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-

---

Received April 21, 2009; accepted January 20, 2010.

Haydee M. Hampton (haydee.hampton@nau.edu) is research associate, and Steven E. Sesnie (steven.sesnie@nau.edu) is assistant research professor, School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, AZ 86011. John D. Bailey (John.Bailey@oregonstate.edu) is associate professor of silviculture, Oregon State University, Corvallis, OR. Gary B. Snider (gsnider02@fs.fed.us) is natural resource planner, Kaibab National Forest, Williams, Arizona (Northern Arizona University School of Forestry, graduate student, during project period). *The primary author received funding for this project from the Southwestern Region of the US Forest Service. The authors thank Gilbert Zepeda, Deputy Regional Forester, and others at the Southwestern Regional Office and Intermountain West Forest Inventory Analysis (FIA) Office for their insightful comments and data assistance. They appreciate the significant time and effort contributed by working group members, land management and academic experts, and the public. They are grateful for the substantial guidance provided throughout, including contributions to and reviews of this article, by the project steering committee (Robert Davis, Forest Energy Corporation; Steve Gatewood, Wildwood Consulting and representative of the Greater Flagstaff Forests Partnership; Todd Schulke, Center for Biological Diversity; Elaine Zieroth and Robert Taylor, Apache-Sitgreaves National Forests; and Diane Vosick, Ecological Restoration Institute). The authors recognize contributions by Jada Ach, Tony Becker, Brett Dickson, Rosemary Romero, Jill Rundall, and Thomas Sisk. This article benefited greatly from the insight of three anonymous reviewers.*

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

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

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 decisionmaking (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

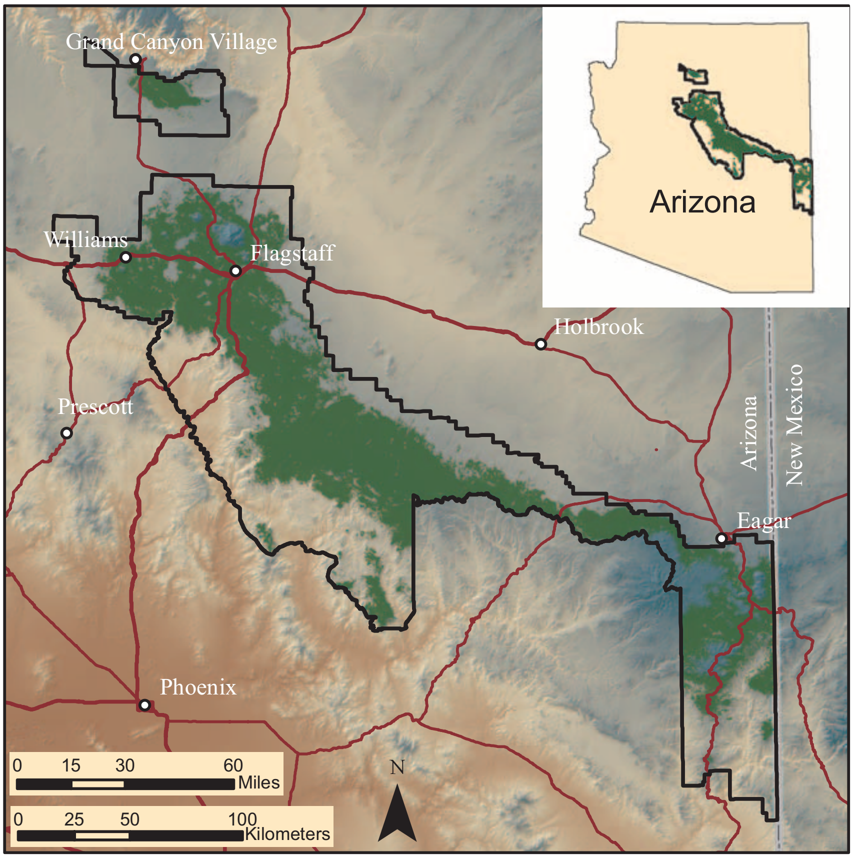


Figure 1. Map detailing the 2.4 million–ac wood supply analysis area in northern Arizona. The study area includes ponderosa pine and pine–oak vegetation (shown in green) south of the Grand Canyon and across the Mogollon Plateau to the border of Arizona and New Mexico within the proclamation boundaries 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).

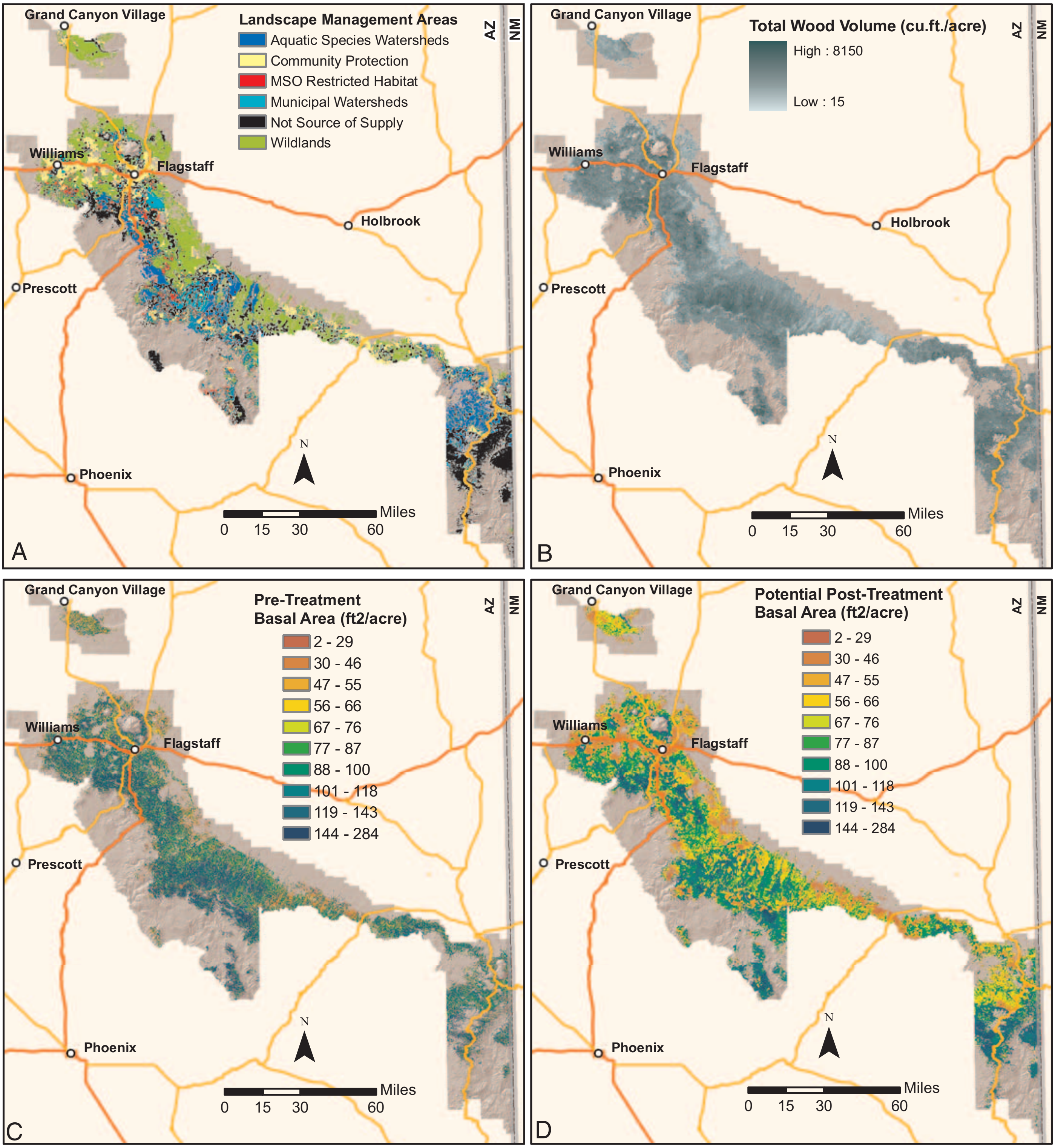


Figure 2. (A) Areas not considered a source of wood supply from mechanical thinning treatments (black) and landscape management areas (various colors) used to define desired posttreatment conditions in working group treatment scenarios. (B) Estimated ponderosa pine bole volume for 2006 across the analysis 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).

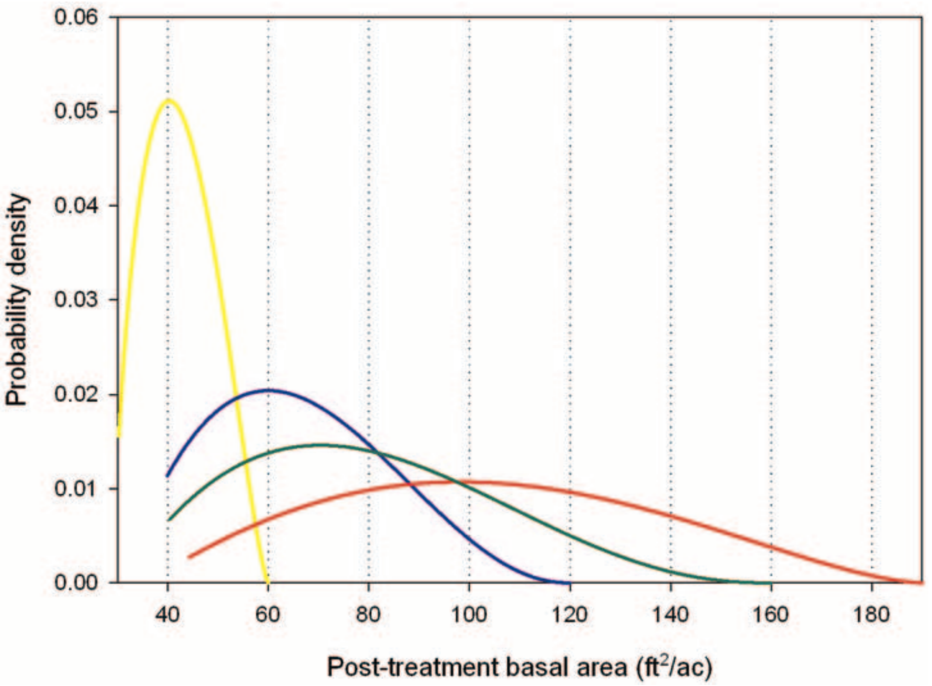


Figure 3. Continuous probability distributions of desired posttreatment ponderosa pine basal area for each landscape management area used in consensus and majority scenarios. Locations with pretreatment basal areas lower than levels described by these curves were not decreased after potential treatments.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

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).

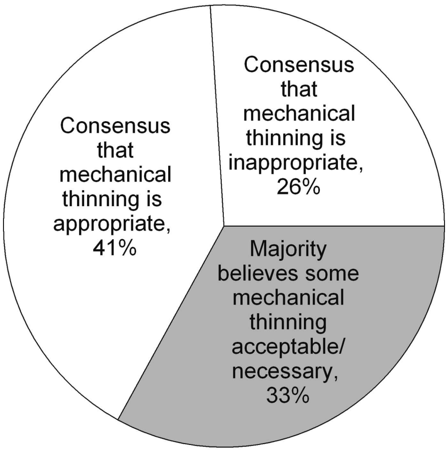


Figure 4. Pie chart representing the level of agreement among stakeholders as a percentage of the entire analysis area. Areas in white represent full agreement over a total of 67% of the landscape. Areas in gray represent the remaining 33% of the landscape where there is a lack of consensus, but for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

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

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).

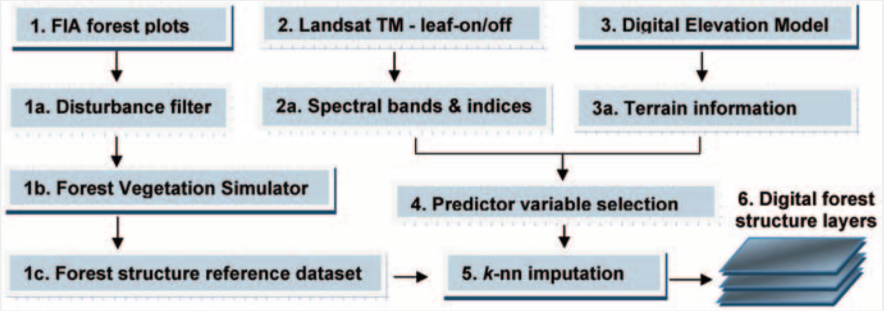
A central objective of the wood supply estimate was to determine the amount of wood supply from thinning small-diameter trees. For the purposes of this study, the group selected a 16-in. dbh threshold because of its common use within the analysis area as a break differentiating "small"- and "large"-diameter 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 $\geq$1-in. dbh) from years 1996 to 2005 were used to develop a region-scale ground reference data set for mapping ponderosa pine forest structure.
   a. **Disturbance filter**—FIA plots were selected by using remote sensing change detection techniques to identify plots without severe wildfire, timber harvest, and other disturbance events since the date of establishment.
   b. **Forest Vegetation Simulator (FVS)**[1]—Selected FIA forest plots representative of the ponderosa pine forest type ($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.

Literature Cited

ALLEN, C.D., M. SAVAGE, D.A. FALK, K.F. SUCKLING, T.W. SWETNAM, T.P. SCHULKE, P.B. STACEY, P. MORGAN, M. HOFFMAN, AND J.T. KLINGEL. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. *Ecol. Applic.* 12:1418–1433.

BAILEY, J.D., AND D. IDE. 2001. *Four corners regional assessment*, Table B-3. Northern Arizona Univ., School of Forestry, Flagstaff, AZ. 75 p.

BEIER, P., AND J. MASCHINSKI. 2003. Threatened, endangered, and sensitive species. P. 306–327 In *Ecological restoration of southwestern ponderosa pine forests*, Friederici, P. (ed.). Island Press, Washington, DC.

BREIMAN, L. 2001. Random Forests. *Mach. Learn.* 45:5–32.

CESTERO, B. 1999. *Beyond the hundredth meeting: A field guide to collaborative conservation on the West's public lands.* Sonoran Institute, Tucson, AZ. 92 p.

CHAMBERS, C., AND S. GERMAINE. 2003. Vertebrates P. 268–285 in *Ecological restoration of southwestern ponderosa pine forests*, Friederici, P. (ed.). Island Press, Washington, DC.

COGGINS, G.C., C. WILKINSON, AND J. LESHY. 2001. *Federal public land and resource law*, 4th Ed. Foundation Press, New York. 1,232 p.

COHEN, W.B., T.A. SPIES, AND M. FIORELLA. 1995. Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, U.S.A. *Int. J. Remote Sens.* 16:721–746.

COVINGTON, W.W., AND M.M. MOORE. 1994. Southwestern ponderosa forest structure: Changes since Euro-American settlement. *J. For.* 92:39–47.

CROOKSTON, N.L., AND A.O. FINLEY. 2007. *yaImpute: An R package for k-NN imputation.* The yaImpute package. Available online at www.cran.r-project.org/web/packages/yaImpute/yaImpute.pdf.; last accessed Sept. 18, 2007. 37 p.

CUTLER, D.R., T.C. EDWARDS, JR., K.H. BEARD, A. CUTLER, K.T. HESS, J. GIBSON, AND J.J. LAWLER. 2007. Random forest for classification in ecology. *Ecology* 88:2783–2792.

DIXON, G.E. 2002. Essential FVS: A user's guide to forest vegetation simulator. US For. Serv., For. Manag. Service Center, Fort Collins, CO.

DRYZEK, J.S. 1990. *Discursive democracy: Politics, policy, and political science.* Cambridge University Press, Cambridge, UK. 254 p.

EVANS, J.S., AND S.A. CUSHMAN. 2009. Gradient modeling of conifer species using random forests. *Landsc. Ecol.* 24:673–683.

FIEDLER, C.E., C.E. KEEGAN III, S.H. ROBERTSON, T.A. MORGAN, C.W. WOODALL, AND J.T. CHMELIK. 2002. *A strategic assessment of fire hazard in New Mexico*. Final Rep. submitted to the Joint Fire Sciences Program, Feb. 11, 2002. 27 p.

FINNEY, M.A. 2006. A computational method for optimizing fuel treatment locations. P. 107–123 in *Proc. of conf. on Fuels management—How to measure success*, Andrews, P.L., and B.W. Butler (comps.). US For. Serv. RMRS-P-41, Fort Collins, CO.

FINNEY, M.A., R.C. SELI, C.W. MCHUGH, A.A. AGER, B. BAHRO, AND J.K. AGEE. 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. *Int. J. Wildl. Fire* 16:712–727.

FISCHER, F. 2000. *Citizens, experts and the environment: The politics of local knowledge.* Duke University Press, Durham, NC. 336 p.

FLEEGAR, W.E. 2008. Collaborating for success: Community wildfire protection planning in the Arizona White Mountains. *J. For.* 106(2): 78–82.

FULÉ, P.Z., A.E.M. WALTZ, W.W. COVINGTON, AND T.A. HEINLEIN. 2001a. Measuring forest restoration effectiveness in reducing hazardous fuels. *Ecol. Res.* 99:24–29.

FULÉ, P.Z., C. MCHUGH, T.A. HEINLEIN, AND W.W. COVINGTON. 2001b. Potential fire behavior is reduced following forest restoration treatments. P. 28–35 in *Ponderosa pine ecosystems restoration and conservation: Steps toward stewardship*, Vance, G.K., C.B. Edminster, W.W. Covington, and J.A. Blake (comp.). Proc. RMRS-P-22, US For. Serv., Rocky Mtn. Res. Stn., Ogden, UT.

GOVERNOR'S FOREST HEALTH COUNCILS, STATE OF ARIZONA. 2007. *The statewide strategy for restoring Arizona's forests*, Aumack, E., T. Sisk, and J. Palumbo (eds.). Arizona Public Service, Phoenix, AZ. 151 p.

GRAHAM, R.T., S. MCCAFFREY, AND T.B. JAIN. 2004. *Science basis for changing forest structure to modify wildfire behavior and severity.* US For. Serv. Gen. Tech. Rep., RMRS-GTR-120, Ogden, U. 43 p.

HAMPTON, H.M., E.N. AUMACK, J.W. PRATHER, B.G. DICKSON, Y. XU, AND T.D. SISK. 2006. Development and transfer of spatial tools based on landscape ecology principles: Supporting public participation in forest restoration planning in the southwestern U.S. P. 65–95 in *Forest landscape ecology: Transferring knowledge to practice*, Perera, A., L. Buse, and T. Crow (eds.). Springer Publishing, New York, New York.

HICKE, J.A., J.C. JENKINS, D.S. OJIMA, AND M. DUCEY. 2007. Spatial patterns of forest characteristics in the western united states derived from inventories. *Ecol. Applic.* 17:2387–2402.

HJERPE, E.E., AND Y.S. KIM. 2008. Economic impacts of southwestern national forest fuels reductions. *J. For.* 106:311–316.

KEELE, D.M., R.W. MALMSHEIMER, D.W. FLOYD, AND J.E. PEREZ. 2006. Forest Service land management litigation 1989–2002. *J. For.* 104:196–202.

LAIRD, N.L. 1993. Participatory analysis, democracy, and technological decision making. *Sci. Technol. Hum. Val.* 18(3):341–361.

MAST, J.N., P.Z. FULÉ, M.M. MOORE, W.W. COVINGTON, AND A.E.M. WALTZ. 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. *Ecol. Applic.* 9:228–239.

MOISEN, G.G., AND T.S. FRESCINO. 2002. Comparing five modelling techniques for predicting forest characteristics. *Ecol. Model.* 157:209–225.

MOOTE, M.A., AND K. LOWE. 2008. *What to expect from collaboration in natural resource management: A research synthesis for practitioners.* Ecological Restoration Institute, Northern Arizona Univ., Flagstaff, AZ. 20 p.

NEARY, D.G., AND E.J. ZIEROTH. 2007. Forest bioenergy system to reduce the hazard of wildfires: White Mountains, Arizona. *Biomass Bioenerg.* 31:638–645.

O'BRIEN, R. 1999. *Arizona's forest resources.* US For. Serv. Resour. Bull. RMRS-RB-2:1, Ogden, UT. 116 p.

OHMANN, J.L., AND M.J. GREGORY. 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon, U.S.A. *Can. J. For. Res.* 32:725–741.

PEARSON, G.A. 1950. *Management of ponderosa pine in the southwest as developed by research and experimental practices*. Agric. Monograph 6, US For. Serv. Washington, DC. 218 p.

POCEWICZ, A.L., P.E. GESSLER, AND A. ROBINSON. 2004. The relationship between effective plant area index and Landsat spectral response across elevation, solar insolation and spatial scales in a northern Idaho forest. *Can. J. For. Res.* 34:465–480.

POLLET, J., AND P.N. OMI. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *Int. J. Wildland Fire* 11:1–10.

SAVAGE, M. 1991. Structural dynamics of a southwestern ponderosa pine forest under chronic human influence. *Ann. Assoc. Am. Geogr.* 81:271–289.

SCHOENNAGEL, T., T.T. VEBLEN, AND W.H. ROMME. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *Bioscience* 54(7):661–676.

SEAGER, R., M. TING, I. HELD, Y. KUSHNIR, J. LU, G. VECCHI, H. HUANG, N. HARNIK, A. LEETMAA, N. LAU, C. LI, J. VELEZ, AND N. NAIK. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–1184.

SESNIE, S.E., P.E. GESSLER, B. FINEGAN, AND S. THESSLER. 2008a. Integrating Landsat TM and SRTM-DEM derived variables with decision trees for habitat classification and change detection in complex neotropical environments. *Remote Sens. Environ.* 112:2145–2159.

SESNIE, S.E., S.E. HAGELL, S.M. OTTERSTOM, C.L. CHAMBERS, AND B.G. DICKSON. 2008b. STRM-DEM and Landsat ETM+ data for mapping tropical dry forest cover and biodiversity assessment in Nicaragua. *Rev. Geogr. Acad.* 2:53–65.

SISK, T.D., J.W. PRATHER, H.M. HAMPTON, E.N. AUMACK, Y. XU, AND B.G. DICKSON. 2006. Participatory landscape analysis to guide restoration of ponderosa pine ecosystems in the American Southwest. *Landsc. Urban Plann.* 78:(4)300–310.

STEPHENS, S.L., AND L.W. RUTH. 2005. Federal forest-fire policy in the United States. *Ecol. Applic.* 15:532–542.

SWETNAM, T.W., C.D. ALLEN, AND J.L. BETANCOURT. 1999. Applied historical ecology: Using the past to manage for the future. *Ecol. Applic.* 9:1189–1206.

TOMPPO, E., H. OLSSON, G. STAHL, M. NILSSON, O. HAGNER, AND M. KATILA. 2008. Combining national forest inventory field plots and remote sensing data for forest databases. *Remote Sens. Environ.* 112:1982–1999.

US DEPARTMENT OF THE INTERIOR (USDI) FISH AND WILDLIFE SERVICE. 1995. *Recovery plan for the Mexican spotted owl*, Vol. I. USDI, Albuquerque, NM. 347 p.

US FOREST SERVICE. 2002–2007. *Environmental Assessments for the following restoration and fuel reduction projects in the Coconino, Apache-Sitgreaves, Tonto, and Kaibab National Forests in Arizona: Eastside, Mormon Lake, Kachina, Munds Park, Mountainaire, Rocky Park, Woody Ridge, Smith/Schultz, Upper Beaver, Victorine, Huffer, Elk Park, East Clear Creek, Fort Valley, Blue Ridge, Chitty Creek, Greer, Eager South, Nutrioso, Long Jim, Twin, Jacob Ryan, East Rim, Dogtown, City, Nagel, and Los Burros*. US For. Serv. Southw. region. 1080 p.

US FOREST SERVICE. 2007. Forest inventory mapmaker. Version 1.2. Forest Inventory and Analysis Program. No longer available online. Last accessed Oct. 16, 2007.

US PUBLIC LAW 108-7. 2003. *Consolidated appropriations resolution*. H.J. Res. 2, 117 Stat. Section 323 Feb. 20, 2003. p. 275 16 U.S.C. 2104 Note. (Revised Feb. 28, 2003 to reflect Section 323 of H.J. Res. 2 as enrolled.)

VAN MANTGEM, P.J., N.L. STEPHENSON, J.C. BYRNE, L.D. DANIELS, J.F. FRANKLIN, P.Z. FULÉ, M.E. HARMON, A.J. LARSON, J.M. SMITH, A.H. TAYLOR, AND T.T. VEBLEN. 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323:521–524.

VOSICK, D., D.M. OSTERGREN, AND L. MURFITT. 2007. Old-growth policy. *Ecol. Soc.* 12(2):19. Available online at www.ecologyandsociety.org/vol12/iss2/art19/; last accessed Apr. 16, 2010.

WESTERLING, A.L., H.G. HIDALGO, D.R. CAYAN, AND T.W. SWETNAM. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313(5789):940–943.