Nondestructive Testing of Ponderosa Pine Wood Quality

Influence of Stand and Tree-Level Variables on Acoustic Velocity and Wood Density

Submitted to the faculty of the Northern Arizona University School of Forestry in partial fulfillment of the requirements for the degree of Master of Forestry

Matthew Ruggirello[1]

Advisor: Dr. David Auty

Readers: Dr. Kristen Waring, Dr. Thomas Kolb

Fall 2017

[1]*Candidate for Master of Forestry, Northern Arizona University School of Forestry*

Abstract

The Four Forest Restoration Initiative (4FRI) is a landscape-scale collaborative project aimed at reducing the threat of catastrophic wildfires and improving forest health by moving forest ecosystems in northern Arizona on a trajectory that is more resilient to future disturbances and guided by historical reference conditions. A key component of this initiative aims to support sustainable forest industries by increasing markets for value-added wood products made from small-diameter trees. Currently, traditional markets for ponderosa pine in the region consist of mainly low-value products.

The aim of this study was to provide information to forest managers and investors on the quality of the wood harvested during 4FRI operations. In the Centennial Forest, near Flagstaff, Arizona, we measured acoustic velocity (a proxy for wood stiffness) and radial density profiles to investigate the relationship between internal wood properties and stand- and tree-level variables. We also collected acoustic velocity data from the Taylor Woods levels-of-growing-stock study on the Fort Valley Experimental Forest. Wood density and acoustic velocity relate to stiffness and strength, important properties that determine end-use potential.

Acoustic velocity was higher, on average, in trees from stands with higher basal areas, while basal area had only a small effect on wood density. This indicates that wood quality may improve with increasing basal area, but these gains may be offset by lower volume production from harvesting small-diameter material. Our findings may help dispel the notion that wood from small-diameter ponderosa pine trees is unsuitable for high-value applications. We hope these findings encourage investment in wood processing infrastructure in the region; without such investment, forest restoration projects in the Southwest may not be economically viable over the long-term.

Part One: An Overview of Forest Operations and the Wood Products Industry in Norther Arizona

Introduction

More than a century of inappropriate forest management activities in northern and central Arizona, principally fire suppression and exclusion, grazing, and irresponsible logging practices, has resulted in high basal area stands of predominantly small-diameter trees vulnerable to catastrophic wildfire, insect attacks, and disease outbreaks (Covington and Moore 1994; Covington et al 1997). In response, the United States Forest Service has undertaken a massive restoration initiative known as the Four Forest Restoration Initiative (4FRI). Across four national forests, the Forest Service has begun work to "restore the structure, pattern, composition, and health of fire-adapted ponderosa pine ecosystems; reduce fuels and the likelihood of unnaturally severe wildfires; and provide for wildlife and plant diversity" (http://www.fs.usda.gov/4fri, 6 September 2016). More than 600,000 acres of forest are scheduled to be treated over the next 20 years (http://www.4fri.org/background.html, 6 September 2016), potentially producing over one million cubic feet of stem wood and 9.6 million green tons of biomass from tree crowns (Hampton et al 2008). However, ponderosa pine (*Pinus ponderosa*), is considered to be of little commercial value in much of the southwestern United States. Though commercially exploited in other parts of its range, including in other parts of Arizona, processing of ponderosa pine is not seen as economically lucrative throughout much of Arizona and New Mexico (Covington et al 1997).

Public skepticism and resistance from environmental groups to timber removal has largely limited the Forest Service's social license to implement forest restoration and fire-hazard reduction treatments that are ecologically and economically sensible (Chapman N, pers. comm., April 2017). Though ambitious in its scope, 4FRI has been limited in its operational objectives. Operations are generally limited to the harvesting of trees under 16 inches in diameter, which often results in basal areas and trees per acre above the historical range of variation for the region (USFS Old Growth and Large Tree Retention Strategy 2011). There is evidence that a considerable number of larger ponderosa pine trees should in fact be removed from the forest for a variety of reasons, including reducing torching indices and improving water yield and seedling regeneration post-treatment (Abella et al 2006, Sánchez Meador et al 2015, Flathers et al 2016).

Given the negative perceptions of ponderosa pine wood in the region, policies that impede the harvesting of larger trees present challenging economic barriers to efficient, self-sustaining restoration initiatives. This resistance among the public and environmental groups stems from a history of irresponsible logging practices. After Euro-American settlement in the late 1800s, the largest pine trees in the region were cut without restraint: "in the late 1800s, the northern Arizona forests provided an abundant timber supply of valuable and easily harvested southwestern yellow pine [*i.e. Pinus ponderosa*] for railroad ties. The harvesting process required the heavy cutting of old-growth timber with little attention given to future productivity" (Geils 2008, pp1-2). By the early 1900s, intensive logging of large ponderosa pine trees threatened the viability of the logging industry in northern Arizona. As a result, the Fort Valley Experimental Forest was established to conduct studies relating to the health and sustainability of forests in the region. Though the logging industry declined from an initial boom period, industry remained relatively stable in the Flagstaff area until the early 1990s. It was during this period that unfavorable market conditions and high volumes of unmerchantable stems, coupled with lawsuits from environmental groups, applied even more pressure on an already stressed wood industry (Ffolliott 2008). The result was the near total collapse of the private, commercial logging industry of north-central Arizona.

After a period without significant logging operations and wood products manufacturing, the U.S. Forest Service became essentially the only significant forest management group in the region. With high frequency, low-intensity fire and private commercial logging largely removed from the landscape, non-commercial, mechanical thinning has become the dominant silvicultural technique applied to reduce stocking levels in the high basal area forests around Flagstaff. To date, the Forest Service claims to have mechanically thinned approximately 150,000 acres across the 4FRI project area (https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd544111.pdf, 18 June 2017). However, the consensus among the scientific and forest industry communities is that 4FRI is significantly delayed, with some sources claiming that the Forest Service is approximately 140,000 acres behind schedule (https://www.williamsnews.com/news/2017/may/30/treatment-continues-kaibab-despite-slow-4fri-progr/, 18 June 2017).

Although the obstacles to efficient, successful forest restoration across the 4FRI area are complex, a lack of market demand for wood, which could help offset treatment costs, is often cited as the main cause of operational delays. Only a handful of small mills are functioning in north-central Arizona. NewPac Fibre is one of these facilities. It is largely through collaboration with The Nature Conservancy that NewPac has been able to stay in business, producing cants that are exported to Mexico as low-value pallet stock (Chapman N, pers. comm., September 2017). Small operators like these are simply unable to absorb the large volume of small-diameter trees from fuels reduction and other treatments in the region.

A relatively successful project in eastern Arizona known as the White Mountain Stewardship Project also stimulated local industry and partially met restoration goals: through the stewardship program, loggers received subsidies from the federal government to treat tens of thousands of acres of vulnerable forest in eastern Arizona; local wood products manufacturers received substantial support as well (Sitko and Hurteau 2010). Given the near complete absence of significant industry in north-central Arizona, such stewardship agreements will be an essential component of reestablishing the wood products industry around Flagstaff. The White Mountain Stewardship Project, though innovative and somewhat successful, was not without its challenges and pitfalls (Mottek et al 2017). The myriad of lessons learned while implementing stewardship projects in the White Mountains can be applied to improve initiatives in the Flagstaff area aimed at reinvigorating local industry while reducing fire-hazard (Mottek et al 2017).

Despite relative success in other parts of Arizona reviving local wood products industries, larger-scale manufacturers have so far been deterred from returning to the Flagstaff area. The reasons for this include, in addition to a lack of detailed information about ponderosa pine wood properties, the Forest Service's complicated contract system sometimes discouraging industry growth, and small logging contracts of only a few thousand acres being offered to loggers with no guarantee of long-term supply (Chapman N, pers. comm., September 2017). Both loggers and mills are limited by the annual fluctuation in the size of these contracts. Loggers awarded contracts to fell timber near Flagstaff often cannot obtain sufficient capital loans to complete operations and frequently subcontract their work to other operators (Chapman N, pers. comm., September 2017). This lack of operational continuity results in an inefficient and imperfect implementation of restoration prescriptions, which is an impediment to entrepreneurial commitment and large-scale investment in high volume, value-added wood processing facilities in the region.

At present, hopes for meeting restoration and fuel-hazard reduction objectives on the western extent of the 4FRI area lay in the potential construction of biomass energy facilities (http://azdailysun.com/news/local/fri-looks-to-reboot/, 18 June 2017). Despite the completion of several feasibility studies and ongoing plans to use ponderosa pine wood as biomass feedstock, the construction of a fully operational plant has not yet been realized. In eastern Arizona, however, the utilization of small-dimeter pine as biomass, supported by federal grants, has helped to address lackluster regional markets while simultaneously boosting rural economies (Davis et al 2014). However, directing the entire wood supply of north-central Arizona toward biomass facilities neglects the fact that much of the volume across the landscape may be appropriate for higher-value uses. Though directing some small-diameter ponderosa pine for use in biomass energy plants may be an appropriate part of a larger plan to solve the region's resource oversupply problems, it is likely not a stand-alone solution.

Ultimately, landscape-scale restoration efforts in the region will depend on more efficient and profitable utilization of small-diameter logs (Lowell and Green 2001). A key component in realizing this goal is a more accurate and comprehensive understanding of the properties of the wood supply. Current knowledge about ponderosa pine wood properties is largely anecdotal: many foresters in the region view the wood as soft, knotty, and unfit for structural applications. Scientific quantification of the wood properties of these trees is therefore an essential component in dispelling these conceptions.

Significance of Acoustic Velocity and Wood Density

Wood stiffness and strength are often seen to be of paramount importance by the wood industry, as they play a large part in determining the end-use potential of logs (Grabianowski et al 2006; Wang et al 2007a; Wang et al 2007b; Auty and Achim 2008). Measured in miles per second, the speed at which sound travels through a tree correlates directly to its dynamic wood stiffness, which in turn correlates to the stiffness determined in static bending. Assuming green wood density remains constant, faster acoustic speeds suggest stiffer wood. This relationship is driven by, among other factors, the proportion of latewood present in a stem (Carter et al 2005). Theoretically, acoustic velocity is directly related to the dynamic modulus of elasticity, or dynamic wood stiffness, and wood density by the equation:

$$MOE_D = \rho v^2$$

MOE_D = dynamic modulus of elasticity (lb in^{-2}), ρ = green wood density (lb ft^{-3}), v = acoustic velocity (mi sec^{-1}).

Though acoustic tools provide individual, tree-level values, they are most useful at the forest level where they can be used to compare wood stiffness across stands for proper segregation of stems. Toward such ends, field use of acoustic tools has increased in recent years throughout both the commercial and research forestry sectors (http://www.fibre-gen.com/research-papers, 12 October 2016). The use of acoustic tools for early genetic selection of stock in commercial tree-breeding programs is also increasing, as wood stiffness is strongly influenced by genetics (Jayawickrama et al 2011, Lenz et al 2013, Lowell et al 2014). This has encouraged forest geneticists to consider acoustic velocity when selecting families for commercial tree breeding (DeBell J, pers. comm., July 2017). Geneticists and reforestation foresters are also empowered through acoustic velocity measurements to include wood stiffness in their reforestation plans, further increasing managers' ability to maximize profits from their forested lands. Further commercial applications for acoustic tools exist at the wood-processing level: in New Zealand and Australia, for example, acoustic testing of logs before processing has enabled more efficient segregation of stems based on their structural qualities (Carter et al 2013).

Though more difficult to collect, wood density measurements are also strong indicators of the mechanical properties of a stem (Shmulsky and Jones 2015). Wood density can be measured through X-ray densitometry, where the radial density profiles of samples prepared from increment cores are scanned at a fine scale using X-rays. As this is a complex and costly process, it is not applied widely by field foresters; companies and organizations likely do not have the financial capital or manpower necessary to collect, cut, and scan wood samples from their forests. Still, models for commercially valuable species such as Scots pine and Sitka spruce do exist that link wood density to stand and tree-level variables (Guilleya et al 1999, Repola 2006, Gardiner et al 2011, Auty et al 2016). The potential exists for these models to be applied in determining the end-use potential of stems on a commercial scale. No such model or basic relational description exists for ponderosa pine in the Southwest.

Together, wood density and acoustic velocity data give a strong indication of the structural properties of a stem by providing information on the strength and stiffness of trees and logs. For structural applications, most timber must meet certain minimum standards for strength and stiffness as expressed through the moduli of elasticity (MOE) and rupture (MOR) (Auty and Achim 2008). Higher strength and stiffness values may allow for the use of stems in higher-value structural applications such as building construction or composite lumber manufacturing. Still, such utilization depends largely on the variance and uniformity of strength and stiffness properties across an entire stem. Stems producing wood with poor or highly variable strength and stiffness properties have traditionally been chipped for landscaping, utilized as biomass energy, piled and burned in the forest, or processed into cants to manufacture low-value products such as pallets.

Factors Impacting Wood Properties and End-Use Potential

Of importance in understanding the results of this study is a discussion of the role of latewood in determining wood density and stiffness. Commonly, latewood is the term used to describe the thick-walled tracheid fibers added radially to a tree's stem toward the end of a growing season. Latewood contains more densely compacted xylem tracheids than earlywood, which is developed in spring and early summer. The open cavities at the center of xylem tracheids, or lumen, are also smaller in latewood fibers. The proportion of latewood in a stem relative to earlywood is correlated to wood density and the end-use potential of a log: "wood density may be closely approximated and evaluated by the proportion of latewood in the growth rings" (Larson 1963, p28).

Many factors contribute to latewood proportion in annual growth rings. Of these, the extent of a tree's live crown is strongly linked to earlywood formation. The live crown produces auxin, a growth-regulating hormone that increases in concentration with crown growth and size. Large crowns generally lead to greater auxin production, resulting in higher earlywood percentages in annual growth rings. Additionally, the presence of photosynthates, often linked to live crown vigor, late into the growing season is commonly associated with the thickening of cell walls and the formation of latewood (Larson 1969). However, trees with exceptionally small crowns will not produce enough photosynthates to allow for the formation of thick latewood bands during late summer and autumn (Larson 1969, Shmulsky and Jones 2015).

The relationship between the live crown and water demands is also related to latewood proportion: larger crowns require more water from their roots to satisfy greater photosynthetic demands; a greater proportion of earlywood cells would therefore be expected, as they are better conduits for water (Larson 1963). Smaller crowns, associated with lower photosynthate production and reduced water demands, correlate to higher percentages of latewood in a stem (Larson 1969). In the United States Southwest, latewood formation may be connected most closely to late-season soil moisture availability and summer vapor pressure deficits (Kerhoulas et al 2017).

The proportion of juvenile wood in trees also helps determine end-use potential. Juvenile wood tends to be low in density, contains considerable amounts of tension and compression wood, and is generally of inferior quality with respect to structural uses than mature wood (Shmulsky and Jones 2015). Dependent on species and site conditions, trees between the ages of 15 and 25 begin to reduce production of low-density juvenile wood and transition to the formation of structurally superior mature wood (Zobel and Sprague 2012). After this, juvenile wood production is restricted to the areas close to the live crown. Therefore, trees with larger crowns will likely produce relatively high amounts of juvenile wood, regardless of their age.

Conventionally, manufacturers of solid wood products have sought uniformity in wood properties, namely the evenness with which latewood and earlywood bands are distributed across annual growth rings. Larson (1969, p47) states that “one of the greatest wood quality problems facing all wood-using industries is lack of uniformity…the more erratic the growth conditions, the greater the non-uniformity of the wood produced.” Ponderosa pine in the Southwest grows under such erratic conditions; largely due to the region’s dry climate, ponderosa pine’s annual growth is highly variable. Additionally, intense crowding in many stands can compound drought stress, increasing irregularities in internal wood properties (Martinez-Meier et al 2015). Highly variable stand basal areas and intense competition also contribute to the formation of irregularly sized growth rings that result in variable internal strength and stiffness properties.

However, with the development of composite wood products, a greater variety of raw material is suitable for commercial use. Irregularities in growth ring width, variation in latewood and earlywood bands, and stress-gradients created by knots can be mitigated by many of the processes that form composite wood products (Shmulsky and Jones 2015). With the growth of composite wood industries, less dense, structurally inferior wood may sometimes be preferred, as it is more mechanically efficient to process this weaker wood into products such as oriented strand board (Shmulsky and Jones 2015). A feasibility study from the early 2000s concluded that a small number of ponderosa pine logs may be of suitable quality for use as structural lumber and that a greater number may be appropriate for use in composite wood products, such as glulam beams and oriented strand board (LeVan-Green and Livingston 2001).

Still, the investment necessary to establish a composite wood product manufacturing plant is extremely prohibitive: depending on the product to be manufactured, processing plants require capital investment levels in the tens to hundreds of millions of dollars. Small-diameter ponderosa pine in the United States Southwest will be harvested almost exclusively from federal lands and investors are likely wary of their investments depending entirely on operational contracts administered by the federal government. Additionally, the climate and fire regime of the region further destabilize the resource base necessary to maintain composite wood product plants.

Ultimately, resolving the economic and scientific problems facing the region will require complex, nuanced, and proactive strategies that target a cluster of end-uses and forest industries to diversify markets. It is unlikely that a single product or market will suffice to absorb the bulk of ponderosa pine wood removed in fire-hazard reduction operations. Only a thorough quantification of the strength, stiffness and other important wood properties across the regional landscape will determine the appropriate potential end-uses for the stems harvested in northern Arizona.

Part Two: Using nondestructive techniques to assess wood quality in ponderosa pine forests near Flagstaff, Arizona.

Study Objective

To use nondestructive testing (NDT) methods to investigate the relationship between internal wood properties, namely wood density and stiffness, and tree and stand-level variables in replicated ponderosa pine levels-of-growing-stock experiments.

Methods

Study Sites

Data were collected in the summers of 2015 and 2016 in Northern Arizona University's Centennial Forest and the Forest Service's Taylor Woods levels-of-growing-stock study, both near Flagstaff, Arizona. The area has a semi-arid climate with most significant precipitation falling as winter snow or as late summer, monsoonal rain. The forest at our sites is dominated by ponderosa pine and Gambel oak (*Quercus gambelii*).

Throughout this study, stand density is expressed in terms of basal area. At the Centennial Forest, a thinning in 2005 resulted in the creation of five replicated basal area treatments of 60, 80, 100, 120, and 150 ft^2 ac^{-1} across a total of 20 treatment blocks, each approximately five acres in size. Post-thinning basal areas ranged from 62 ft^2 ac^{-1} to 175 ft^2 ac^{-1} across the twenty distinct treatment units. The study was created using an uneven-sized group selection with even spacing; pre-treatment basal areas ranged from 58 ft^2 ac^{-1} to 174 ft^2 ac^{-1} (Gaylord et al 2011). The experiment has not been treated again since the initial thinning. Pre-treatment basal areas and trees per acre across the site were highly variable: several replicates were already at post-thinning targets in 2005 and did not require thinning; however, in most replicates, there was no apparent link between pre- and post-thinning basal area (Gaylord et al 2011). Basal area classes did not exist in any distinct, systematic manner prior to 2005. The study at Taylor Woods had a similar design. It was established in 1962 and has been periodically thinned to maintain replicate treatment units near 30, 60, 80, 100, 120 and 150 ft^2 ac^{-1}, which range in size from 0.75 to 1.24 acres (Bailey 2008). Taylor Woods also contains unthinned and non-forested units. As of 2016, actual basal areas varied slightly from targets (Flathers et al 2016).

Many of the stands to be treated by the Forest Service under 4FRI are above 55% of maximum stand density index (SDI) and have basal areas greater than 200 $ft^2 ac^{-1}$ (McCusker et al 2014). However, a certain number of treatments will occur in stands with basal areas between 150 $ft^2 ac^{-1}$ and 200 $ft^2 ac^{-1}$ (4FRI Landscape Restoration Strategy for the First Analysis Area 2010). Comparatively, the highest basal area stands at our two study sites are analogous to the most open stands to be treated across northern Arizona. The lower basal area stands at the Centennial Forest and Taylor Woods more closely resemble some of the desired post-treatment conditions detailed in 4FRI's objectives (USFS Proposed Action for Four-Forest Restoration Initiative 2011, McCusker et al 2014).

Sampling Techniques and Data Collection

In the Centennial Forest, three randomly located fixed-area 0.1-acre plots were established in each of the 20 treatment blocks, for 60 plots in total. Study plots were chosen by selecting a random number of paces and a random azimuth. We established the first plot by walking the decided number of paces along a random azimuth from the corner of a given treatment unit; the two subsequent plots in each unit were established using the same technique, starting from the center of the previous plot. In this way, we hoped to overcome the natural bias to walk toward open areas. We repeated this process at Taylor Woods, but sampled in fewer total replicate treatment blocks than at the Centennial Forest. Total trees per plot varied greatly depending on a given treatment unit's basal area. In some of the most open treatment blocks, fewer than six live ponderosa pine trees greater than five inches in diameter were suitable for measurement per sample plot. In the highest basal area stands, as many as 40 trees per plot were appropriate for sampling.

At Taylor Woods, tree diameter at breast height (DBH, in.), total tree height (ft.), height to the base of the live crown (ft.), and acoustic velocity were recorded for each tree over five inches in DBH in a given plot, for a total of 333 trees. Due to permission restrictions, increment cores were not taken from trees at Taylor Woods. In the Centennial Forest, we measured tree diameter and recorded acoustic velocity for 720 individuals. Total tree height and height to crown base were measured on a subsample of approximately six trees per plot, totaling 279 measurements. A single increment core was extracted at breast height (4.5 feet from ground level) from the same subsamples of 279 trees, using standard increment boring techniques. To select our subsample of trees, we chose individuals that would theoretically be suitable for commercial harvest and utilization based on DBH, total height, crown height, and stem straightness. After extraction, cores were secured in modified drinking straws and placed in a freezer for storage.

Measuring Acoustic Velocity

Acoustic velocities were recorded at both Taylor Woods and the Centennial Forest using the ST300 Hitman tool (Fibre-gen, Christchurch, New Zealand). Gambel oak trees were not tested, nor were ponderosa pine trees under five inches in diameter due to the heightened risk of damage to the trees from the insertion of the ST300's acoustic probes. In addition, acoustic velocity measurements from the Hitman tool are known to be less reliable in trees under five inches in diameter. We placed the tool's two probes in each ponderosa pine tree to be sampled, one near the base of the tree and the other, for practical purposes, just above breast height (Figure A2). Though recording acoustic velocity at breast height may seem to be an inappropriate technique for measuring the internal qualities of an entire stem, various studies have concluded that such data can be interpolated to an entire stem with relative confidence (Haines and Leban 1997, Auty and Achim 2008). Additionally, acoustic data allow for a very accurate comparison of internal wood properties between trees at a specific, user-determined point along a stem.

To operate the ST300 tool, the user taps the lower probe 24 times with a hammer, producing a velocity measurement. The distance traveled by the wave from the lower probe to the upper probe is measured and the transit time is recorded. Knowing the distance between probes, velocity (miles per second, mi s^{-1}) is calculated as the distance over the time-of-flight of the acoustic wave (Figure A3). Opinions vary on whether consistent placement of probes on a specific side of a tree is important. Wang et al (2007a) chose a side randomly for each individual tree, while Mora et al (2009) did not identify consistency in probe placement as a significant factor in producing accurate acoustic readouts. We chose to take measurements on the north side of all trees for consistency.

Measuring Wood Density

Wood density was measured on samples from the Centennial Forest using the Quintek QMRS-01X Tree Ring Scanner (Quintek Measurement Systems Inc., Knoxville TN). Before scanning, the cores were conditioned in a climate-controlled chamber to approximately 6-8% moisture content. As the QMRS-01X is unable to analyze intact cores, our samples were prepared with the assistance of Dr. Joseph Dahlen from the Warnell School of Forestry and Natural Resources, University of Georgia. In the scanning process, 2-mm-thick bark-to-pith samples were secured in a five-millimeter cartridge and mounted on a linear stage. The stage then moves in 25-µm increments and the X-ray beam scans the sample on the tangential face. A camera also creates a detailed image of the radial profile of the sample. The result is a graphical representation of a sample's radial density profile, measured in pounds per square inch (lb in^{-2}), accompanied by a photograph of the sample. The QTRS-01X software also produces a ring-level density summary, which quantifies, in tabular format, the average density for each year of growth based on the density variation between adjacent latewood bands. As wood density is usually averaged for each annual ring, we often refer to our results in terms of ring-level wood density throughout this work. The ring-level summaries also include average earlywood and latewood density values for each annual ring.

Before scanning, we calculated a mass attenuation coefficient, which is used to calibrate the densitometer. This coefficient is an estimate of the amount of energy that is absorbed by any given wood sample. The mass attenuation coefficient is species- and region-specific and is necessary for accurate density measurement. To calculate this, we measured the specific gravity of ten randomly selected intact cores by suspending them in a beaker of water. Dividing the mass of each core (lb) by its volume (ft^3) gave us the specific gravity of each sample. We averaged the samples to get an approximation of average specific gravity for our cores in lb ft^{-3}. We entered this average into the scan set-up parameters as the target wood density value for a particular sample. We then scanned the sample and the software used the known specific gravity of the core to calculate a mass attenuation coefficient for use in future scans.

In measuring wood density, our methods paralleled closely those of Antony et al (2012), who also used non-destructive sampling methods, *i.e*., extraction of increment cores. Nondestructive methods for testing wood properties may limit the amount of information one can gather from a given sample: for example, strength and bending tests to determine the exact moduli of rupture and elasticity for a sample can only be performed on destructively sampled trees. Still, nondestructive sampling allows significantly more samples to be extracted for wood density analyses, providing the opportunity to collect data from many more individuals.

Data Analysis

The following analyses were conducted on the data from the Centennial Forest and Taylor Woods:

- Centennial Forest: we linked tree height and DBH to basal area treatment and acoustic velocity using 720 diameter measurements and 279 height measurements.
- Centennial Forest: we described a linear relationship correlating acoustic velocity to wood density using paired velocity and wood density measurements from 279 trees. Acoustic measurements were averaged over the last 50 years of growth, as acoustic waves tend to travel through the stiffest material, *i.e.*, the outerwood portion of the stem.
- Centennial Forest: using 279 wood density samples, we described relationships between wood density and cambial age, year of ring formation, and stand-level basal area, as well as the relationship between cambial age and average annual ring width.
- Centennial Forest: using data from 279 trees we linked DBH and average tree height to tree age at breast height.
- Taylor Woods: we established relationships between acoustic velocity and tree height and diameter and basal area treatment using 333 data points per analysis.

Study Limitations

This experiment did not have pure controls; untreated stands were not included in our study. In part, untreated stands were not sampled because their trees were too small for both application of the ST300 Hitman acoustic probes and safe extraction of increment cores; these stands also contain trees with insufficient volume for value-added uses, making their internal wood quality properties largely irrelevant.

Our analysis was limited in that it did not relate wood quality characteristics directly to climate variables. Drying and warming patterns throughout the Southwest have their own effects on wood formation in ponderosa pine; some of these effects have already been documented (Martinez-Meier et al 2015, Dannenberg and Wise 2016). Drought, for example, is known to induce production of smaller diameter tracheids, resulting in “false rings” (Larson 1969). These slight changes in wood density and color can make proper delineation of ring boundaries difficult. Though an X-ray densitometry analysis of the average wood density of an entire sample is unaffected by these false rings, examining annual variation in wood density becomes challenging when many false rings are present; determining the true end of a tree's annual growth can become nearly impossible. For this work, cores were not cross-dated due to time constraints. Without matching annual ring patterns across multiple cores, identifying the true location of a given year on a particular scan or ring-level density summary was difficult. Consequently, years of ring formation and dates associated with wood density scans contain a degree of error. Future experiments might address this by cross-dating cores and may incorporate climate data more directly into analyses of wood density and acoustic velocity. Such a study may help determine the relative influence of stand basal area and climate on ponderosa pine internal wood properties.

Another limiting factor of this research was that levels-of-growing-stock studies at the Centennial Forest and Taylor Woods have not been strictly maintained. Lower basal area classes are beginning to converge with higher ones. This may confound results linking stand-level basal area to wood density and acoustic velocity. Future studies would benefit from stricter maintenance of target basal areas. Our analysis may also be limited in its scope of inference: we did not sample stands from across the southwestern United States. Such ambitions were beyond the scope of this pilot study.

Results and Discussion

Acoustic velocity results incorporate data collected from both Taylor Woods and the Centennial Forest, while wood density results have been derived from increment cores collected only from the Centennial Forest.

General Trends

Tree Characteristics by Site and Basal Area Treatment

The summary statistics presented in Table 1 allow comparisons to be made across study sites. Mean tree DBH and heights were generally higher at Taylor Woods than at the Centennial Forest, which is likely related to of the longer duration of the study at Taylor Woods. The levels-of-growing-stock study at Taylor Woods was established in 1962, so trees in the more open treatment blocks at Taylor Woods would likely have had greater access to resources for longer than at the Centennial Forest. Basal areas would have been higher across much of the Centennial Forest until the thinning of 2005 (Gaylord et al 2011). The standard deviations for both tree heights and diameters tended to be greatest at the Centennial Forest, with only a few exceptions in the lowest basal area treatments of Taylor Woods, where new cohorts of young ponderosa pine have established.

Average tree age at the Centennial Forest was highest for trees in the lowest basal area class, while the inverse was true for trees for the highest treatment class, suggesting that older trees were present before the thinning of 2005 in the 60 ft^2 ac^{-1} replicates and were retained post-thinning. Still, average tree ages suggest that few trees across the study site would have established before Euro-American settlement. Ranges of recorded acoustic velocity values were more variable at the Centennial Forest and the maximum velocity values in the Centennial Forest's highest basal area classes were considerably higher than values from comparable stands at Taylor Woods. Relatively high standard deviations for acoustic velocity values at both sites may be a result of crowded growing conditions and limited access to soil moisture causing differential wood formation across trees sharing space and resources.

Table 1: Mean tree characteristics by site; CF = Centennial Forest and TW = Taylor Woods. Lacking increment cores from Taylor Woods, average tree age per treatment class could not be calculated.

Site	Treatment	No. of Trees	BA 2015	Mean DBH (SD) Range (in.)	Mean Ht (SD) Range (ft.)	Mean Vel (SD) Range (mi s^{-1})	Avg. Age (yrs)
CF	60	67	89	16.2 (3.8) 5.7 – 23.6	58.1 (10.7) 20.4 – 77.4	2.17 (0.25) 1.47 – 2.67	99
CF	80	100	83	12.8 (4.1) 5.6 – 21.3	53.0 (11.9) 24.1 – 80.3	2.12 (0.26) 1.30 – 2.55	86
CF	100	143	130	13.3 (4.3) 5.0 – 24.1	56.7 (11.0) 23.8 – 80.3	2.18 (0.25) 1.34 – 2.66	90
CF	120	191	130	11.4 (4.0) 5.3 – 28.0	51.9 (15.3) 24.6 – 84.0	2.28 (0.27) 1.32 – 3.06	82
CF	150	219	149	11.2 (3.6) 5.0 – 23.5	52.9 (11.7) 25.8 – 85.0	2.23 (0.26) 1.29 – 2.99	81
TW	30	15	57	16.8 (7.3) 6.1 – 24.5	56.2 (19.7) 28.5 – 79.2	1.82 (0.28) 1.32 – 2.19	–
TW	60	23	70	18.2 (1.4) 16.0 – 21.3	66.4 (5.4) 57.0 – 75.0	2.09 (0.19) 1.79 – 2.46	–
TW	80	46	108	15.9 (1.9) 11.9 – 21.7	64.6 (5.7) 51.8 – 81.0	2.19 (0.15) 1.80 – 2.55	–
TW	100	70	124	13.8 (2.1) 9.4 – 18.9	61.3 (8.2) 39.1 – 82.4	2.29 (0.15) 1.81 – 2.67	–
TW	120	37	134	14.0 (1.8) 10.7 – 17.7	63.0 (5.8) 51.5 – 73.8	2.29 (0.13) 2.03 – 2.56	–
TW	150	142	167	11.2 (2.1) 7.4 – 16.6	56.6 (6.2) 38.2 – 70.4	2.41 (0.15) 1.91 – 2.68	–

Average Tree Height and Diameter at Breast Height vs Basal Area Treatment

At the Centennial Forest, tree height and DBH decrease with increasing target basal area (Figure 1). This negative relationship is stronger for DBH than for total tree height, suggesting that trees with limited access to resources will prioritize height growth over diameter growth. These results are as expected since in higher basal area stands, fewer resources will be available to individual trees as competition will be more intense, thereby restricting growth. However, in a following section, we show that acoustic velocity, a surrogate for wood stiffness, likely increases with increasing stand basal area. This phenomenon suggests that there are tradeoffs between stiffness gains and volume losses in higher basal area stands. Though higher basal area stands may contain trees with stiffer wood, volume losses and the loss of total harvestable material in these stands may offset improvements in wood stiffness. We would expect to see similar trends at Taylor Woods.

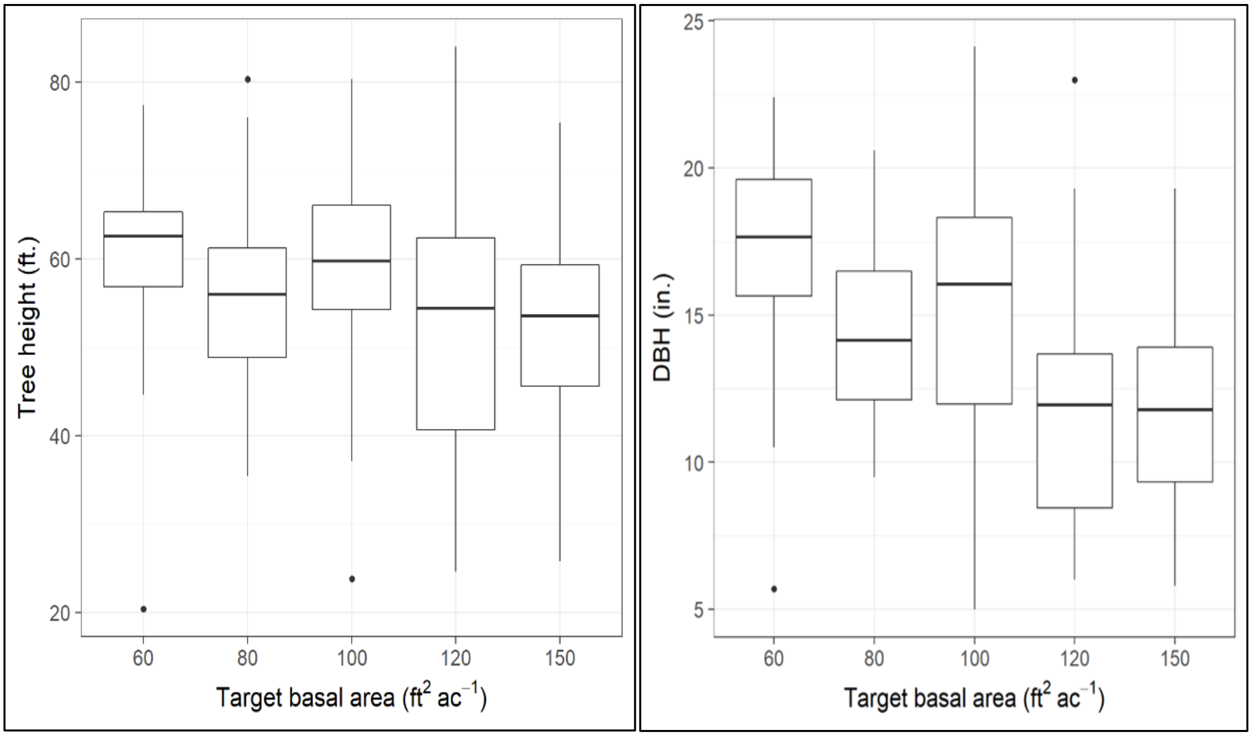

Figure 1: Boxplots of average tree height and DBH for each basal area treatment at Centennial Forest and Taylor Woods. Both average tree height and DBH decrease with increasing basal area. These results are from the Centennial Forest; n = 279 (height); n = 720 (DBH).

Average Tree Height and Diameter at Breast Height vs Age at Breast Height

There was a positive correlation between average tree height and age at breast height in the Centennial Forest. This correlation is weakest in our lowest basal area treatment, as more open-growing trees have less need to emphasize height growth (Figure 2). The positive relationship between height and tree age was strongest in the 80 ft^{2}ac^{-1} and 120 ft^{2}ac^{-1} classes. Individuals in stands that are under moderate competition have likely allocated resources to height growth to achieve more favorable crown positions; this growth has closely paralleled age at breast height. The relationship weakens in the highest basal area class; though crown height is still likely to be important, more intense crowding may have limited trees' access to resources to allocate toward height growth.

Though in the intermediate treatments there was a moderate positive correlation between diameter at breast height and tree age at breast height, this relationship was significantly weaker in our lowest and highest basal area treatments. In the 60 ft^2 ac^{-1} class, this may be a result of larger tree diameters. As trees become larger, they experience less overall diameter growth for the same amount of overall growth. Trees must form more woody material around their stem as their cross-sectional area increases. However, the lower correlation in the 150 ft^2 ac^{-1} was likely caused by other factors. Competition for soil moisture, light, and space in the higher basal area treatment blocks have likely reduced the amount of resources available for individual trees to allocate toward diameter growth. This obscures the relationship between tree diameter and age in higher basal area stands. This phenomenon is common across much of the forested Arizona landscape, where many stands have had basal areas over 200 ft^2 ac^{-1} for decades.

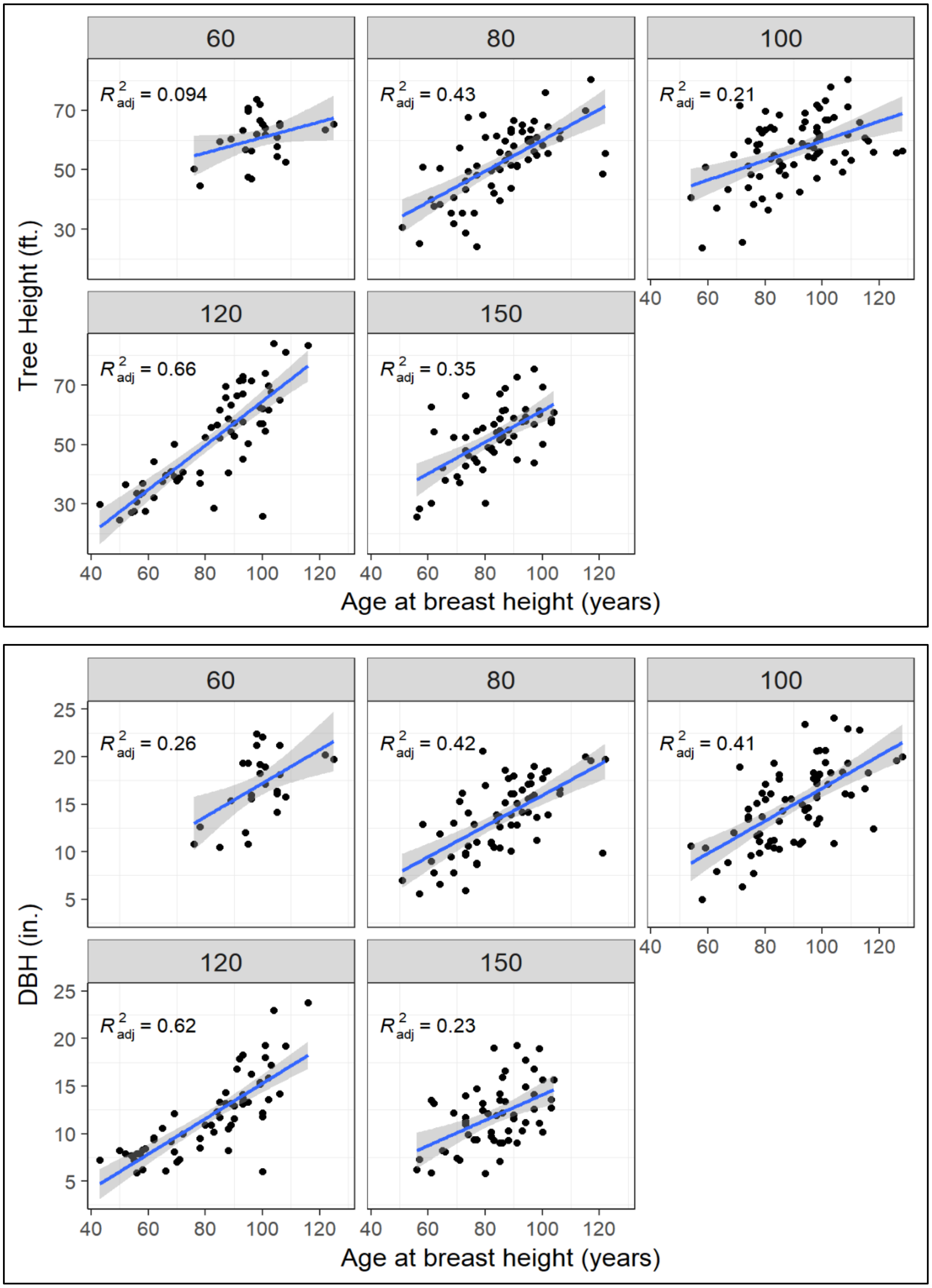

Figure 2: Scatterplots of tree height (top) and DBH (bottom) vs. tree age at breast height for each basal area treatment at the Centennial Forest. In the Centennial Forest, average tree height increases with age. The relationship between diameter at breast height and age at breast height is also positive, yet both relationships vary significantly by basal area class; n = 279.

Acoustic Velocity

Acoustic Velocity vs Basal Area Treatment

Our results indicate that acoustic velocity is positively correlated with basal area treatment (Figure 3). This phenomenon is likely explained by an increase in the proportion of latewood present in the annual rings of the relatively slow-growing trees in the higher basal area treatments. Sound waves are conducted more rapidly through the compact, thick-walled cells of latewood relative to the thinner-walled earlywood cells with wider lumen. Many factors influence the ratio of latewood to earlywood cells in an annual ring. These include crown size; at the individual tree level, the smaller crowns of trees in higher basal area stands have lower water demands than the larger crowns of trees in open-grown stands and thus require less earlywood to conduct water upward from the roots.

While we found only a weak correlation between acoustic velocity and basal area treatment at the Centennial Forest, there was a stronger trend at Taylor Woods. The reasons for this are not clear, though it may have to do with generally larger trees being present at Taylor Woods. This suggests the possibility that trees at Taylor Woods with more extensive root systems may have greater access to late-season soil moisture, allowing for increased latewood formation.

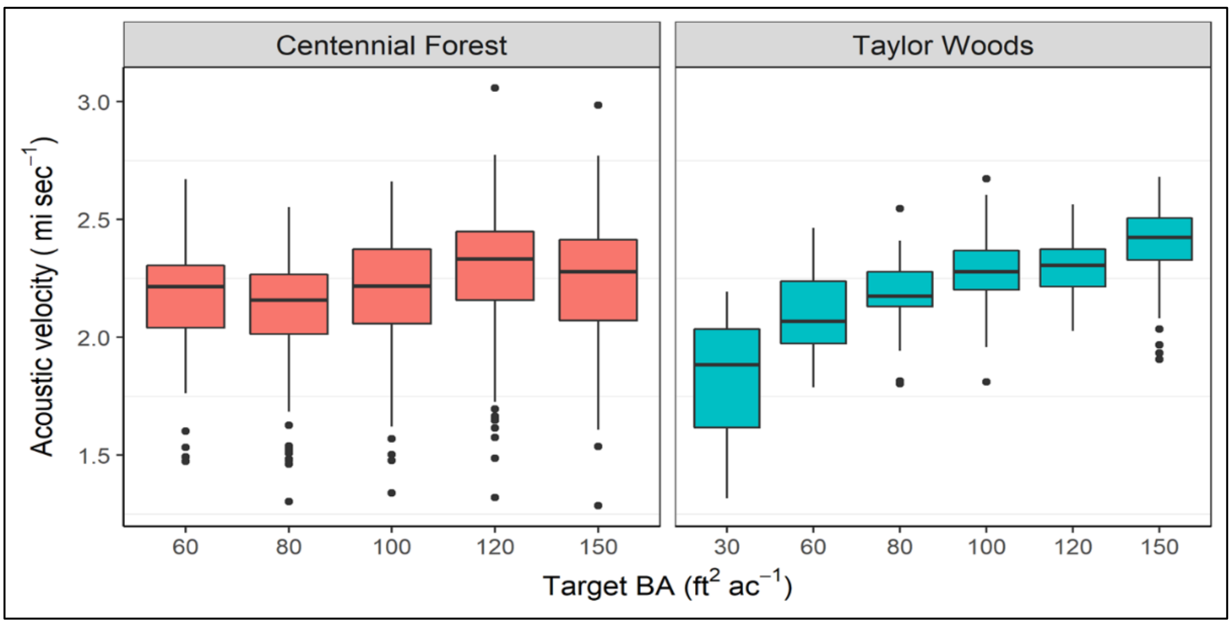

Figure 3: Boxplots of acoustic velocity for each target BA treatment. Mean velocity (i.e. dynamic wood stiffness) is positively correlated with stand basal area; this relationship is significantly stronger at Taylor Woods; n = 720 (Centennial Forest); n = 333 (Taylor Woods).

In addition to analyzing the relationship between acoustic velocity and basal area treatment classes, we must consider a more fundamental question: are our reported acoustic values "good" from a wood products perspective? Our reported acoustic velocity values in the highest basal area units of 120 and 150 $ft^2 ac^{-1}$ at both Taylor Woods and Centennial Forests ranged from approximately 1.24 mi sec^{-1} to 3.11 mi sec^{-1}. Most values were clustered between 1.86 and 2.48 mi sec^{-1}; however, approximately 10% of values were above 2.48 mi sec^{-1}.

In general, acoustic tools allow for precise characterization of the forest resource before processing. This deeper understanding of the internal wood properties of a stem gives foresters and mill operators the power to maximize their profits by segregating logs based on their internal properties. Examples of acoustic tools being used to study ponderosa pine in the United States Southwest do not exist. It was thus inherently difficult to determine whether the ranges of acoustic velocity values reported for ponderosa pine in this study should inspire confidence that trees removed from 4FRI operations will be suitable for high-value end-uses.

Though problematic, we must look to other species to contextualize our results. In a study of acoustic properties in plantation-grown New Zealand radiata pine (*Pinus radiata*), the authors reported standing-tree acoustic velocity values ranged from just above 1.86 mi sec^{-1} to just below 3.11 mi sec^{-1}, with the bulk of acoustic measurements clustered near the mean of 2.34 mi sec^{-1} (Matheson et al 2002). Although the relationship between downed log acoustic velocity and static wood stiffness was stronger than that between standing-tree acoustic velocity and wood stiffness, acoustic velocity in standing trees was still moderately correlated with dynamic wood stiffness and had the power to inform pre-processing segregation decisions. The authors ultimately concluded that based on wood stiffness, the top 50% of stems were appropriate for structural end-uses while the bottom 50% would be best suited for non-structural applications.

Another study looked at acoustic velocity in white spruce (*Picea glauca*) growing in plantations in Quebec, Canada (Bérubé-Deschênes et al 2016). The plantations were ready for a first commercial thinning at around twenty years of age. The average acoustic velocity pre-thinning ranged from 1.86 to 2.17 mi sec^{-1}. The authors also described a similar relationship between dynamic wood stiffness and crowding pre-thinning, where increased competition and reduced crown size increased latewood percentages in stems and, ultimately, improved wood stiffness. Ultimately, slow growth was also associated with higher latewood percentage and acoustic velocity.

Drawing strong conclusions on appropriate end-uses for ponderosa pine through cross-species comparisons would be problematic. Ponderosa pine wood from northern Arizona will have to compete with domestic and international wood products from plantation settings; thus, a broad contextualization of ponderosa pine wood properties relative to "the competition" is still appropriate. Though standing tree acoustic velocities are not perfect for assessing the potential end-use of a given stem, relative comparisons of acoustic velocities do allow us to understand the stiffness of ponderosa pine in our region relative to stems growing elsewhere (DeBell J, pers. comm., September 2017).

The Washington State Department of Natural Resources Genetic Resources Program has set up over 30 Douglas-fir (*Pseudotsuga menziesii*) progeny test sites throughout the state. The oldest sites were established in the 1970s, but currently the agency also maintains second- and third-generation test sites. The department began collecting acoustic velocity data in its second-generation sites, planted in the early 1990s. In second-generation sites, Douglas-fir trees between 20 and 30 years old had average acoustic velocities between 2.49 mi sec^{-1} and 3.11 mi sec^{-1} (DeBell J, pers. comm., September 2017). Comparing these progeny sites with our study results, average acoustic values from the second-generation Washington state sites are higher than the majority of values recorded from Taylor Woods and the Centennial Forest. It is not surprising that Douglas-fir trees, with access to abundant resources in plantation settings, produced higher acoustic velocity readouts than ponderosa pine growing in natural stands in the southwestern United States. This suggests that, in terms of intrinsic wood properties, ponderosa pine wood from our region will clearly struggle to compete with plantation-grown Douglas-fir from the Pacific Northwest. Still, this does not preclude the possibility that stiffer, denser ponderosa pine wood from certain stems may still be suitable for higher-value uses, rather than as biomass feedstock or low-value pallet stock.

Ultimately, further, detailed information is needed about the intrinsic properties of wood from our region, for example, mechanical bending tests need to be conducted on trees from across the landscape to enhance results from this pilot study. Our results suggest that certain individuals growing in higher basal area stands (120 ft^2 ac^{-1} or above) may be suitable for higher value, structural uses based strictly on their acoustic properties and predicted improved wood stiffness. The average acoustic velocities in the highest basal area stands we measured approached 2.50 mi sec^{-1}; based on results from the studies detailed above, 2.50 mi sec^{-1} may be an approximate cutoff for structural uses.

Undoubtedly, a threshold exists where the relationship between stand-level basal area and acoustic velocity collapses. Very stressed trees in higher basal area stands may not have sufficient resources to produce higher quality, denser and stiffer wood. Additionally, trees from completely unthinned stands, with basal areas well above 200 ft^2 ac^{-1}, may simply be too small for any uses other than as biomass energy feedstock. Researchers might focus future studies solely on higher basal area stands (100 ft^2 ac^{-1} – 200 ft^2 ac^{-1}) to determine up to what point the relationship described in this subsection holds true.

Acoustic Velocity vs Diameter at Breast Height

In general, there was a weak relationship between acoustic velocity and DBH across the different treatments at both study sites (Figure 4). While in the Centennial Forest there was a positive relationship across all basal area treatments, this was not the case for Taylor Woods. Potential confounding effects relating to differences in site quality or stand history may have affected our results. The fact that fewer trees were sampled at Taylor Woods and that these trees had a narrower range of diameters might also contribute to the differences seen between the two sites.

Confirmation of the Centennial Forest results by future studies would indicate a significant tradeoff between intrinsic wood properties and tree volume. Taller, small-diameter individuals growing in relatively high basal area stands are likely to produce stiff wood suitable for high-value applications; however, larger-diameter trees may also produce stiff wood, while generating more merchantable volume. Additional work is needed across a greater range of sites to confirm the relationship between diameter and acoustic velocity in ponderosa pine growing in the Southwest U.S.

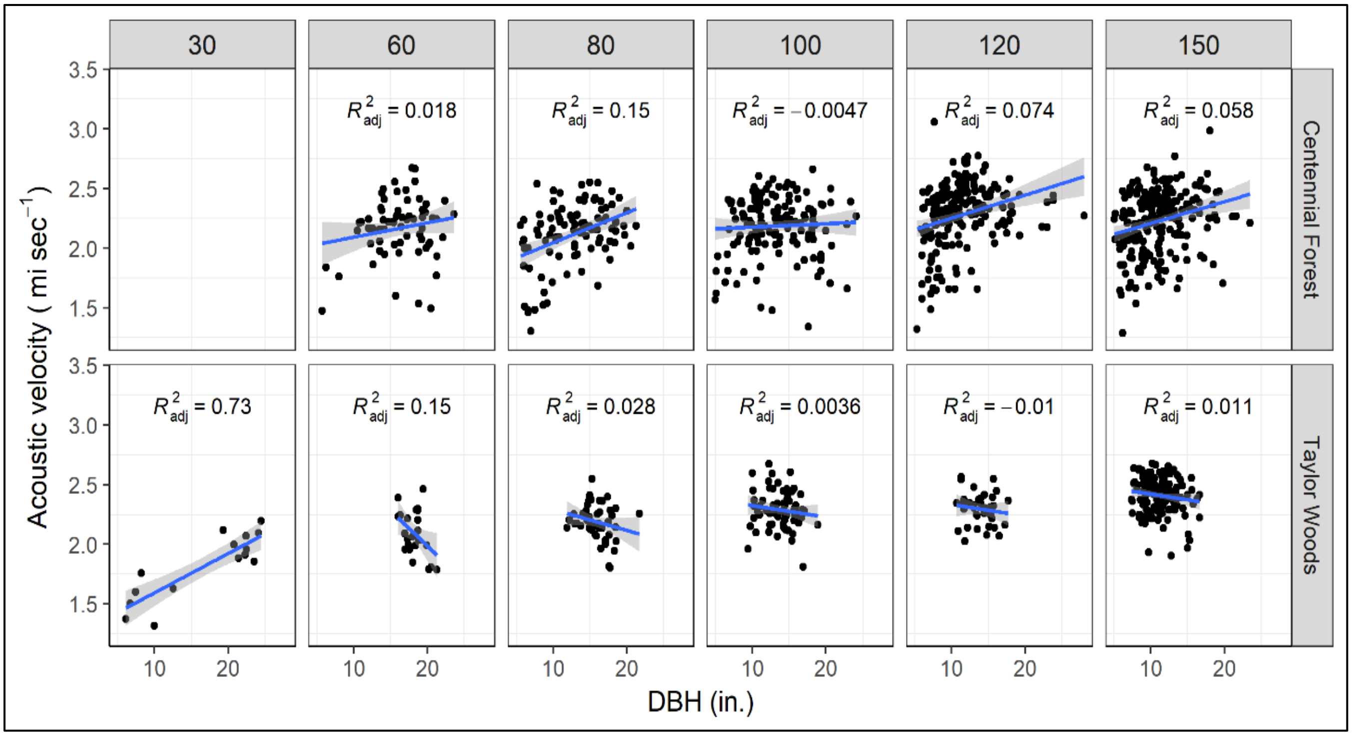

Figure 4: Acoustic velocity vs DBH for each basal area treatment at the Centennial Forest and Taylor Woods. There was generally a positive correlation between acoustic velocity and DBH for trees in the Centennial Forest. Patterns are less clear at Taylor Woods; n = 720 (*Centennial Forest*)*; n = 333* (*Taylor Woods*)*.*

Acoustic Velocity vs Total Tree Height

The correlations between acoustic velocity and tree height were weak overall (Figure 5), although a positive relationship between average tree height and acoustic velocity does appear to exist across both study sites. For all basal area treatments at both Taylor Woods and the Centennial Forest, acoustic velocity increased with increasing tree height. This relationship was weakest in the mid-level treatments of 80 and 100 $ft^2 ac^{-1}$, but was still slightly positive. This general relationship could be explained by a combination of factors: the relationship between tree height and age likely played a role in shaping our results. Taller trees tend to be older (Figure 2), and older trees tend to form denser wood (Figures 7 and 8). If we assume that denser wood correlates with higher stiffness, this wood would transmit a sound wave more quickly between the two probes of the ST300.

Additionally, after reaching approximately 25 years of age, trees will have transitioned from producing juvenile wood to producing mature wood, which tends to be stiffer and denser than juvenile wood. Somewhat independent of age, taller trees may also have more extensive root systems. Coupled with more favorable canopy positions, taller individuals are likely better prepared to sequester resources later into the growing season. However, higher basal area treatments generally contain smaller, shorter trees. This suggests there may be tradeoffs between dynamic stiffness gains and volume losses in these higher basal area stands.

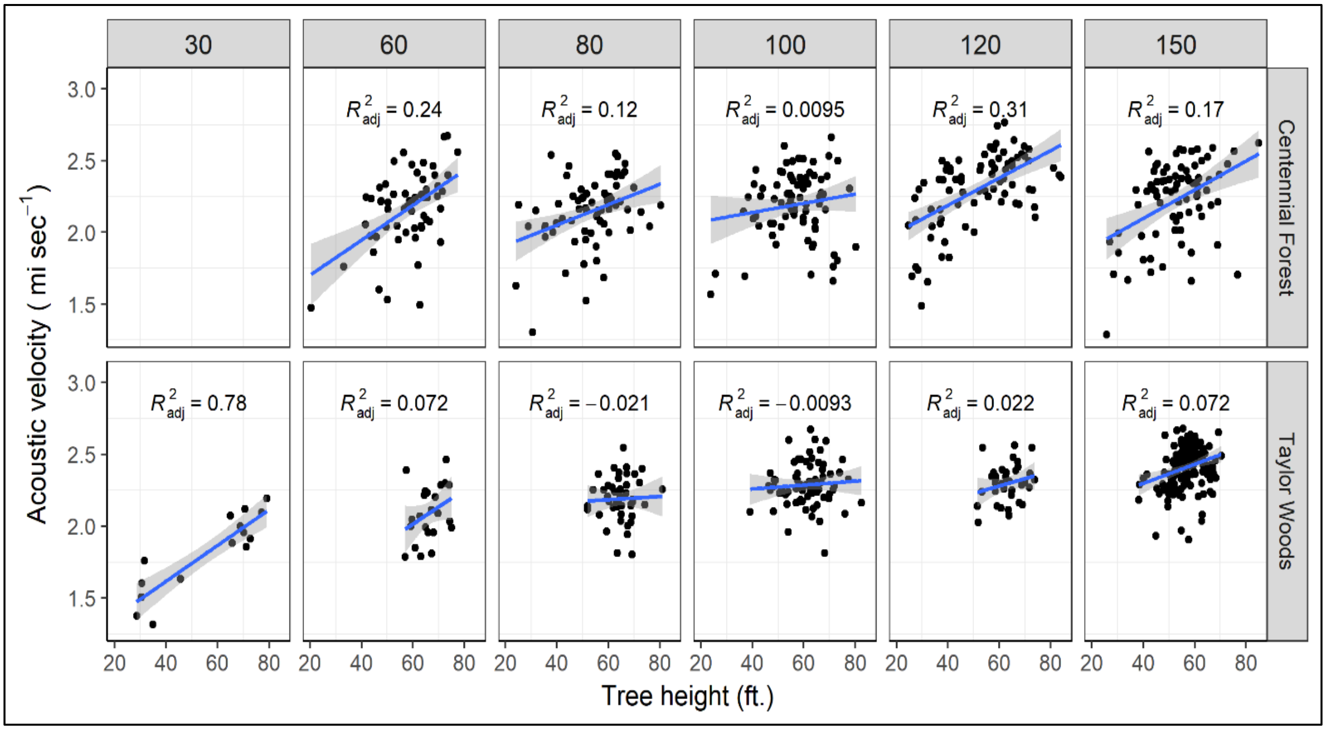

Figure 5: Acoustic velocity vs total tree height in each basal area treatment at the two study sites. A clear, positive correlation exists between tree height and acoustic velocity across both sites, with the pattern most clearly expressed in the lowest and highest basal area treatments; n = 279 (*Centennial Forest*)*; n = 333* (*Taylor Woods*).

Acoustic Velocity vs Ring-level Wood Density

The correlation between acoustic velocity and ring-level wood density was examined over the last fifty years of growth, as an acoustic wave only travels through the outerwood of a stem. Our results indicate a weak positive correlation between acoustic velocity and wood density (Figure 6). Regardless of treatment class, denser wood correlates to higher acoustic velocity. These results are not entirely surprising. As discussed, wood density is often linked to higher latewood percentage in a stem. Denser wood, containing higher amounts of latewood, will likely conduct sound waves faster than wood with a lower proportion of latewood. These results suggest that wood density may be inferred from acoustic velocity measurements. Such an inference could be significant: whereas it is a laborious process to measure wood density at the stand level, it is relatively simple to measure acoustic velocity in sample plots across multiple stands.

The next logical step in this line of research would be to bolster this predictive model for wood density based on acoustic velocity, which would allow analysts to infer both dynamic stiffness and wood density from easily obtained acoustic measurements, among other variables. The positive relationship between acoustic velocity and wood density across all basal area treatments suggests that trees in higher basal area stands, regardless of their size, may not only have stiffer wood than previously thought, but also denser wood.

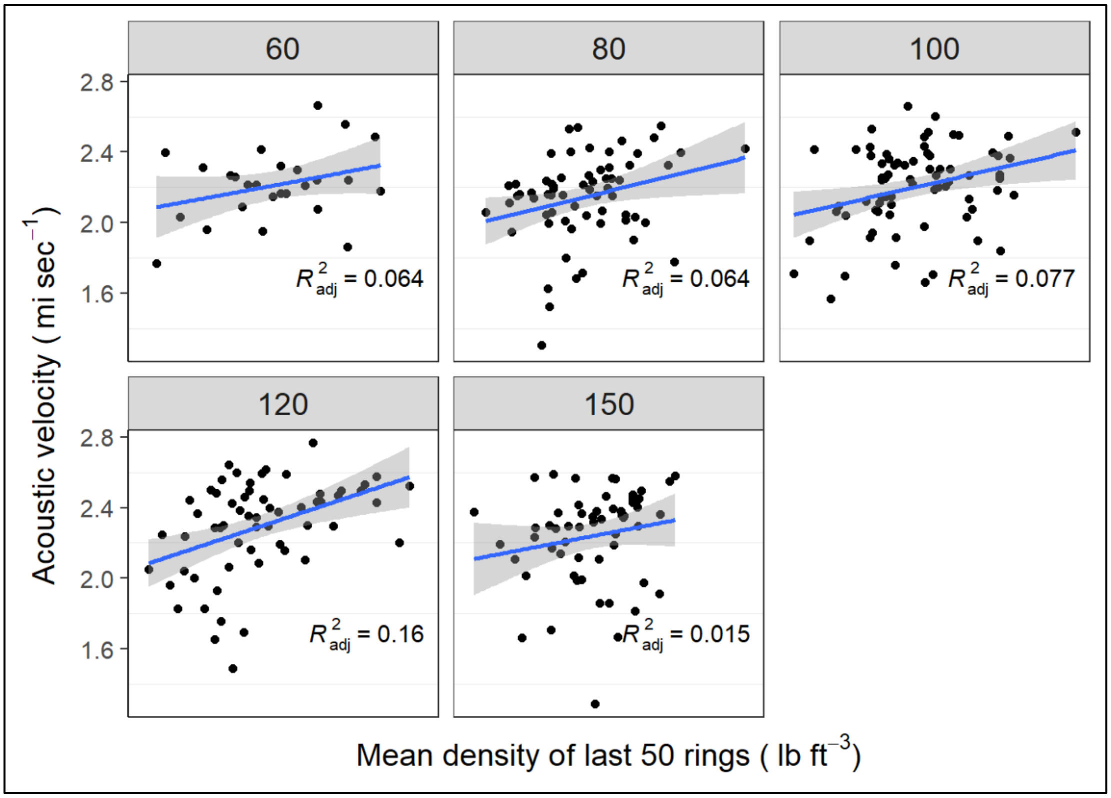

Figure 6: Acoustic velocity vs the mean density of the last 50 annual rings in each basal area treatment. Results exclusively from the Centennial Forest show a weak, yet positive relationship between acoustic velocity and wood density across all basal area treatments; n = 279.

Wood Density

Ring-level Wood Density vs. Cambial Age and Year of Ring Formation

When comparing ring-level wood density to cambial age and year of ring formation, most trees exhibited irregular density early in their lives (Figures 7 and 8). However, as might be expected, ring-level wood density stabilized and slightly increased in recent years. This is most likely linked to a reduction in juvenile wood production as trees age. Climatic variation, undeniably tied to competition, also likely played a significant part in shaping these results. Significant drought events and particularly strong summer monsoons at different times during the 2000s likely contributed to spikes and dips in wood density over the last two decades.

Treatments of 100ft^2 ac^{-1}, 120ft^2 ac^{-1}, and 150ft^2 ac^{-1} show a weak yet positive correlation between cambial age and ring-level wood density, while in the lowest basal area stands there appears to be no correlation between these variables. It is possible that in open stands (60ft^2 ac^{-1} and 80 ft^2 ac^{-1}) greater production of earlywood offsets wood density gains associated with the shift from juvenile to mature wood production. Open-grown trees should have greater radial growth rates than trees growing in higher basal area stands. Much of this additional radial growth will consist of thin-walled, low-density earlywood cells with wide lumen. In general, our results suggest that the internal wood properties of ponderosa pine vary widely based on multiple variables. Forest managers should consider average tree age when anticipating the intrinsic wood properties of trees and their potential end-uses.

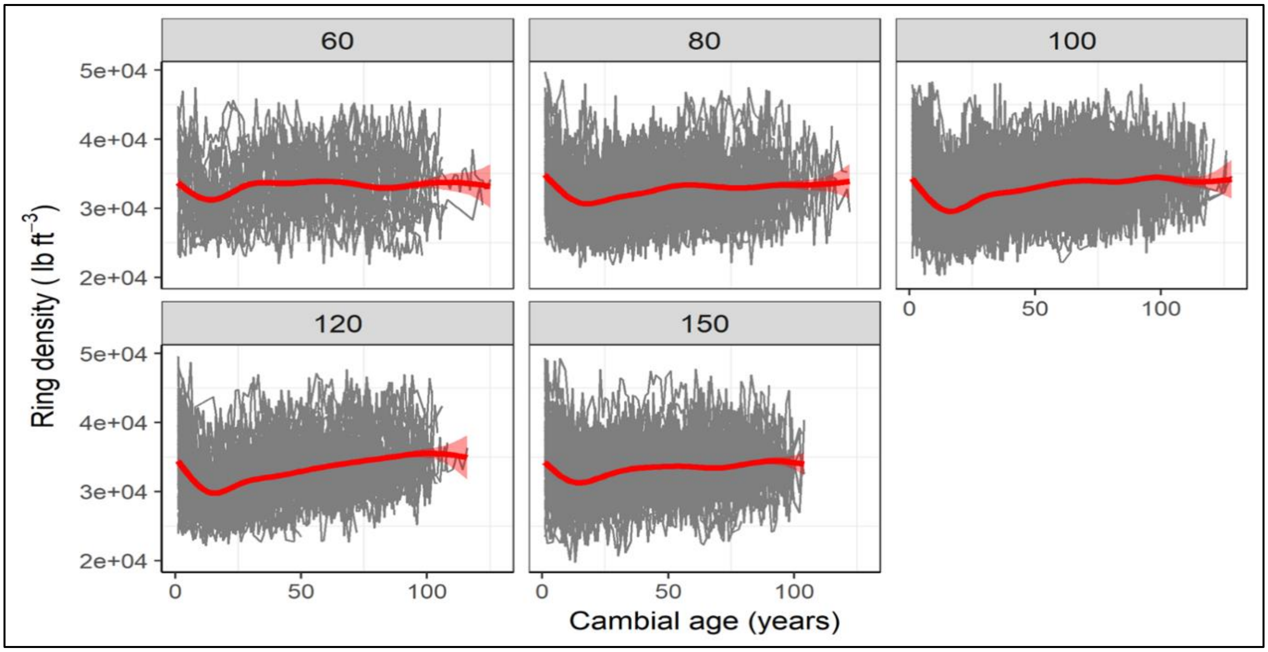

Figure 7: Mean ring density vs cambial age for all basal area treatments at Centennial Forest. The decrease in wood density near the pith is followed by a weak trend of increasing ring-level wood density at higher cambial ages, as shown by the red line representing a smoothed moving average. Grey lines represent individual tree density profiles; n = 279.

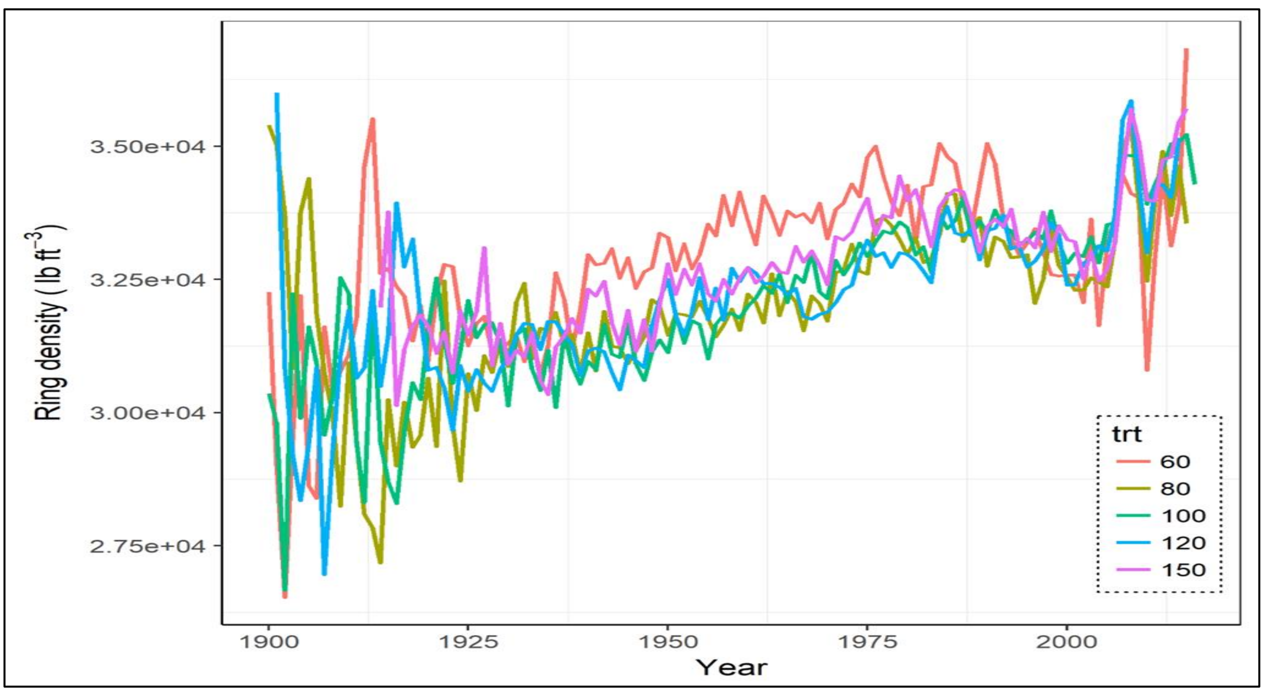

Figure 8: Mean ring density vs year of wood formation averaged across all basal area treatments at Centennial Forest. Excluding large variation in young trees, ring-level wood density generally increased with year of ring formation; n = 279.

Ring-level Wood Density vs Basal Area Treatment

Given the highly variable conditions at the Centennial Forest before the thinning of 2005, it is not possible to accurately link stand-level basal area to wood density before 2005 (Gaylord et al 2011). In general, increased water availability late in the growing season is one of the most significant factors influencing latewood formation and thus wood density in our region. It is logical to assume that late-season water availability was historically a major contributing factor in wood density differences over time.

We may more conclusively hypothesize about the causes of trends in wood density across basal area treatment classes after the thinning of 2005 (Figure 9). As we did not cross-date our samples, the position of 2005 on our graph is an approximation and it is therefore difficult to detect the exact impact of thinning on wood density. Still, general trends and differences between basal area treatments can be analyzed with relative confidence from the last ten years. In the 2000s, the higher basal area treatments of 120ft^2 ac^{-1} and 150 ft^2 ac^{-1} had generally slightly higher average ring-level wood densities than the basal area treatment classes of 60ft^2 ac^{-1}, 80ft^2 ac^{-1}, and 100ft^2 ac^{-1}. Several factors may have influenced the surprisingly high ring-level wood density of trees in the highest basal area treatment blocks. Trees in higher basal area stands have less opportunity for diameter growth; thinning blocks to 120ft^{2}ac^{-1}and 150ft^2 ac^{-1} would not necessarily have resulted in significant radial growth, depending on pre-treatment basal areas. However, after the thinning of 2005, trees in these higher basal area stands would have had more resources available to them later in the growing season. With small crowns and limited room to grow radially, there would be little reason for trees in higher basal area treatment blocks to add wide-lumen, earlywood cells. Given the smaller crowns of trees from higher basal area stands, it seems logical that resources made available after a forest thinning would be preferentially directed toward forming compact, latewood cells rather than low-density, earlywood cells (Larson 1969).

Regardless of the cause of the phenomena described above, the implications for wood utilization are significant: trees in higher basal area stands form wood that is at least as dense as the wood formed by trees in more open stands. We do not know the point at which this relationship might break down: doghair thickets of bent-over ponderosa pine may not be producing particularly dense wood. This pattern may already be present in our data: the 150ft^2 ac^{-1} treatment class exhibits lower average wood density at many points in time relative to the slightly more open 120ft^2 ac^{-1} treatment class.

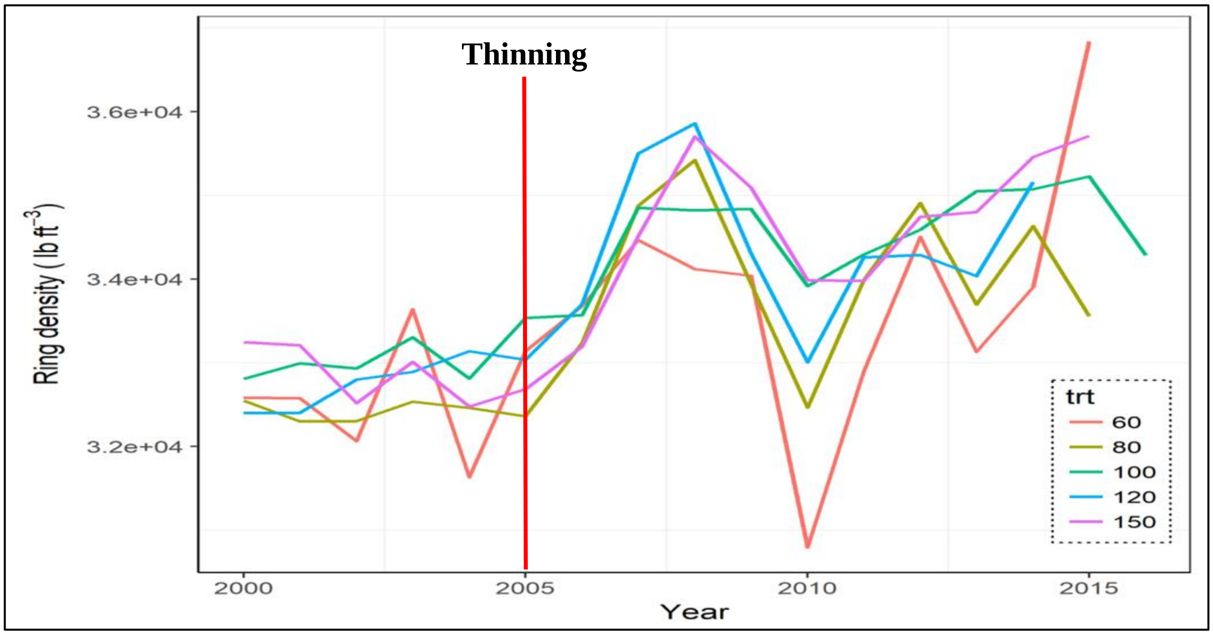

Figure 9: Annual ring density vs year of wood formation by treatment for the last 16 years of wood formation at the Centennial Forest. Actual basal areas were not accurately known before the thinning of 2005 when the study was established. Trees in the highest density treatments of 120 ft^2ac^{-1} and 150 ft^2ac^{-1} appear to form slightly denser wood than those in lower basal area treatments; n = 279.

Annual Ring Width vs Cambial Age

A general trend of decreasing ring width with increasing age exists in trees from the Centennial Forest (Figure 10). An initial rapid decrease stabilized over time; across most basal area treatment classes, ring width leveled off between the ages of 25 and 50, except for in the 60 ft^2 ac^{-1} treatment. The initial decrease in ring width as a tree ages is likely a result of wider annual rings and more rapid growth when trees are younger and subject to less competition. Older trees must produce increasingly more wood to cover their larger circumferences, resulting in progressively narrower rings until diameter growth stabilizes at a much lower level.

However, wood formation at a finer scale is highly variable, resulting in annual fluctuations in ring width. Irregular ring widths are present across all treatments. These anomalies suggest that growth rates have been inconsistent over time, resulting in latewood and earlywood bands that are highly variable in width. Images and graphical readouts of scanned samples confirm this variability across many of our wood samples.

The semi-arid climate of the region is likely a significant driver of these results. Limited soil moisture and periodic drought, coupled with years of heavy monsoonal rains, directly affects latewood growth and consequently ring width (Kerhoulas et al 2017). Coupled with intense crowding and increased competition in the highest basal area treatments, these factors likely explain much of the variability in ring width seen in our results. Production of latewood that varies in density by year results in inconsistent ring widths, likely creating highly variable mechanical wood properties within a given stem.

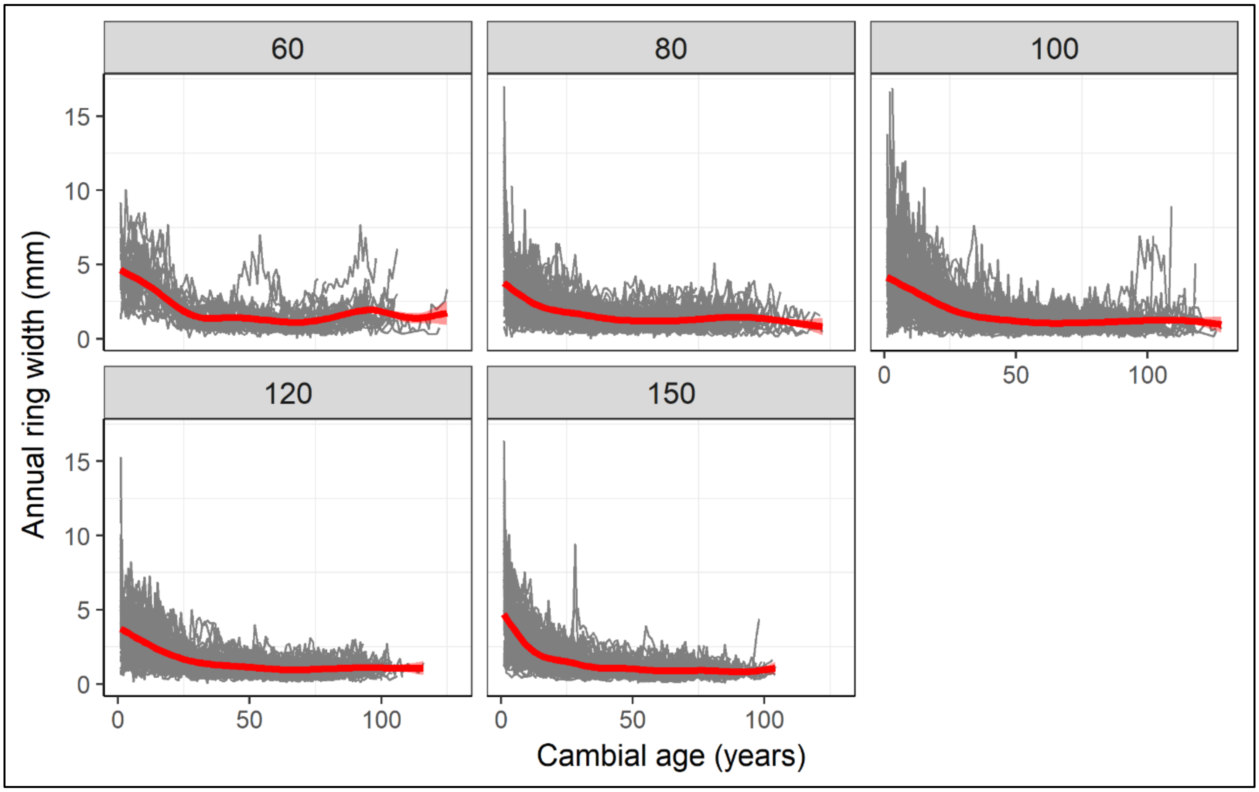

Figure 10: Average annual ring width vs cambial age for each treatment at Centennial Forest. Annual ring width initially decreased rapidly in the annual rings near the pith, but stabilized over time across all basal area treatments. Red line indicates a smoothed moving average. At the individual tree level (gray lines), ring width was highly variable; n = 279.

Broader Significance

In general, the significance of our results is nuanced and complex. In understanding these results, perhaps the most significant factor to consider is the relationship between age and tree size across much of the forested landscape of the southwestern United States. Though the vast majority of the trees in our region are under 12 inches in diameter, many of these individuals are approaching one-hundred years old. This potentially misleading age-diameter relationship suggests that traditional, plantation-based knowledge of the wood quality of smaller trees cannot be applied to many of the forests of the southwestern United States. Whereas throughout much of the world, small, young trees will produce low-density, juvenile wood, small, older trees produce much different wood. As our results suggest, small-diameter ponderosa pine that have survived significant competition for resources are likely to have a high percentage of mature wood. Furthermore, as annual rings are narrow in width in these trees, a substantial proportion of these stems will be composed of high-density, latewood.

However, growth irregularities confound our results and may impede the utilization of ponderosa pine wood in the region regardless of the intrinsic wood properties. Many stands in northern Arizona have experienced cycles of rapid and slow growth. Variations in growing conditions and climate have resulted in inconsistent ring widths in many trees. Traditionally, wood processing industries have valued consistent, uniform growth. These growth irregularities will most likely preclude the use of a given stem for structural applications as high-value solid lumber products.

Incorporating the knowledge presented in this study into forest management decisions may be difficult if direct acoustic and wood density measurements cannot be taken across the 4FRI landscape. Still, by considering stand development histories, managers may be able to segregate forest resources more efficiently without taking these measurements. If basic stand-level basal area information dating back several decades are available to forester managers, internal wood properties may be roughly approximated at the stand level: individuals that grew in relatively constant, moderately-high basal area stands may have stiffer, denser wood that may be suitable for higher-value end-uses.

Conclusions

Wood density and acoustic velocity results from this study give cause for tempered optimism in the northern Arizona forestry community. From our results, we have concluded that a certain proportion of small-diameter ponderosa pine trees in the region could likely produce wood suitable for high-value applications. Increased fundamental knowledge of the internal wood properties of trees in our region is essential to helping address some of the crucial issues facing northern Arizona's researchers and forest managers. I would like to conclude by providing some closing thoughts on how the oversupply of small-diameter timber and absence of significant wood industry in north-central Arizona might be addressed:

1. *Develop a more nuanced and informed understanding of the actual internal wood properties of the trees in our forests*.

This understanding will allow for the proper segregation of stems before processing, and will ultimately contribute to more efficient and informed planning of forest treatments, directing trees from different stands to appropriate markets for the wood products they will ultimately produce. At present, a lack of local processing facilities and heavy competition from domestic and international markets has impeded large-scale utilization of ponderosa pine in the Southwest. There likely exists no "golden egg" solution to this problem. A diverse cluster of processing facilities in terms of size and output must be encouraged to develop around Flagstaff. The first step towards achieving this is to have detailed information on the properties of the available timber supply. This pilot study provides an initial step toward this more complete understanding of ponderosa pine and its true value. Faculty and students at Northern Arizona University are already at work on studies that will further increase our knowledge of the internal properties of the ponderosa pine growing in the Southwest.

2. *Increase stewardship programs for loggers and entrepreneurs.*

Given the international nature of wood markets and competition from regions that more easily grow timber suitable for structural applications, there is simply no way the private sector can establish and maintain itself in northern Arizona without some degree of outside assistance. In the long-term, the federal and state government should look to help establish a mix of composite wood product manufacturers and biomass plants in the region. The responsibility of such stewardship does not fall squarely on federal and state governments though: The Nature

Conservancy has been active in forging new relationships and supporting local mills through unfavorable economic times. The Nature Conservancy is open to greater participation in worthwhile restoration projects where their capital and technical support can help achieve restoration goals through supporting efficient forest operations and the growth of local industry (Chapman N, pers. comm., September 2017).

The city of Flagstaff has also pioneered innovative projects to increase forest treatments around the city: following the Schultz fire of 2010, which burned approximately 15,000 acres near Flagstaff's Timberline and Doney Park neighborhoods, the residents of the city approved a ten-million-dollar bond that was paid through taxes levied on individuals (http://www.flagstaffwatershedprotection.org/, 10 Sept 2017). This money has been used to fund the Flagstaff Watershed Protection Project, which connects forest managers with loggers from the region to treat the forested landscape around the city, focusing on areas that are essential to the long-term quality and stability of the town's water supply.

In our neighboring state of Colorado, the state forestry division has been active in multiple areas of the wood utilization process. Through the Colorado Forests Products Program, experts in wood utilization, research, and forest management are working across agency and social boundaries to increase the local use and value of their forest resources (http://csfs.colostate.edu/cowood/cfp/, 8 Nov 2017). These experts provide technical support to a diverse group of forest landowners, conduct applied research to improve wood utilization in the region, and work to both educate and train the public in issues and skills relevant to local wood utilization. To the author's knowledge, no such program to assist private and public landowners exists in Arizona.

Although there are examples of successful, creative partnerships to improve restoration and wood utilization throughout the Southwest, the U.S. Forest Service and the Arizona Department of Forestry and Fire Management have been reluctant to play an active part in establishing creative partnerships with local loggers, landowners, and entrepreneurs. Consequently, potential industry and investors avoid north-central Arizona. Implementation of restoration and fire-hazard mitigation treatments in the region continues to be impeded by a poor wood-processing landscape and an uniformed local consumer base.

3. *Develop and implement a certification system for wood sourced from local fire-hazard reduction treatments and cultivate responsible wood-products consumers.*

When we consider the suitability of southwestern ponderosa pine wood for high-value uses in a national and international context, encouraging industry to invest in large-scale processing plants near Flagstaff seems problematic. The dry conditions in the Southwest mean that trees producing high quality wood will grow faster and cheaper elsewhere. Currently, it is a near certainty that ponderosa pine wood products from north-central Arizona cannot compete with products from Douglas-fir grown in the Pacific Northwest, or those from Southern yellow pine species from the Southeast. The local public must therefore be encouraged to pay a premium for wood removed to save their homes and communities. This will require long-term collaboration between foresters, marketing professionals, entrepreneurs, and consumers to emphasize the "hidden value" of locally-produced wood products.

In the southwestern U.S., increased consumer awareness must accompany any revitalization of industry. We must convince the public to view wood products as many view their food: local is better. The details of how to develop this consumer consciousness are beyond the scope of this work. However, it is important to note that communities elsewhere in the U.S. have embarked on a similar mission: local wood-workers and builders throughout Colorado have begun to use beetle-killed wood to construct homes, floors, and more (http://www.denverpost.com/2011/09/27/beetle-killed-wood-being-used-in-home-construction/, http://www.cswoods.com/localwoods.htm, 10 Sept 2017). These projects remove flammable wood from the forested landscape, while infusing new life into local communities. Capitalizing on markets in Flagstaff, Tucson, and Phoenix, there is no reason to believe similar projects, using wood removed during fire-hazard reduction treatments, could not have success throughout Arizona.

4. *Provide training to community members in woodworking, construction, tree felling, and basic wood processing.*

In searching for the "golden egg" solution to the wood oversupply problem in the Southwest, we often think of large-scale projects, such as biomass energy, OSB and particleboard plants, or chipping large amounts of wood for use in landscaping. However, smaller, local-level solutions remain an important part of these efforts. Incorporation of local landowners, builders, and woodworkers into solutions aimed at utilizing the bi-products of forest restoration and fuels reduction treatments is crucial. Focusing on small landowners, training and encouraging them to remove and utilize small-diameter ponderosa pine on their properties would be an easy and straightforward way to encourage people to reduce fire hazard on their own lands. Interested community members should be supported in purchasing portable mills. Support in drying methods for ponderosa pine lumber, which has a reputation for warping and cracking, is also important. This training and support could be more significantly incorporated into the Firewise USA program (http://www.firewise.org/wildfire-preparedness/be-firewise/home-and-landscape.aspx, 10 Sept 2017). In considering the large amount of woody material we need to remove from our landscape, we must not forget the role that individual communities can play in forging solutions.

The resolution of the issues surrounding wood utilization in north-central Arizona will have to be nuanced and multi-disciplinary, functioning at various levels of society and government. Ultimately, foresters may have to venture into unfamiliar territory in search of long-term solutions. However, as a first step toward addressing the wood oversupply problem in the region, we must understand the basic internal wood properties of the trees to be removed and retained during thinning operations. Incorporated at the stand level, information on acoustic velocity and wood density can be used to more efficiently identify and categorize the quality of the forest resource, maximizing yields and potential economic gains from stands and ultimately enticing industry back to the region (Matheson et al 2002; Wang et al 2007a). It is our hope that forest managers will be able to incorporate the results of our analysis in their landscape-scale planning, and that our study will help direct silvicultural treatments toward more careful consideration of the end-use potential of trees removed in restoration and hazardous-fuels treatments. This will require additional research on ponderosa pine wood quality, which will help refine and broaden these results to the greater southwestern United States forested landscape.

Acknowledgments

I would like to thank my wife, Alejandra, for supporting me throughout this process and my parents for their unwavering, constant support of my pursuit of higher education. I am also very grateful for the support of Northern Arizona University: without the financial aid offered to me by the university, I would not have been able flourish in such a rigorous academic environment. I would like to thank my readers Dr. Tom Kolb and Dr. Kristen Waring for their time and effort in revising my work and would like to extend an additional thanks to both of them for their exemplary teaching and advising, which has truly prepared me for a career in forestry. I would like to thank Dr. Joseph Dahlen from the University of Georgia for his assistance preparing our increment cores for scanning. I would also like to thank the Rocky Mountain Research Station Forest Service Staff, with a special thanks to Dr. Keith Moser, for their collaboration with this project. I would like to thank Mr. Neil Chapman of The Nature Conservancy and Dr. Jeff DeBell of the Washington State DNR for providing me with detailed background information that greatly aided me in completing this work. Lastly, I owe a very special thanks to my advisor Dr. Dave Auty. Dr. Auty has offered me constant guidance and attention throughout my time at the university. His dedication and availability serve as a shining example of faculty mentorship and I am extremely indebted to him for his guidance and support. Thank you.

Literature Cited

Abella S, Fulé P, Covington W. 2006. *Diameter caps for thinning Southwestern ponderosa pine forests: Viewpoints, effects, and tradeoffs*. Journal of Forestry 104(8):407-414.

Antony F, Schimleck L, Hall D, Clark A, Daniels R. 2012. *Modeling the Effect of Midrotation Fertilization on Specific Gravity of Loblolly Pine (Pinus taeda L.)*. Forest Science 57(2):145-152.

Auty D, Achim A. 2008. *The relationship between standing tree acoustic assessment and timber quality in Scots pine and the practical implications for assessing timber quality from naturally regenerated stands.* Forestry 81:475-487.

Auty D, Achim A, Macdonald E, Cameron A, Gardiner B. 2014. *Models for predicting wood density variation in Scots pine*. Forestry 87:449-458.

Auty D, Achim A, Macdonald E, Gardiner B. 2016. *Models for Predicting Clearwood Mechanical Properties of Scots Pine.* Forest Science 62:1-9.

Bailey J. 2008. *Forty years later at Taylor Woods: Merging the old and new*. Fort Valley Experimental Forest—A Century of Research 1908-2008. Proceedings RMRS-P-55:100-105.

Bérubé-Deschênes A, Franceschini T, Schneider R. 2016. *Factors Affecting Plantation Grown White Spruce (Picea Glauca) Acoustic Velocity*. The Journal of Forestry 114(6):629-637.

Carter P, Briggs D, Ross R, Wang X. 2005. *Acoustic testing to enhance western forest values and meet customer wood quality needs*. Productivity of Western forests: a forest products focus general technical report – Pacific Northwest Research Station: 121-128.

Carter P, Wang X, Ross R. 2013. *Field application of processor head acoustic technology in forest harvest operations*. Proceedings of the 18th International Nondestructive Testing and Evaluation of Wood Symposium: Sept. 24-27, 2013, in Madison, WI.

Covington W, Moore M. 1994. *Postsettlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests.* The Journal of Sustainable Forestry 2(1-2):153-218.

Covington W, Fulé P, Moore M, Hart S, Kolb T, Mast J, Sackett S, Wagner M. 1997. *Restoring Ecosystem Health in Ponderosa Pine Forests of the Southwest.* The Journal of Forestry 95(4):23-29.

Dannenberg P, Wise E. 2016. *Seasonal climate signals from multiple tree ring metrics: a case study of Pinus ponderosa in the upper Columbia River Basin.* Journal of Geophysical Research: Biogeosciences 121:1178-1189.

Davis E, Mottek A, Kim Y, Moseley C, Bilek T. 2014. *The Impacts of the Woody Biomass Utilization Grant Program in Eastern Oregon and Eastern Arizona*. Ecosystem Workforce Program Working Paper Number 46:1-39.

Ffolliott P. 2008. *Historical Review of Fort Valley Studies on Stand Management*. Fort Valley Experimental Forest—A Century of Research 1908-2008. Proceedings RMRS-P-55:18-24.

Flathers K, Kolb T, Bradford J, Waring K, Moser K. 2016. *Long-term thinning alters ponderosa pine reproduction in northern Arizona*. Forest Ecology and Management 374(14):154-165.

Gardiner B, Leban J, Auty D, Simpson H. 2011. *Models for predicting wood density of British-grown Sitka spruce.* Forestry.

Gaylord M, Hofstetter R, Kolb T, Wagner M. 2011. *Limited response of ponderosa pine bole defenses to wounding and fungi*. Tree Physiology 31:428-437.

Geils B. 2008. *Fort Valley Studies: A Natural Laboratory for Research and Education*. Fort Valley Experimental Forest—A Century of Research 1908-2008. Proceedings RMRS-P-55:1-2.

Grabianowski M, Manley B, Walker J. 2006. *Acoustic measurements on standing trees, logs and green lumber.* Wood Science Technology 40:205-216.

Guilleya E, Hervéb J, Hubera F, Nepveua G. 1999. *Modelling variability of within-ring-level wood density components in Quercus petraea Liebl. with mixed-effect models and simulating the influence of contrasting silvicultures on wood density*. Annals of Forest Science 56(6):449-458.

Haines W, Leban M. 1997. *Evaluation of the MoE of Norway spruce by the resonance flexure method.* Forest Products Journal 47(10):91-93.

Hampton H M, Sesnie S E, Dickson B G, Rundall J M, Sisk T D, Snider G B, Bailey J D. 2008. *Analysis of Small-Diameter Wood Supply in Northern Arizona.* Forest Ecosystem Restoration Analysis Project, Center for Environmental Sciences and Education, Northern Arizona University.

Jayawickrama K, Ye T, Howe G. 2011. *Heritabilities, Inter-trait Genetic Correlations, G x E Interaction and Predicted Genetic Gains for Acoustic Velocity in Mid-Rotation Coastal Douglas-fir*. Silvae Genetica 60(1): 8-18.

Kerhoulas L, Kolb T, Koch G. 2017. *The Influence of Monsoon Climate on Latewood Growth of Southwestern Ponderosa Pine.* Forests 8(140).

Larson P. 1963. *Stem Form Development of Forest Trees*. Forest Science-Monograph 5:1-42.

Larson P. 1969. *Wood Formation and the Concept of Wood Quality*. Yale School of Forestry Bulletin No.74.

Lenz P, Auty D, Achim A, Beaulieu J, Mackay J. 2013. *Genetic improvement of white spruce mechanical wood traits—early screening by means of acoustic velocity.* Forests 4: 575-594.

LeVan-Green S, Livingston J. 2001. *Uses For Small-Diameter Trees: Exploring the Uses for Small-Diameter Trees.* Forest Products Journal 51(9).

Lowell E, Green D. 2001. *Lumber recovery from small-diameter ponderosa pine from Flagstaff, Arizona*. USDA Forest Service Proceedings RMRS-P-22:161-165.

Lowell E, Todoroki C, Dykstra D, Briggs D. 2014. *Linking acoustic velocity of standing Douglas-fir trees to veneer stiffness: a tree-log-product study across thinning treatments*. New Zealand Journal of Forestry Science 44(1).

Martinez-Meier A, Fernandez M, Dalla-Salda G, Gyenge J, Licata J, Rozenberg P. 2015. *Ecophysiological basis of wood formation in ponderosa pine: Linking water flux patterns with wood microdensity variables.* Forest Ecology and Management 346:31-40.

Matheson A, Dickson R, Spencer D, Joe B, Ilic J. 2002. *Acoustic segregation of Pinus radiata logs according to stiffness.* Annals of Forest Science 59:471-477.

McCusker N, Gonzales R, Fuller R. 2014. *Silviculture Specialist Report Coconino and Kaibab National Forests Four Forest Restoration Initiative.* The United States Department of Agriculture Southwestern Region.

Mora C, Schimleck L, Isik F, Mahon J, Clark A, Daniels R. 2009. *Relationships between acoustic variables and different measures of stiffness in standing Pinus taeda trees*. Canadian Journal of Forest Resources 39:1421-1429.

Mottek L, Kim Y S, Greco B, Becker D R, Hjerpe E E, Abrams J. 2017. *Social and Economic Contributions of the White Mountain Stewardship Project: Final 10-Year Assessment—Lessons Learned and Implications for Future Forest Management Initiatives.* Journal of Forestry 115(6):548-558.

Paradis N, Auty D, Carter P, Achim A. 2013. *Using a Standing-Tree Acoustic Tool to Identify Forest Stands for the Production of Mechanically-Graded Lumber*. Sensor 13(3): 3394-3408.

Repola, J. 2006. *Models for Vertical Wood Density of Scots Pine, Norway Spruce and Birch Stems, and Their Application to Determine Average Wood Density*. Silva Fennica 40(4):673-685.

Sánchez Meador A, Waring K, Kalies E. 2015. *Implications of Diameter Caps on Multiple Forest Resource Responses in the Context of the Four Forests Restoration Initiative: Results from the Forest Vegetation Simulator*. Journal of Forestry 113(2):219-230.

Shmulsky R, Jones D. Forest Products & and Wood Science: An Introduction. 6th edition. Ames, IA: Wiley-Blackwell, 2015.

Sitko S, Hurteau S. 2010. *Evaluating the Impacts of Forest Treatments: The First Five Years of the White Mountain Stewardship Project.* The Nature Conservancy. Phoenix, Arizona.

Wang X, Carter P, Ross R, Brashaw B. 2007a. *Acoustic assessment of wood quality of raw forest materials: a path to increased profitability.* Forest Products Journal 57:6-14.

Wang X, Ross R, Carter P. 2007b. *Acoustic evaluation of wood quality in standing trees. Part 1: Acoustic wave behavior in standing trees.* Wood Fiber Science 39:28-38.

Zobel B J, Sprague J R. Juvenile Wood in Forest Trees. Syracuse, New York: Springer Science & Business Media, 2012.

Appendix

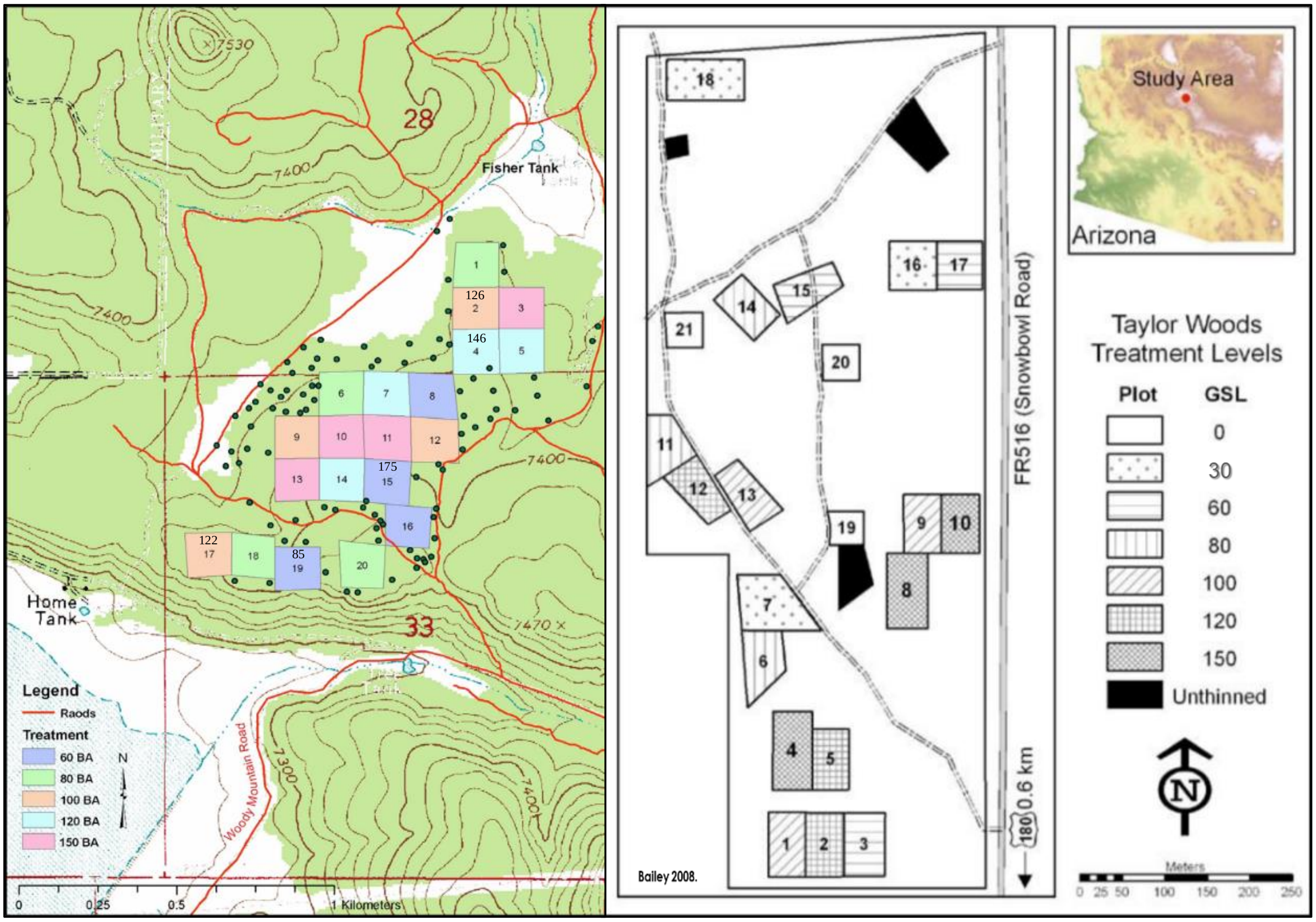

Figure A1: Maps showing the layout of treatment units sampled at Centennial Forest (left) and the U.S. Forest Service's Taylor Woods (right) levels-of-growing-stock studies outside of Flagstaff, Arizona. In the Centennial Forest, twenty treatment units have been maintained at or near five basal area classes of 60, 80, 100, 120, and 150 ft^2 ac^{-1}. Each basal area class contains four replicated treatment units. Actual basal areas that were 20 ft^2 ac^{-1} or greater over their targets at the time of sampling are labelled above replicate unit numbers. In the Taylor Woods levels-of-growing-stock study, measurements were taken from trees from GSL 30 – 150 ft^2 ac^{-1}.

Figure A2: The ST300 Hitman in use at the Centennial Forest experimental site (left); the ST300 Hitman acoustic measurement tool (right). Photo credit: Fibre-gen.

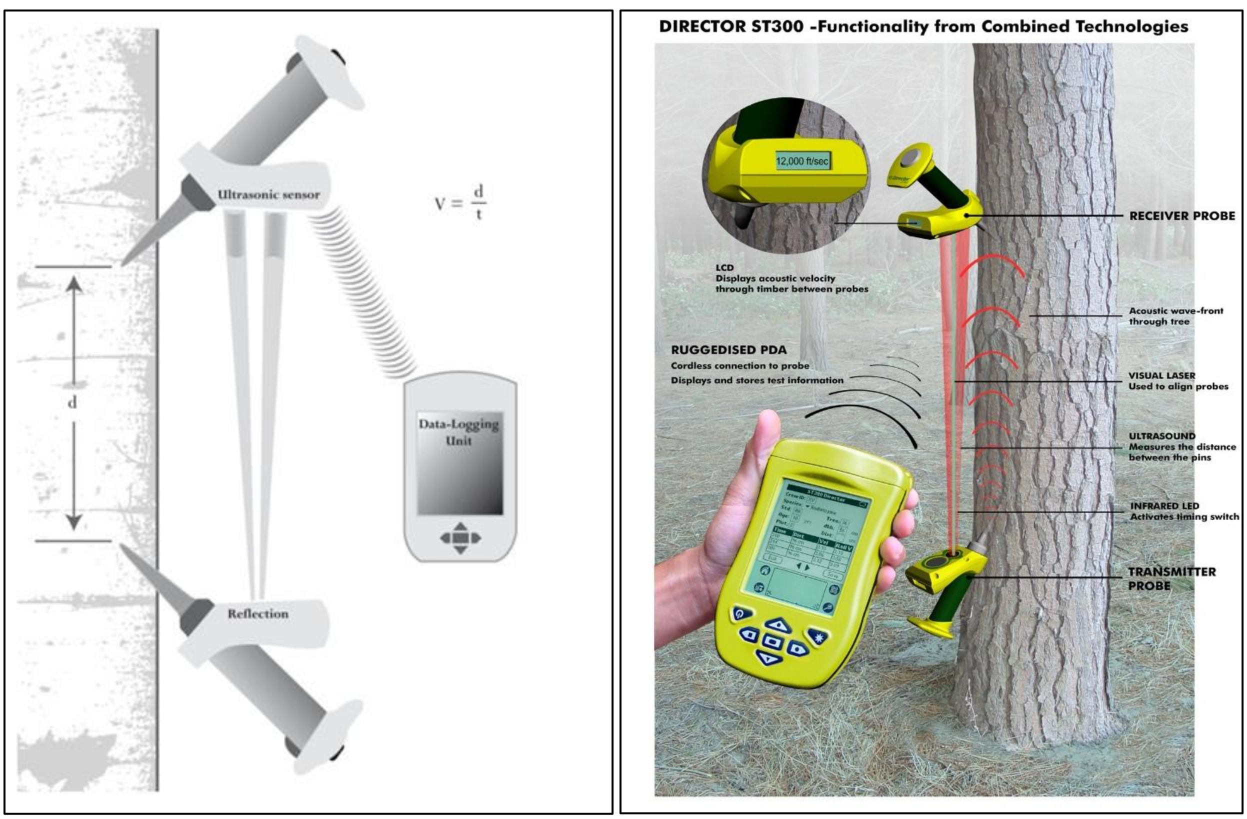

Figure A3: Diagrams of the ST300 operating principles (left) and operating system (right). An acoustic wave produced by a specialized hammer travels between the lower and upper probes of the ST300 Hitman acoustic tool. The transit-time of the wave between the two probes is recorded and velocity calculated in miles per second and stored on a portable data logger. Photo credit: Paradis et al 2013, Fibre-gen.

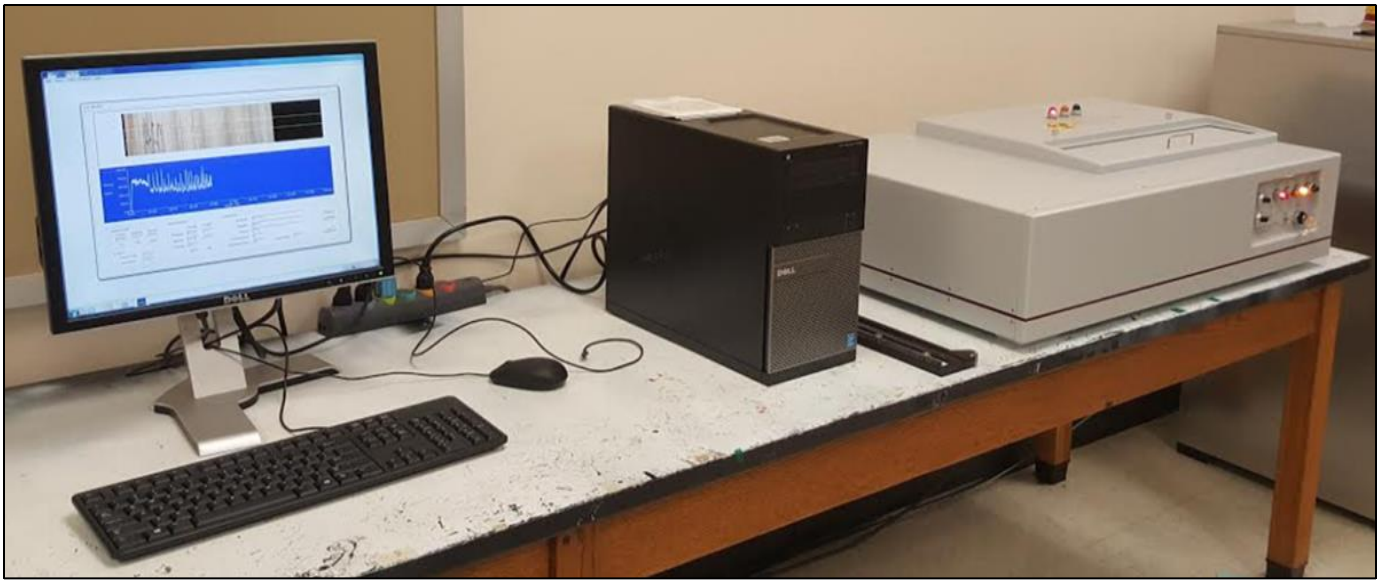

Figure A4: The Quintek QTRS-01X Tree Ring Scanner scanning and recording the wood density profile of a ponderosa pine sample.

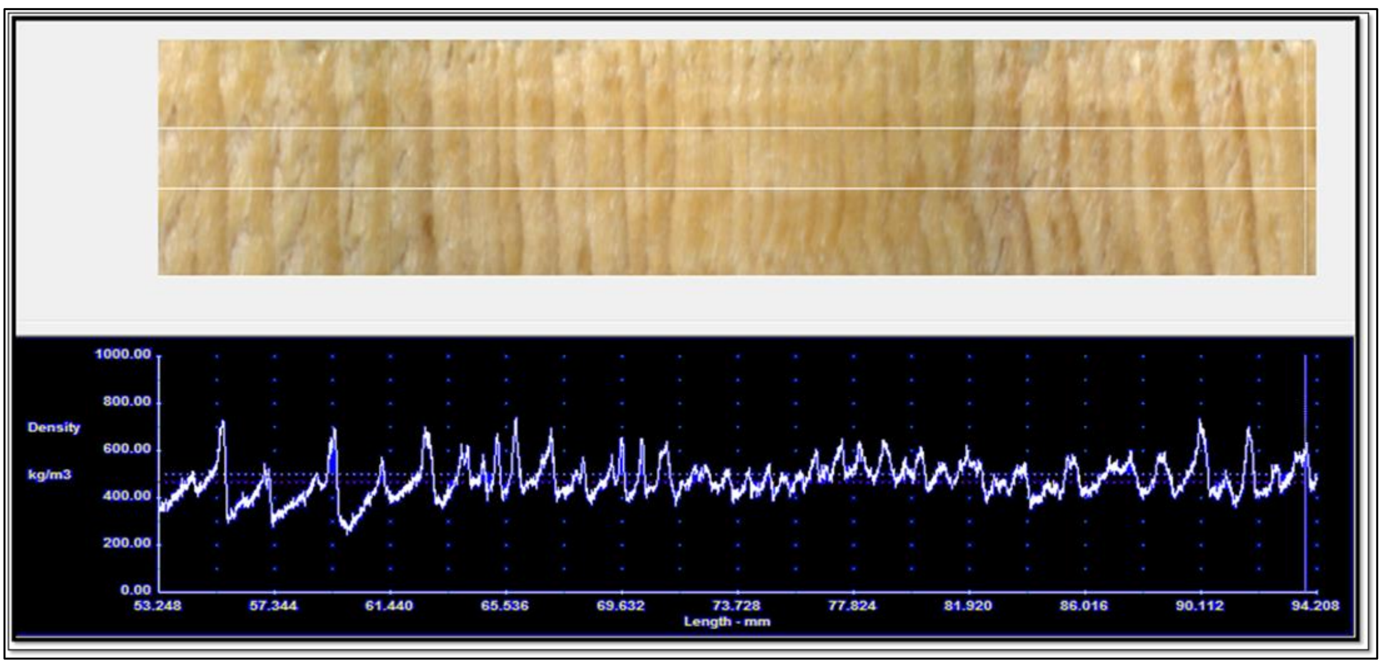

Figure A5: A sample readout from the QTRS-01X Tree Ring Scanner X-ray densitometer. A photograph of the wood sample accompanies the pith-to-bark density profile. Peaks and valleys in the readout indicate spikes and drops in wood density correlated with latewood and earlywood bands across the annual rings.

Ring No.	Year	End mm	Start mm	Late Wood Width mm	Ring Width mm	Late Wood Percent	Early Wood Density	Late Wood Density	Ring Average Density
97	2015	1.60	2.15	0.53	0.55	96.36	463.33	647.55	640.85
96	2014	2.15	2.70	0.46	0.55	83.64	485.42	676.88	645.55
95	2013	2.70	3.23	0.33	0.53	62.26	477.21	580.45	541.49
94	2012	3.23	3.69	0.22	0.46	47.83	459.37	556.44	505.79
93	2011	3.69	4.68	0.60	0.99	60.61	481.36	562.03	530.75
92	2010	4.68	5.20	0.35	0.52	67.31	476.82	584.79	548.12
91	2009	5.20	5.57	0.29	0.37	78.38	476.07	611.69	582.37
90	2008	5.57	6.66	0.66	1.09	60.55	466.12	586.28	538.88
89	2007	6.66	7.45	0.28	0.79	35.44	451.59	542.45	483.79
88	2006	7.45	8.12	0.36	0.67	53.73	470.58	620.94	551.37
87	2005	8.12	8.49	0.22	0.37	59.46	473.66	568.49	530.05
86	2004	8.49	9.67	0.57	1.18	48.31	436.69	638.91	534.38
85	2003	9.67	10.57	0.37	0.90	41.11	446.95	580.71	501.94
84	2002	10.57	11.12	0.20	0.55	36.36	457.71	551.20	491.71
83	2001	11.12	12.19	0.67	1.07	62.62	466.86	589.27	543.51
82	2000	12.19	13.21	0.20	1.02	19.61	442.29	660.76	485.12
81	1999	13.21	15.25	1.06	2.04	51.96	446.75	659.04	557.06
80	1998	15.25	16.03	0.45	0.78	57.69	479.23	587.22	541.53
79	1997	16.03	16.77	0.30	0.74	40.54	429.40	697.81	538.21
78	1996	16.77	17.80	0.60	1.12	61.61	475.87	642.20	578.40

Figure A6: Ring-level summaries provided by the QMRS-01X Tree Ring Scanner provide the user with information on average ring density, ring width, and earlywood and latewood proportion of each annual ring.

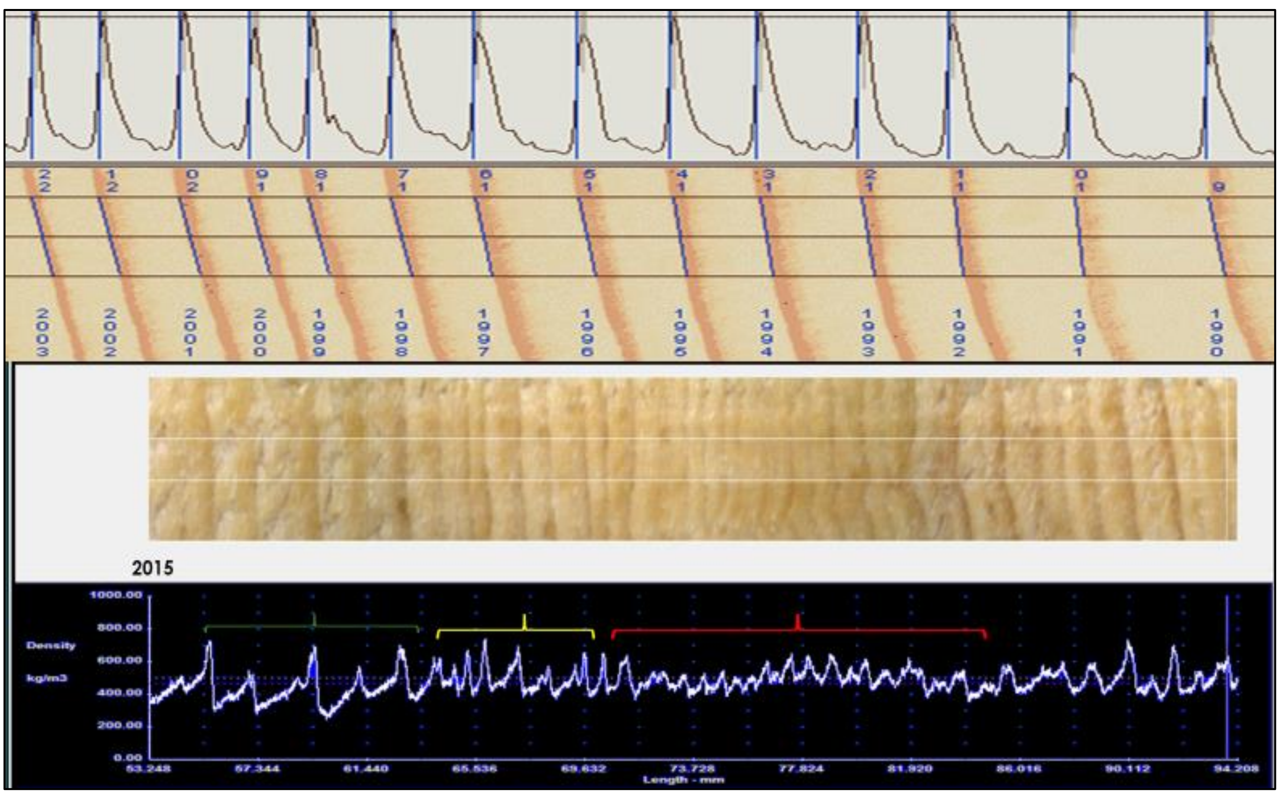

Figure A7: A comparison of a plantation-grown softwood density scan (top) and a native Arizona ponderosa pine density scan (bottom) reveals significant growth irregularities in ponderosa pine. In ponderosa pine, peaks in wood density vary considerably from year to year, revealing large variation in annual growth. Growth varies from rapid (green line) to slow (red line). These irregularities may make it difficult to use such trees for high-value end-uses.

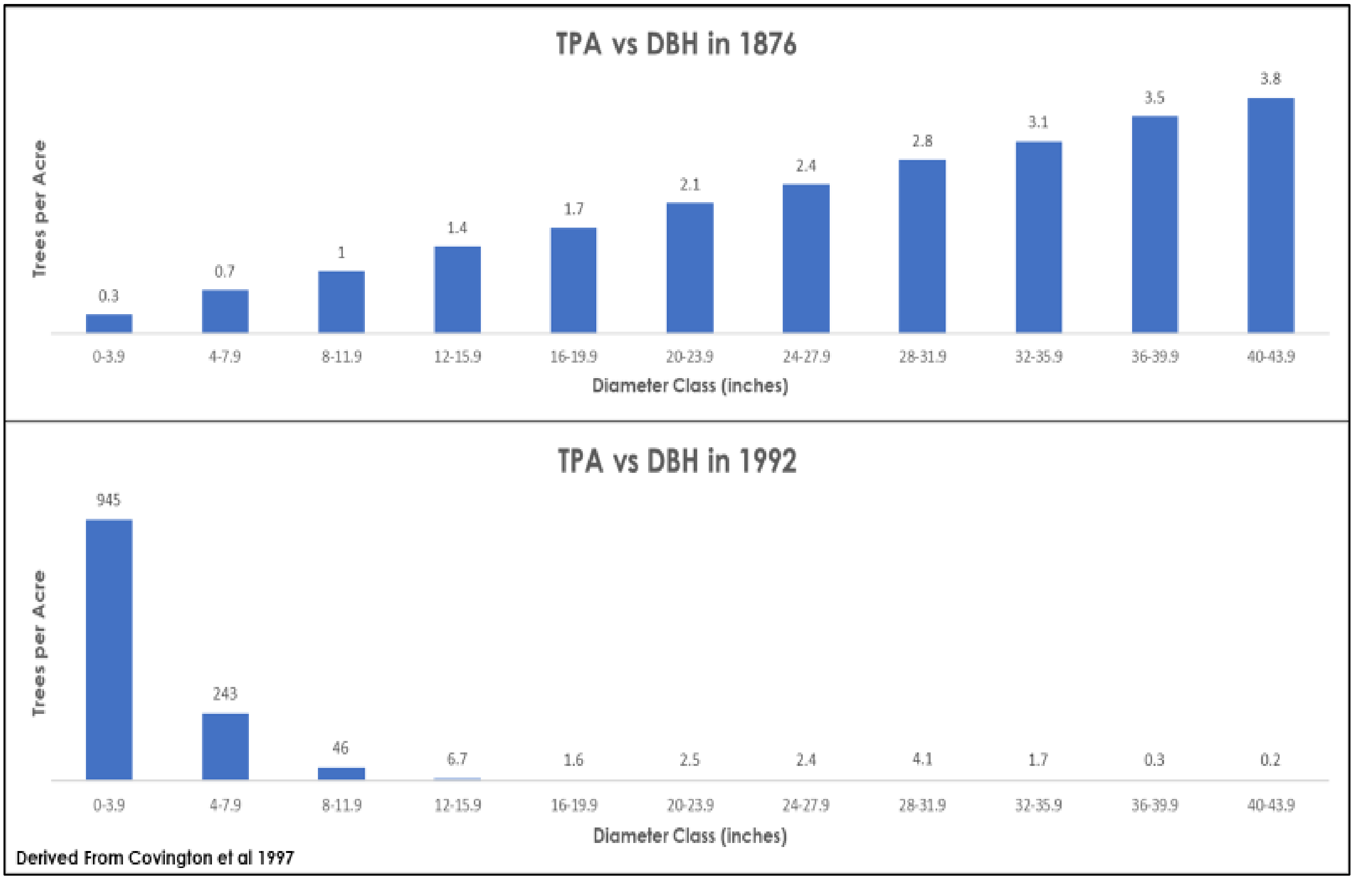

Figure A8: The forested landscape throughout much of northern Arizona has transitioned from being dominated by trees over 20 inches in diameter to having a preponderance of trees under 12 inches in diameter (Covington et al 1997); this has had drastic ecological and economic implications for the region.