo collage of legacy ponderosa pine, western larch, Douglas-fir, and grand fir on the Boise National Forest.

(1) young, (2) mature (<150 years old), and (3) legacy (≥150 years old). This means that for the purposes of the field guide, all trees that exhibit characteristics of older trees (i.e., meet the rating for mature ≥150 years old and old tree ≥250 years) are identified as legacy. The purpose of labeling mature and old trees as legacy in the field guide is to assure the highest likelihood of conserving the oldest trees as well as those approaching older ages. Field personnel rated all trees using the BNF field guide and assigned either "Not Legacy" (fell into age category 1 or 2) or "Legacy" (fell into age category 3). This categorization was conducted independent of the results of the tree-age coring.

Data Sampling

Two to six belt transects were subjectively placed in ArcGIS to broadly cover a representative sample, in terms of topography and vegetation, within each project area. Field crews flagged and geospatially located the transect line with a GPS. On each transect, crews measured and painted all large trees (≥20.0 in. [50.8 cm] dbh) within 22 feet (6.7 meters) of either side of the line. The transect length was determined by the distance required to obtain reliable increment core age samples from a minimum of 15 ponderosa pine, Douglas-fir, and grand fir (45 in total) trees. Crews painted sample trees with a unique number and also added a paint mark at the base of the bole (downhill side) to allow for future monitoring following treatment. All sample trees had the following measurements recorded: species, dbh, legacy tree status (BNF guide), age at dbh when possible, and radial growth (USDA Forest Service 2014).

Table 1. Rating system for determining young, mature and legacy developmental stages for ponderosa pine trees (USDA Forest Service 2015).

	Score
Lower bole bark condition*	
Dark bark with small fissures	0
Outmost bark ridge flakes reddish, fissures small	1
Colorful plates, plate width about equal to fissure widths	2
Maximum plate width between fissures >6 inches and <10 inches	3
Maximum plate width between fissures >10 inches	5
	Score
Knot indicators on main bole below crown	
Dead branches below main crown, whorl indicators extending nearly to tree base	0
Old knot/whorl indicators visible below main crown	1
No knot/whorl indicators visible	3
	Score
Crown vigor[a]	
Narrow crown but with a defined dominant leader	0
Broad crown with a dominant leader	3
Top of crown may be dead, and if alive the tree has a broad crown with a flat top, and it is difficult to identify a dominant leader	5
	Combined score
Developmental stage scoring key**	
Young tree	<2
Mature tree	2–5
Legacy tree	>6

Note: [a]The legacy tree guide refers to sketches to illustrate crown vigor, which we have not included in this paper.
*Determine bark conditions on the uphill side of tree at dbh.
**Choose one score from each category and sum scores to determine developmental stage.

Tree Age and Statistical Analysis

Trees were aged using a 24 in. (61 cm) long increment borer. The ability to obtain reliable tree ages was constrained by the length of the increment borer and presence of stem decay. Tree ages fell into two categories: trees with no age (unable to obtain an age because the tree either was too large for the increment bore to hit the pith or had stem decay) and trees with a reliable age (age was obtained through the pith). The experimental design used in the analysis considered each tree as a single replicate across the four locations. We conducted a regression analysis to identify the age–diameter relation for all trees, nonlegacy trees, and legacy trees (question 2—stated as a hypothesis). The regression analysis used a logarithm transformation of age to fulfill regression assumptions of normality and random error (Myers 1990). The analysis was conducted using SAS statistical software (Myers 1990, SAS Version 9.4 2016). Each hypothesis was evaluated at $\alpha = 0.05$. For some species, we had very low sample sizes (western larch and Engelmann spruce) with reliable ages, so we conducted the regression analysis for three species, ponderosa pine, Douglas-fir, and grand fir when evaluating the age and diameter relations. Subalpine fire had so few observations that we did not add these to the analysis. We did not conduct any statistical analyses on parameters to inform the legacy tree guide (question 1) but did identify omission and commission error from our field evaluation.

Results

Distribution of Sampled Trees

Data were collected from 1,538 trees including ponderosa pine, western larch, Douglas-fir, Engelmann spruce, grand fir, and subalpine fir. Grand fir represented 45 percent of the sample followed by Douglas-fir (31 percent) and ponderosa pine (20 percent) (Table 2). Other species in combination made up approximately 4 percent of the sample. Of the 1,461 ponderosa pine, Douglas-fir, and grand fir sampled, 32 percent (95 trees) of the ponderosa pine, 6 percent (30 trees) of the Douglas-fir, and 10 percent (70 trees)

Table 2. Number and percentage of all trees, legacy trees, all trees with a reliable age, and legacy trees with a reliable age.

Species	All trees		All legacy trees		Trees with reliable ages		Legacy trees with reliable ages	
	(*N* = 1538)		(*N* = 198)		(*N* = 691)		(*N* = 104)	
	N	%	*N*	%	*N*	%	*N*	%
Ponderosa pine	300	20	95	32	146	21	62	42
Western larch	7	<1	3	42	7	1	3	42
Douglas-fir	474	31	30	6	222	32	23	10
Engelmann spruce	67	4	0	0	30	4	0	0
Grand fir	687	45	70	10	285	41	16	6
Subalpine fir	3	<1	0	0	1	<1	0	0

of the grand fir were legacy trees. The number of nonlegacy and legacy trees by diameter range varied depending on the species (Table 2). Grand fir trees tended to have the most stem decay and unreliable ages, which likely partially accounts for the lower proportion of legacy grand fir older than 150 years, since older trees have greater levels of stem decay (Bull et al. 1997). There were 95 ponderosa pine categorized as having legacy characteristics, with most of these trees ranging from 25 to 45 in. dbh (63.5 to 114.3 cm). In contrast, nonlegacy trees primarily ranged from 20 to 35 in. dbh (50.8 to 88.9 cm). Douglas-fir legacy trees occurred throughout most diameters measured, whereas nonlegacy Douglas-fir were primarily <30 in. dbh (76.2 cm). A similar pattern occurred in grand fir with legacy trees dominating the 30 to 45 in. dbh (76.2 to 114.3 cm) and nonlegacy trees dominating the 20 to 30 in. dbh (50.8 to 76.2 cm).

There were 691 trees with reliable ages, and of those 660 trees were Douglas-fir (32 percent), ponderosa pine (21 percent), and grand fir (41 percent) (Table 2). Only 101 trees were classified as legacy, and of these, 62 trees were ponderosa pine, 23 were Douglas-fir, and 16 were grand fir (Table 3). Most of the legacy trees (84 percent) were 150 years and older. In contrast, of the 552 trees that did not meet the legacy rating, most were grand fir (269 trees), but only 4 percent of these trees were 150 years and older. In fact, 96 percent of the trees that did not meet the legacy rating were younger than 150 years old. A 16 percent commission error was recorded for trees that were rated as legacy, meaning they had legacy characteristics, but were <150 years old. A 5 percent omission error was recorded for trees that were not rated as legacy, but were ≥150 years old.

Diameter and Age Relations

For trees that had reliable ages, the regression analysis identified different results depending on whether or not the tree expressed legacy characteristics (Figure 5). Nonlegacy trees consistently had a strong significant relation between diameter and age ($P < .0001$), although the variation explained by this relation was low. The r^2 for ponderosa was 0.29, and for the other species, r^2 was 0.16 or 0.17. For legacy trees, only ponderosa pine had a statistically significant ($P = .0047$) relation between diameter and age when tested at the $P = .05$ level. However, the r^2 was only 0.12. The other two tree species did not have a significant relation between diameter and age. If we impose 27.5 in. dbh (69.8 cm) as a possible diameter threshold, many nonlegacy trees have diameters larger than this threshold, some exceeding 35 in. dbh (88.9 cm), although the majority of these trees do occur below this threshold. In contrast, legacy trees can be smaller than this diameter threshold. These results indicate that the legacy tree guide is a necessary component when implementing projects that desire retention of old trees. However, when conducting environmental analysis with computer models (such as the Forest Vegetation Simulator [Dixon 2018]), a field verified diameter, such as 27.5 in. (69.8 cm), provides a useful indicator of old trees.

Discussion

The BNF undertook this study to accomplish three goals: (1) to assess whether a legacy tree guide can provide a consistent and accurate method to identify old trees in the field using tree characteristics; (2) to quantify information on large tree abundance and diameter–age relations to inform and improve efficiencies in planning; and (3) to build stakeholder trust and support that the Forest's integrated restoration projects could conserve old trees through methods other than diameter caps.

The BNF adapted concepts from Van Pelt's (2008) legacy tree guide with the hope it would provide a fast, efficient, repeatable, and less costly method for identifying old trees that did not rely on tree cores. Although the rating system can appear subjective, the legacy tree characteristics are distinct and easy to quantify. Field personnel were able to identify older trees based on legacy tree characteristics; in fact, the majority of trees older than 150 years were characterized as legacies using the field guide (Table 3). Additionally, field crews comprising a variety of experience levels and backgrounds were able to incorporate legacy tree conservation into marking and layout without any noticeable loss in production. With adjustments for local species and conditions (Lindenmayer and Laurance 2017), this type of guide has potential application for other National Forests facing similar questions about the relation of diameter to age, particularly for National Forests where diameter caps have been built into Forest Plans (Brown 2012). Although the BNF has also used mensuration-based approaches to conserve older trees, this study demonstrates that the use of diameter caps comes with tradeoffs, and an ecologically based approach, such as the legacy tree guide, can be more effective and just as efficient at conserving old trees.

Based on data analyses for all trees with reliable ages, trees at least ≥150 years old were generally larger than 27.5 in. (69.8 cm) dbh, and many trees were larger than the commonly applied 20.0 in. (50.8 cm) dbh cap; however, these trees were not necessarily old. This indicates that a 20.0 in. (50.8 cm) dbh diameter cap can capture large numbers of younger, often shade-tolerant species like Douglas-fir and grand fir. Although a diameter cap may be a useful tool for modeling (e.g., using the Forest Vegetation Simulator [Dixon 2018]) to represent older trees during the environmental planning phase, the legacy tree guide appears to be a more appropriate tool for conserving older trees during implementation. The BNF Forest Plan highlights the need to conserve large as well as old trees in order to promote important attributes of ecosystem integrity. However, this study demonstrated and validated Van Pelt (2008) who stated that not all large trees were old, and not all old trees were

Table 3. Percentage of trees with reliable ages that met and did not meet legacy characteristics by species, categorized around a 150-year age break.

Species	Meets legacy			Does not meet legacy		
	Total (*N*)	<150 years (%)	≥150 years (%)	Total (*N*)	<150 years (%)	≥150 years (%)
Ponderosa pine ($N = 146$)	62	8	92	84	88	12
Douglas-fir ($N = 222$)	23	17	83	199	95	5
Grand fir ($N = 285$)	16	38	62	269	96	4
Total ($N = 660$)	101	–	–	552	–	–

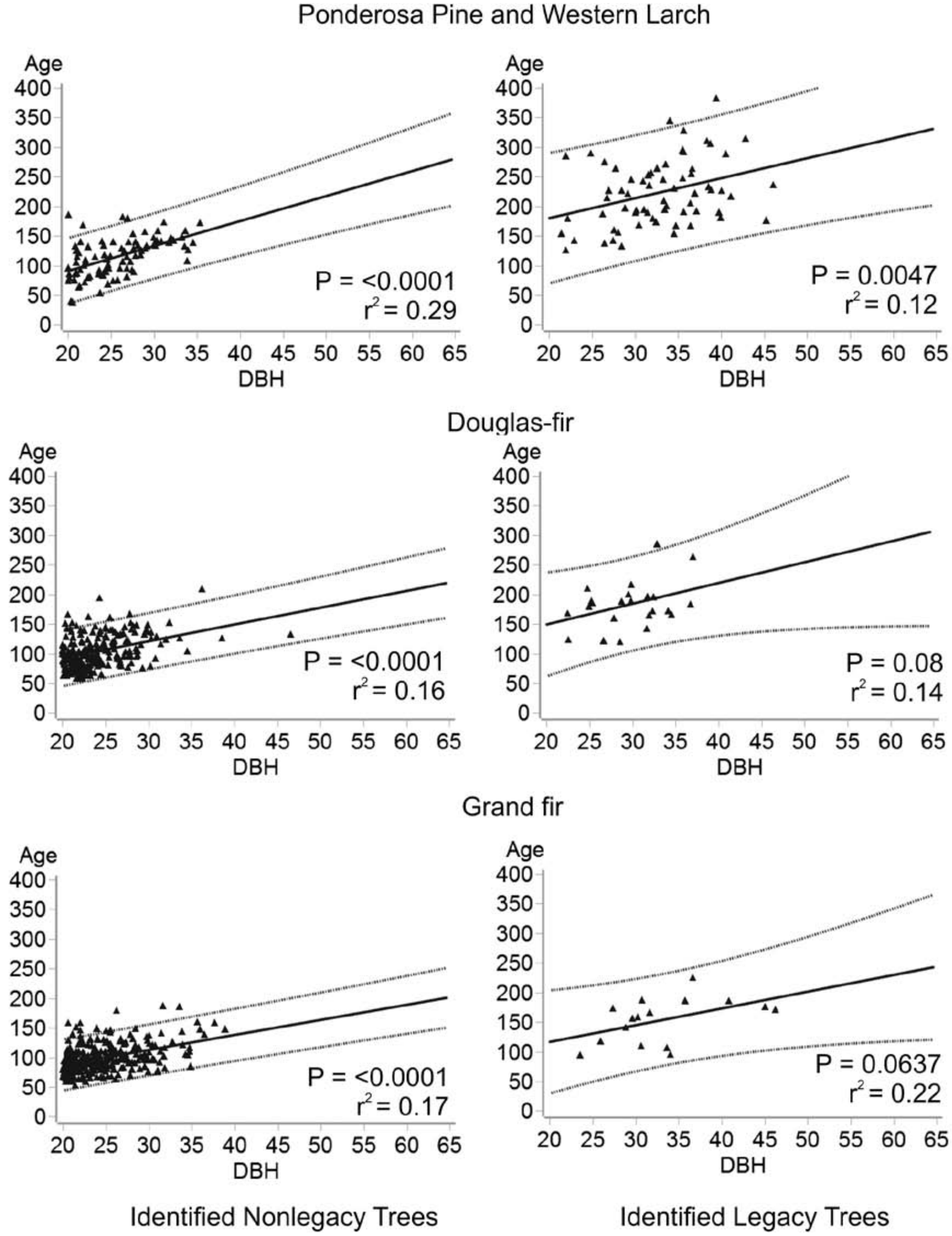

Figure 5. Relation between diameter and age for three species groups: statistical results and proportion of the variation explained by the relation (r^2).

large. Restoration incorporating age as opposed to a strict diameter, especially for dry forest types, can help conserve smaller older trees important to ecosystem complexity and function (Franklin 2012). However, although it is easy to identify tree diameter, the intensive sampling needed to acquire tree age becomes impractical and does not guarantee accurate results (Sanchez Meador et al. 2015). For example, of the 1,538 trees included in this sample, reliable ages were obtained from only 691 (45 percent) because of size or degree of rot. In addition, this study verified that even when a site-specific diameter for age is quantified, this alone is not a good indicator, as there were many trees larger than 27.5 in. (69.8 cm) dbh that did not express legacy characteristics and several trees smaller than the diameter threshold that were legacy trees (Figure 5). Moreover, this study illustrated how unsubstantiated diameter caps may create tradeoffs, limiting the ability to achieve long-term ecologically based objectives that focus on maintaining legacy trees, particularly for dry forest types. The BNF legacy tree guide was shown to retain an average of 95 percent of trees at least 150 years old. A diameter cap of 20.0 in. (50.8 cm) dbh would retain more old trees, but it could come at the expense of other objectives (e.g., fire, insects/disease, competition) that would increase the likelihood that those 150+ year old trees would persist on the landscape. Although 16 percent of trees that were rated as legacy were in fact less than 150 years old, conserving trees with legacy characteristics, regardless of age, is important for functional wildlife habitat, which was accomplished with the use of the legacy tree guide.

Of the four locations used in this study, the first project area (Scriver Creek) did not integrate a collaborative process. This project included a variety of diameter cap design features for the proposed action, as well as an alternative for a project wide 20.0

in. (50.8 cm) diameter cap, which was developed in response to scoping comments (USDA Forest Service 2013). Results of the environmental analysis as well as feedback during implementation raised questions about whether or not either approach (stand-level or project-level diameter caps) would develop post-treatment conditions that would move toward the Forest Plan desired conditions. Particular concerns were whether old forest habitat focused on shade-intolerant species such as ponderosa pine and western larch could be achieved given that a large proportion of the species larger than the diameter caps were younger shade-tolerant Douglas-fir and grand fir. These questions in part led to the data collection included in this study. Based on preliminary results from the first project area and supplemented by data collected from the subsequent three project areas, the Forest presented the concept of using a method based on ecological metrics (legacy tree guide) rather than mensuration metrics (diameter cap) to conserve old trees to the Boise Forest Coalition. The Coalition was supportive, particularly in light of the robust dataset provided by the Forest, which helped the subsequent three projects move through the NEPA environmental planning process without the use of diameter caps. Marking crews were able to incorporate the legacy tree rating system into timber sale preparation and marking with minimal training and oversight in the three project areas.

Collaborative groups can play an important role working with land managers to clearly define restoration objectives, tradeoffs, outcomes, and expectations for what restored sites should look like after treatment—what trees are left in the forest stand and how restoration sites contribute to more diverse and resilient forest landscapes (IFRP 2017). Incorporating collaborative input early in the process can build support and reduce the potential for litigation. In the event litigation does occur, when collaborative groups support projects, the potential for recruiting intervenors to advocate for a project increases. Having transparent and easily understood objectives and methods for conserving old trees as well as large tree stand structure facilitates candid discussions on tradeoffs, allowing for balanced project recommendations. This study has helped to build collaborative support and trust, and created an opportunity for multiparty monitoring and citizen science. Collaboratively designed projects compel agencies to incorporate shared learning, especially using simple and efficient methods, as a fundamental goal of active management (Davis 2016). With the large tree-age transects geospatially located and marked, stakeholders can revisit transect lines and use the guide to make calls on legacy status and determine which trees were retained following harvesting operations.

Conclusion

Challenges facing federal land managers are only becoming more complex, emphasizing a need for efficient and effective solutions that are transparent and science-driven. Developing planning and implementation tools, such as a legacy tree guide, can help frame the long-term vision for developing and conserving important functional habitat conditions while allowing for active management designed to foster resilient landscapes. Although this study focused on the BNF, it corroborates other findings that diameter is a poor surrogate for age (Van Pelt 2008, Franklin 2012) and provides an easily replicated framework for validating tree-age relations in other forests. Although tree size is an important ecosystem component, this study highlights how inflexible approaches, such as broad application of diameter caps, may be ineffective for achieving some desired conditions particularly in the long-term. Diameter caps often result in tradeoffs related to restoration objectives associated with stand density and species composition, particularly for shade-intolerant species. Building collaborative support early in the process can help focus NEPA planning documents by avoiding extraneous detailed analysis of Alternatives or counterproductive design elements.

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