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measurement

Building the Forest Inventory and Analysis Tree-Ring Data Set

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The Interior West Forest Inventory and Analysis (IW-FIA) program measures forestland conditions at great extent with relatively high spatial resolution, including the collection of tree-ring data. We describe the development of an unprecedented spatial tree-ring data set for the IW-FIA that enhances the baseline plot data by incorporating ring-width increment measured from increment cores collected on IW-FIA plots. Whereas the IW-FIA program has used increment cores consistent with traditional forestry (stand age, site index, and vigor), there are key differences in sampling approaches between foresters and dendrochronologists. We describe a framework for preparation, interpretation, and archiving of the IW-FIA tree rings. Early results suggest that the data produced by this framework are useful for growth-and-yield studies, stand dynamics, and dendroclimatology. We discuss the potential for tree-ring data to become a standard component of the FIA program. We also compare and contrast the applications and procedures of dendrochronology with the FIA approach and show how the two sources of data complement one another.

Keywords: dendroclimatology, dendroecology, dendrochronological principles, forest inventory, tree-ring science

Other articles in the Forest Inventory and Analysis (FIA) special section illustrate the history of the FIA program and the evolution of the program into the diverse forest resource inventory that it is today (e.g., Shaw et al. 2016, Thompson 2016). As has been the case throughout the program's history, this evolution is ongoing, and the program continually strives to both provide a consistent core data set and add components that can be used to address future information needs (Goeking 2015). The collection, analysis, and archiving of tree-ring data is a recent addition to the Interior West Forest Inventory and Analysis (IW-FIA) program that will enhance the core FIA data and provide important ancillary data to previously existing tree-ring data sets (DeRose et al. 2012, 2013).

Tree-ring data have been used to various extents within the FIA program (e.g., Chojnacky 1997, Witt 2010). Stand age is a core variable, and it is usually determined by growth ring count and weighting of size classes within a stand (US Department of Agriculture [USDA] Forest Service 2015). Tree age, combined with height measurements, also provides entry to site index and yield models used in the core data (O'Connell et al. 2015). Many periodic inventories were made up of "initial" plot visits (USDA Forest Service 1999), for which recent radial growth increment data was obtained, and formed the basis for gross growth calculations. Since the national adoption of the current mapped-plot design and the annualized inventory (Gillespie 1999), the measurement of any plots originally established under periodic inventories and retained in the annual inventory design were again considered "initial visits" during the first cycle of annual inventory (e.g., see USDA Forest Service 2001, section 7-4). Although periodic and annual inventories were "bridged" by remeasuring some trees common to both inventory types, population-level growth estimation was largely based on increment cores and not remeasured diameters during the first cycle of annual inventory (O'Connell et al. 2015).

With most states in remeasurement under annual inventory, the need to calculate gross growth, using increment core-derived growth measurements, has decreased substantially. Growth estimation on remeasured FIA plots is based on outside bark remeasurement, with the exception of certain slow-growing species, for which the expected measurement error for outside bark diameter is likely to be a large fraction of the actual growth (e.g., woodland species) (Goeking et al. 2014, p. 13). For the excep-

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tions, we anticipate that increment core measurements will continue to be used in some capacity. Cores will also be obtained, for example, when partial stand replacement requires recomputation of stand age.

However, the utility of tree-ring data is not limited to the applications traditionally used by the FIA program. The myriad uses of tree-ring data are well known and fundamental not only in the field of forestry, but also in related fields such as geography and ecology (Cook and Kairiukstis 1990, Speer 2010). Variations in diameter growth increment potentially record events of stand dynamics (Fritts and Swetnam 1989) and can be excellent proxies for past climate conditions (Fritts 1976). Annual tree-ring formation in mid- to high-latitude trees represents the integration of physiological traits and environmental conditions (e.g., climate, soil, and stand density) over the course of a growing season and is influenced by previous growing seasons (Fritts 1976). Because of these controls on ring width, tree rings are important archives of past growing conditions and can serve as a proxy for them if the drivers can be identified. In the early 20th century, the field of dendrochronology was established based solely on the analysis of tree-ring data (Douglass 1909). For FIA, the potential for deeper (i.e., preinventory) chronological analysis means that tree rings provide a valuable temporal context in which current tree and forest growth could be related to historical growth.

In 2009, the IW-FIA began a partnership with the Dendrochronology Laboratory at Utah State University (USU) with the goal of advancing the use of tree-ring data obtained on the FIA plot system. The initial goal was to prepare, catalog, and read the tree rings of an estimated 20,000 cores in the IW-FIA collection. These cores were collected during the periodic inventories of the 1980s and 1990s to determine tree age for radial growth, site index, and stand age computations (see, e.g., USDA Forest Service 1999, section 10), but ring-width data were recorded, or at least retained, for very few. From 2000 until recently, i.e., during the late periodic inventories and annual inventory before 2010, field procedures did not require that cores used for growth increment or stand age be returned to the laboratory. As a result, only trees from earlier periodic inventories and trees that are common to both periodic and annual inventories were potentially represented in the archival core collection.

In this article, we describe the initial development of an FIA-based tree-ring data archive, present an overview of results we have obtained from preliminary analyses, describe future potential applications, and discuss the potential for tree-ring data to become a standard component of the FIA program. In the process, we also compare and contrast the applications of "traditional" dendrochronological data and procedures with the FIA approach and show how the two sources of data may complement each other.

Development of an FIA-Based Tree-Ring Archive

The IW-FIA core collection was "discovered" during moving activities in the Ogden Forestry Sciences Laboratory in 2007. The cores were in various states of preservation, typically with the cores glued to a grooved wood lath and boxed by state and inventory. Most were labeled with the information essential to linking a core to the corresponding tree records in the FIA database: state, county, plot, species, and diameter. The FIA database contained no information indicating that the core for a given tree was held in the collection, but the potential list of trees with cores could be inferred by the presence of an age value in the TREE or SITETREE tables. An informal sampling of several boxes suggested that there were approximately 12,000 cores, 90% of which were assessed as likely to be useable. After the establishment of agreements between FIA and the USU Dendrochronology Laboratory, all cores were moved to the USU campus for processing.

Shortly after beginning the archiving process, it was determined that it would be most efficient and beneficial for future analysis to remount all cores. FIA crews usually mounted the cores in the field for secure transportation, and the purpose of collecting the cores was only to obtain tree age and recent growth increment data. As a result, the orientation of most cores on the laths was not optimal for what is now considered standard tree-ring measurement and analysis. Cores were correctly oriented and remounted to accentuate the transverse section and then sanded using progressively finer grades of sandpaper, followed by a final hand polishing (Stokes and Smiley 1968). This provides a surface suitable for viewing under a microscope.

A protocol consistent with conventional tree-ring preparation techniques (Speer 2010) was developed to ensure proper processing, labeling, crossdating, measurement, and archiving of the FIA tree-ring data. In addition to establishing a linkage with the FIA database, we maintained metadata consistent with the International Tree-Ring Data Bank (ITRDB) so as to make the archive easily accessible to dendrochronologists and other researchers after it is ready for publication. Increment cores had to be initially cross-referenced with the FIA database to determine origin and measurement year. Decadal dots were labeled, in consultation with a local chronology, before cores were measured on a sliding stage that is paired with a digital readout at 3.94×10^{-5} or 3.94×10^{-4} in. resolution.

Arguably, the most important principle in dendrochronology is crossdating, which is based on matching patterns in ring-width variability among multiple tree-ring series to determine the actual year of ring formation. Although some uses of increment cores in forestry do not rely on calendar year preci-

Management and Policy Implications

Information driving policymaking for the nation's forest resources at the state and national levels is commonly derived from the Forest Inventory and Analysis (FIA) program. Enhancements to FIA improve both the quality and scientific utility of that information. The addition of tree-ring data to the Interior West portion of FIA takes advantage of the semisystematic sampling design inherent to FIA to collect and archive detailed stand and climate history data (recorded in tree rings) that are typically collected at much coarser scales. Although the FIA grid of tree-ring data cannot replace traditional tree-ring chronologies, it is an ancillary data set with features that might be attractive for particular research questions. Future research could combine the FIA data with tree-ring chronologies to achieve spatially and temporally unprecedented gridded data. In mountainous regions with snow-driven hydrologic systems such as the Interior West, forested areas are the most critical for water resources. If the coupling of climate variability and tree-ring data was demonstrated, then high spatial resolution climate reconstructions over these mountain regions could be used for policymaking and management.

sion of ring widths, many avenues of inquiry, such as dendroclimatology (reconstruct climate using tree rings) are reliant on precise control of annual resolution. Quality control was conducted by crossdating (marker-year, line plots, skeleton plot, and COFECHA approaches) (Yamaguchi 1991, Speer 2010) with the closest available public chronology from the ITRDB. The verification program COFECHA (Holmes 1983, Grissino-Mayer 2001) was used to assess the quality of crossdating. State-by-state databases of all available chronologies were constructed, from which technicians can draw the closest species-specific chronology for crossdating, typically within the same county. Oftentimes, nonspecies-specific chronologies were used for comparison. Because the spatial coverage of records in the ITRDB is not as extensive as the FIA plot network, cooperation with other tree-ring researchers has helped us obtain unpublished chronologies in gap areas. These have been crucial for crossdating. It is important to note that by using these chronologies to crossdate the FIA data, characteristics of the individual cores such as ring-width variability are not compromised and should not result in spatial patterns of correlation related to the chronologies used for dating. We explicitly did not seek to improve the strength of relationships in crossdating (i.e., correlation coefficient); rather, patterns of ring width or marker year lists were used to ensure precision of annual dating.

Table 1. Increment cores measured and number crossdated by state.

State	Measured	Crossdated
Arizona*	821	192
Colorado	2,042	506
Idaho	899	461
Montana	5,184	1,602
New Mexico*	72	0
Nevada	1,848	102
Utah	3,420	944
Wyoming	982	391
Totals	15,268	4,198

* Work is ongoing to archive additional periodic cores.

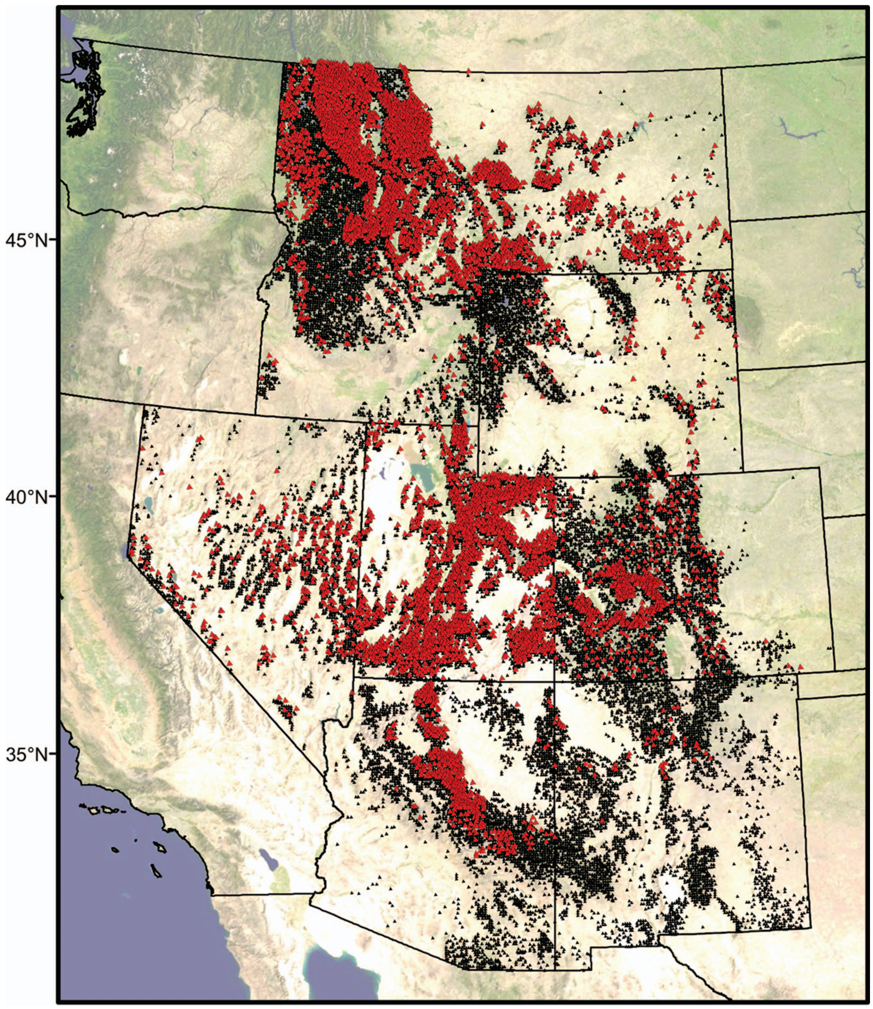

Figure 1. Western United States showing all forested (≥10% canopy cover) FIA plot locations (black triangles), and locations with tree-ring data (red triangles).

Resulting Increment Core Database

The number of cores in various stages of processing, from initial assessment to fully crossdated and used for analysis, is greater than 14,000 at the time of this writing, and more than 3,000 have been fully crossdated (Table 1). Indication of the quality of the core and whether or not it has been crossdated were reported in the metadata. Linkage of archived cores with FIA plot and tree records revealed substantial spatial gaps (Figure 1). For example, no cores were found from the 1980s periodic inventory of Wyoming (Green and Conner 1989), and by the time the last periodic inventory of Wyoming was started (Thompson et al. 2005), cores were no longer being collected from the field. Periodic inventory coverage of Idaho and Colorado was incomplete because of the patchy nature of their respective inventory histories (Goeking 2015), which resulted in sparse coverage of cores. However, the distribution of cores in the states of Montana and Utah was relatively complete in comparison.

Results from Preliminary Analysis

After compilation, several preliminary analyses were run on the tree-ring data to check for usefulness and to compare with forest characteristics found in the FIA database. For example, root collar diameter increments for a subsample of the 50 oldest (>200 years) common pinyons (*Pinus edulis*) in Utah showed that diameter growth in this species generally followed an expected pattern; i.e., many trees exhibit relatively constant growth rates for most of their lives. Furthermore, the plot-based sample was likely to yield a meaningful number of old trees without the need for supplemental sampling (Figure 2), which is useful because older trees are typically sought for long-term climate reconstructions. The distribution of ring counts for cores that have been read, but not necessarily crossdated, follows the general distribution of stand ages across the Interior West (Figure 3). When considering that most of the periodic cores (Figure 3A) were sampled nearly 20 years ago and the stand ages are from the recent annual inventory, the distributions match even better,

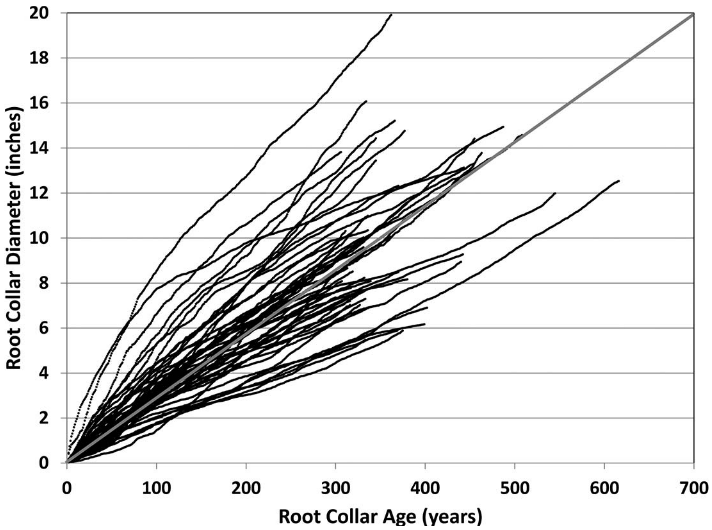

Figure 2. Root collar diameter (calculated from cumulative ring-width increment) of 50 common pinyons (*Pinus edulis*) over root collar age ≥300 years at the time of core collection (increment cores for woodland trees collected at or near the root collar). Most trees appeared to show relatively linear growth patterns (gray diagonal provided as reference) over most of their lives.

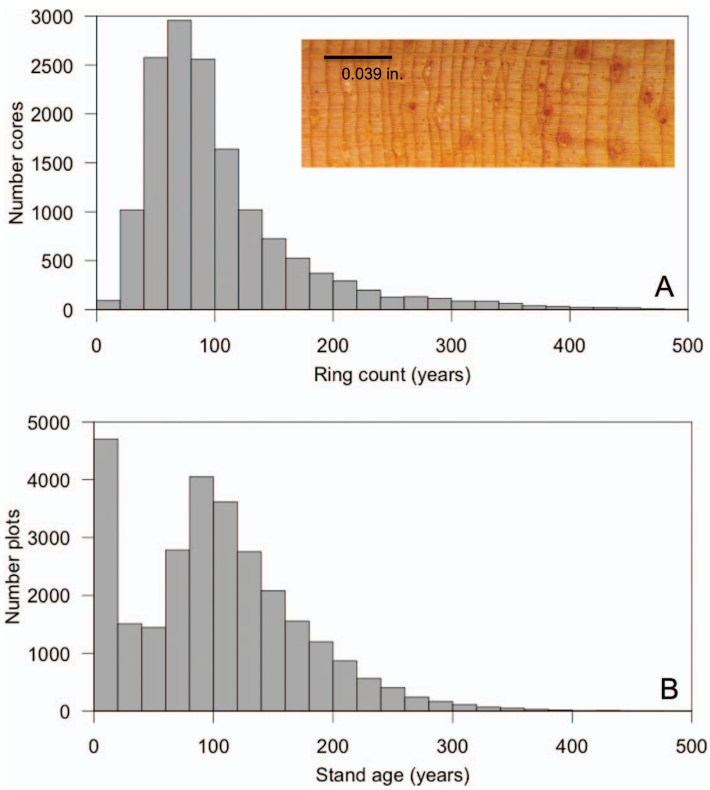

Figure 3. Histograms of ring count for all increment cores in the FIA tree-ring database (A) and stand age for a full panel of Interior West plots (B). Inset: ring width example from common pinyon (Photograph courtesy of Slaton Wheeler.) Note: ages from 500 to 800 years not shown. Panel A includes increment cores sampled from both periodic and annual inventories, whereas panel B includes only trees from the annual inventory.

i.e., closely grouped around ages 80–100, with a tail that extends back several centuries. The distribution of increment cores by species relatively closely matches the distribution of trees on Interior West plots (Figure 4), which would therefore mirror the dominance of major forest types in the Interior West (e.g., O'Brien 2002, Thompson et al. 2005, 2010, Deblander et al. 2010, Witt et al. 2012, Goeking et al. 2014). Finally, preliminary examination of the oldest lodgepole pine (*Pinus contorta*) in the database revealed multiple occurrences of likely disturbance events (e.g., beetles or low-severity fire) (Figure 5). In addition to the somewhat surprising magnitude of release exhibited by a mature lodgepole pine in a dense stand, was a much more subtle pattern of quasi-cyclical growth variation. Whether this pattern represents climatic cycles or some aspect of stand dynamics is still under investigation.

Examining the FIA Tree-Ring Data for Climatological Applications

As a "proof of concept" for the use of FIA plot-based tree-ring data in climatological applications, DeRose et al. (2012, 2013) developed a gridded tree-ring database from FIA cores in Utah. Utah was selected as the study area because the core collection was most complete at the state scale, because the sample included two species known to be useful in dendroclimatological work (common pinyon and Douglas-fir [*Pseudotsuga menziesii*]), and because Utah lies in the climatological tension zone known as the El Niño-Southern Oscillation dipole (Brown and Comrie 2004). Early analysis showed that 1/8° gridded data (~3-mile intervals over Douglas-fir and common pinyon forests) could be used to map past climatic patterns with a higher level of spatial detail than is possible using ITRDB (i.e., site-selected) chronologies. Using the gridded data set, DeRose et al. (2013) (Figures 2 and 3) found a strong correlation ($r > 0.82$) with previously published tree-ring chronologies from the ITRDB and the spatial and temporal correlation between the FIA data and water year precipitation was strong ($r > 0.55$). The fine-scale spatial grid allowed exploration of the spatial and temporal nature of the El Niño-Southern Oscillation dipole, which appeared to exhibit considerable latitudinal fluctuation over the past three centuries. Finally, the lagged correlation ($r > 0.55$) between the FIA data and the Pacific Decadal Oscillation confirmed the quadrature-phase coupling between wet/dry cycles that are generated by Pacific decadal variability known to drive precipitation delivery to the Intermountain West (Wang et al. 2012). These results suggest substantial potential for climate analysis with further development of the FIA data for the western United States.

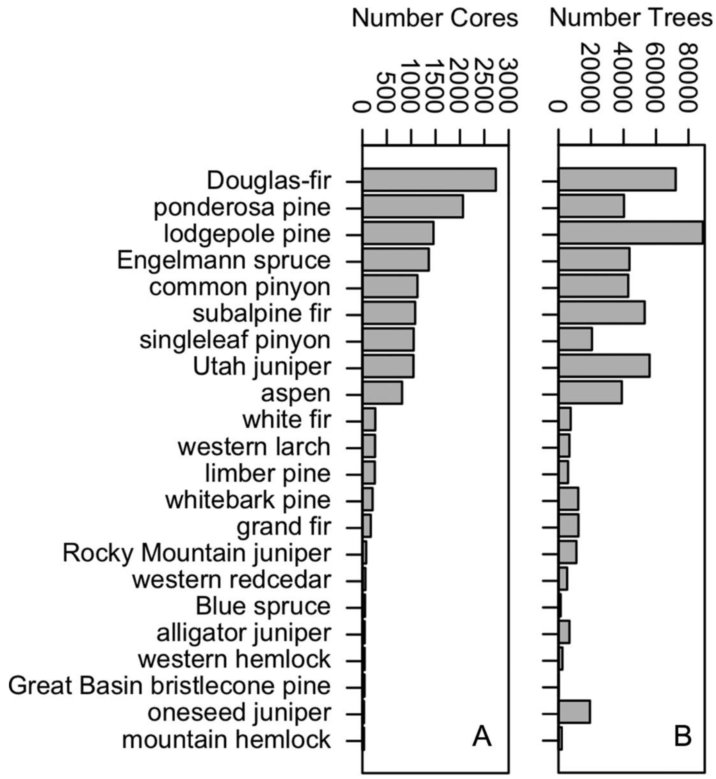

Figure 4. Histograms of increment cores, ordered by species from the FIA tree-ring data (A) and number of trees >5 in. in diameter of the same species sampled from one panel (2005–2014) of annual inventory in the Interior West (B). Species with at least 30 increment cores are shown. Note the different scales for the horizontal axis. Panel A includes increment cores sampled from both periodic and annual inventories, whereas panel B includes only trees from the annual inventory.

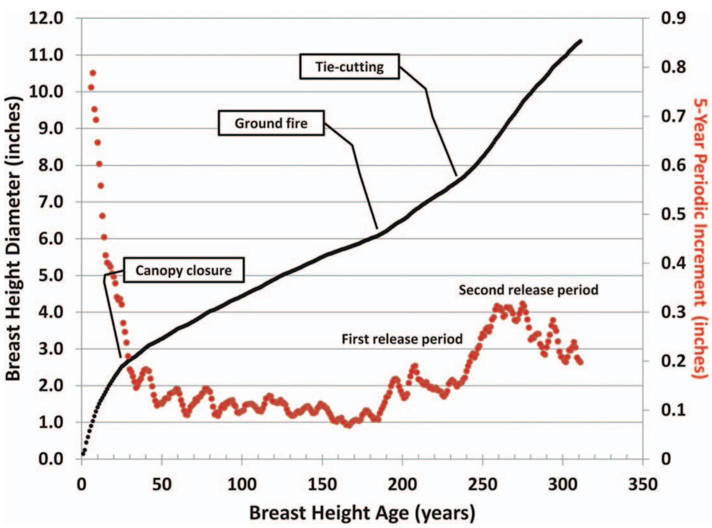

Figure 5. Cumulative ring-width increment for a 311-year-old (breast height age) lodgepole pine in the Uinta Mountains, Utah, showing four periods of growth: free growth before canopy closure, slow growth after canopy closure, and two periods of release after different disturbances. The 5-year periodic increment (current diameter − diameter 5 years prior, in red) suggests a quasi-cyclical influence on diameter growth, even under dense stand conditions.

Discussion

Traditional versus Gridded Approach

The field of dendrochronology is founded on a set of principles that help guide sampling and analysis of tree-ring data (Cook and Kairiukstis 1990, Speer 2010). Understanding these principles provides insight into the tradeoffs associated with the gridded FIA data (Table 2). The principle of site selection posits that trees useful for tree-ring research can be selected from sites where the environmental variable of interest is most sensitive to maximize that signal. The principle of limiting factors states that tree growth (i.e., ring width) will be constrained by the most limiting factor. Therefore, for example, if moisture-sensitive trees are sought, then the researcher might select sites at the lowest elevations (i.e., lower treeline), where moisture is likely to be a limiting factor. The principle of aggregate tree growth suggests that the multiple possible factors affecting ring width can be broken down individually. Doing so allows one to maximize a desired signal in ring width by removing the effect of other contributors to growth. Finally, the principle of replication states that the desired environmental signal can be maximized by sampling multiple tree-ring series from a tree or on a site and minimize the potential noise in ring width caused by undesired factors that we wish to reduce. Appropriate use of these principles with respect to a specific research question, e.g., reconstruction of annual streamflow, can result in highly accurate scientific inference (Fritts 1976). However, the strict adherence to dendrochronological principles in tree-ring studies can also make it difficult to characterize phenomena outside the scope of the question for which the tree-ring data were originally collected.

Dendroecological studies (research of ecological questions using tree-rings) often involve collecting increment cores that do not fully meet the list of principles to answer ecological questions with tree-ring data (Figure 6) (Fritts and Swetnam 1989). Although the signal might be less than expected for a similar species at its ecological margin, the tree-ring data are often interpretable and yield substantial insight into particular processes, e.g., growth release due to beetle outbreaks (Eisenhart and Veblen 2000). The ability to characterize ecological events using tree-ring data from a large range of growing conditions suggests that the level of subjectivity in site and tree selection should match the research questions being asked (Cook and Kairiukstis 1990). In this regard, if population-level estimates of ecological processes are sought, a sampling design to characterize entire populations is desired. The FIA semisystematic sampling grid was designed for this purpose (Bechtold and

Table 2. Tradeoffs between traditional dendrochronology and the FIA semisystematic sampling grid.

Traditional (selective) approach	Grid-based (semisystematic) approach
Sampling locations selected subjectively	Sampling locations based on a semisystematic sampling grid
Trees selected based on their potential to maximize environmental signal of interest	Trees selected systematically by species and size class
Maximizes sensitivity to variables of interest (e.g., precipitation or temperature)	Most trees expected to be less sensitive on most sites, but sensitivity is variable with site characteristics
Little potential for inference to the population level	High potential for inference to the population level; e.g., possible to estimate biomass or carbon assimilation rates per unit land area
Replication of two cores per tree, 20 trees per site	Replication averages ∼5 trees per plot
Selection might minimize influence of other trees in the stand	Influence of other trees in the stand is dependent on stand structure, including density, stand age, and other site factors

Figure 6. Lead author boring Engelmann spruce on the TW Daniel Experimental Forest. Photo by Simon Wang.

Patterson 2005). In its current state, the grid-based FIA tree-ring database appears to be more appropriately suited to dendroecological research than to dendroclimatology, allowing for some climatological applications.

Increment cores collected under FIA procedures may not meet some dendrochronological principles, such as site selection or replication, and will not maximize series length. For example, highly sensitive sites are sampled in the FIA database in proportion to their occurrence on the landscape; i.e., there is no a priori assessment of sensitivity, but some highly sensitive sites are sampled nonetheless. What may not be included in the FIA sample are sites at environmental extremes, because such conditions may not support enough tree cover to be considered forest or occur with sufficient frequency to be picked up in the sample (O'Connell et al. 2015, p. 2–28). However, the FIA sampling grid, which is both spatially and temporally unbiased, represents a sampling intensity that is unlikely to be matched by climate data stations or tree-ring chronologies (Figure 1). The semisystematic nature of the FIA plot system ensures that, if a particular response is present in the population, the resultant tree-ring data will sample it in proportion to its prevalence on the landscape (McRoberts et al. 2005, Gray et al. 2012). In this way, the grid can capture some of the types of sites dendrochronologists seek out (e.g., maximum tree ages or maximum sensitivity to moisture) but at low rates of detection.

In comparison to the often cited dendrochronological "standard" of 2 cores per tree for 20 trees, the sampling rate on FIA plots might be considered low. For example, in the most recent inventories of Utah, age has been determined for an average of 5.3 trees per plot. However, a direct comparison of sampling intensity is difficult. Chronologies in the ITRDB are commonly reported as occurring at point locations, even though the database is designed to accommodate area-bounding coordinates, and locations are commonly reported only to the nearest 0.1 or 0.01°. Therefore, the spatial distribution of trees contributing to a chronology is uncertain and may not be replicable with the information available. Given that FIA plots are spaced at approximately 3-mile intervals (∼0.03° of latitude), clusters of neighboring FIA plots may be considered as comparable to clusters of traditionally selected chronologies. This distribution of sampling intensity may be preferable for at least two reasons: reducing possible pseudoreplication issues and expanding the range of environmental conditions for factors used as independent variables in modeling.

The remaining difference in sampling intensity is that in the FIA system, multiple cores per tree are not taken. Replication is important for determining whether the sample tree contains the desired signal or possibly spurious noise, but also commonly contributes to effective crossdating by allowing the comparison of 2 series per tree (helpful for the location of locally absent rings, or false rings, for example), and also multiple trees per site. However, the prevalence of locally missing rings is actually quite small globally (St. George et al. 2013) and would be expected to be even lower from trees selected at random. Therefore, although the FIA data may be more difficult to crossdate, it is not impossible, and the data set can have calendar year resolution with extra effort. For trees determined to be critical for analysis, additional cores can be obtained on regularly scheduled or special plot visits.

Any forest-grown tree has the potential to contain some signal of stand dynamics in its ring-width pattern (e.g., as in Figure 5). In traditional dendrochronology, this signal is usually treated as noise, and efforts are made to remove it, e.g., through detrending (Biondi and Qeadan 2008). In broader application, this effect can either be minimized or treated as a source of information. In the timber forest types, the site tree represents the tallest, dominant trees in the stand and, therefore, may be the best tree at the site for characterizing an extralocal response (e.g., potential climate response) and minimize the effects of stand dynamics. Similarly, increment cores collected from low-density woodland plots may contain little to no variability associated with stand dynamics, reflecting primarily climatic growing conditions. The availability of considerable additional data on each FIA plot allows for assessment of the current competitive status of trees in the stand and some information on stand history. These observations can be used to associate tree-ring patterns with stand structural and demographic information.

Applications

Although the FIA tree-ring data may not be an ideal data set based on the implementation of a priori dendrochronological principles, the sampling grid was designed to be geographically unbiased. Researchers can take advantage of the gridded sampling design to make ecological inferences and scale to larger areas. The increment cores collected are representative of the forest type to which the plot belongs and therefore characterize forest conditions in proportion to their abundance on the landscape. If large-scale patterns in spatiotemporal coherence to growing season conditions (e.g., water year precipitation) are identified, then the amount and variability of ring-width increment can be explicitly linked to local-to-regional climatic regimes. This will help to reveal whether particular climate teleconnections such as El Niño-Southern Oscillation or the Pacific Decadal Oscillation have historically exerted control on (1) growth patterns, (2) establishment (by linking with FIA seedling data), (3) mortality, and, ultimately, (4) potentially the distribution of Interior West forests.

Not only does the FIA tree-ring sample have higher spatial resolution in comparison to climate station data or tree-ring chronologies archived in the ITRDB, but it also covers a broad range of forest types and species. The IW-FIA gridded tree-ring data potentially represent all forest types, from the lowest elevation woodlands (i.e., pinyon-juniper) to high-elevation spruce-fir forests and alpine environments. The relatively fine spatial resolution of the FIA grid and large number of samples present an opportunity to partition the data by species, environmental factors such as aspect, elevation, or site quality, stand dynamic factors such as successional status or stand age, or even biogeographical attributes such as continentality, in an attempt to retrospectively "select" sites from the FIA data set to answer specific research questions. By collecting increment cores from all coniferous species at high spatial resolution, the data include richness that can be teased apart to take advantage of particular species-specific differences in climatic response. This can be thought of as retrospective "site selection" from the FIA grid. For example, the FIA includes Utah juniper (*Juniperus osteosperma*), a species that is typically ignored for dendrochronology or dendroclimatology. However, recent research suggested that not only can Utah juniper be crossdated (DeRose et al. 2016) and used for dendroclimatic reconstructions (DeRose et al. 2015), but there are large, low-elevation regions in the Interior West where it may be the only tree species with available ring-width data.

The IW-FIA grid of tree-ring data cannot replace tree-ring chronologies such as those available from the ITRDB. Rather, it is an ancillary data set with features that might be attractive for particular research questions. Ultimately, we anticipate future efforts to combine the FIA data with tree-ring chronologies for truly spatial and temporally unprecedented gridded data. Geographical-based model systems exist by which spatially rich data (i.e., FIA) could be combined with temporally rich data (i.e., ITRDB) for a single spatial layer, and this could be combined with climate data sets, such as the parameter-elevation regression on independent slopes model (PRISM) (Daly et al. 2008). Another example, Biondi et al.'s (2014) tree-ring interpolation model is a possible interface between gridded climate data, gridded tree-ring data, and chronologies. Finally, concerns of bias in traditional chronologies (e.g., Carrer and Urbinati 2004) could be explicitly tested using the FIA tree-ring data set.

Future Development

The initial goal for the FIA tree-ring data was to build a plot-linked database of radial growth that could be used for growth model development and other biometric analyses, such as studies of growth and yield and validation of growth models such as those used in the Forest Vegetation Simulator (Dixon 2002). The potential for these types of applications was sufficient justification for undertaking the archiving project, since acquisition of the cores represented a large proportion of the investment but a sunk cost, and the usefulness of the resulting data was nearly certain. The project has made considerable progress toward this goal (Table 1). Any application beyond fundamental biometric application could be considered added benefit. It quickly became apparent that the data set could help answer other research questions, with perhaps the most promising being the development of high spatial resolution climatic reconstructions (DeRose et al. 2012, 2013). The promise of broader-scale application provides incentive to continue development in such a way as to maximize opportunities.

The first priority is filling spatial gaps, which is being done in two ways. The first is to restore the procedure of returning cores to the laboratory in cases where normal FIA field procedures specify that a tree should be cored for age (e.g., trees used for stand age or site index determination). Previously, cores acquired for this purpose were read in the field, the age was recorded with other plot data, and the cores were discarded. The new procedure of retaining cores not only contributes to the dendrochronological archive but also has the added benefits of saving plot time for the crews, and the resulting age data in the FIA database have much greater precision. The latter is an important benefit because FIA quality assurance data have shown tree age to have poor repeatability (e.g., Goeking et al. 2014, p. 13). In states that are in the first cycle of annual inventory, this procedure results in a relatively large number of cores being obtained annually. In states that are in the second cycle of annual inventory, relatively few cores are obtained this way. However, by the beginning of the second annual cycle nearly all trees in a state's inventory will have been measured and a subset will have been aged (i.e., the "discarded core" trees). We therefore are using data from the first cycle to prioritize the acquisition of cores from known trees. Given a limited capacity for processing, we use criteria such as status (live/dead), size, age, and species to target the most useful trees to core.

The next priority is enhancing the overall value of the archive and database. Because the vast majority of cores in the collection were obtained during the 1980s and 1990s, most of the tree-ring records will contain a 20- to 30-year gap. However, unlike historical core collections made under independent studies, where revisitation to update a record probably represents "extra" effort, annual FIA plots are scheduled for revisitation as part of the continuous inventory process. Therefore, the additional field effort required to update any given tree record is nominal. This also applies to any case where there is a need to obtain two or more cores from a given tree. In areas where spatial coverage is relatively complete, we are mining the existing tree data for additional candidates for core collection. Candidates might include trees from which cores in the original collection were potentially valuable but not salvageable, trees known or suspected to be very old, or species that are desired for a particular investigation.

Given the wide potential range of applications and the fact that the FIA program conducts and supports many kinds of research in addition to dendrochronological studies, research partnerships will be valuable for advancing this aspect of the FIA program. Because the project was started within the IW-FIA, only eight states are represented in the collection. In a cooperative effort, the

Pacific Northwest FIA program began to collect cores in the Pacific Coastal states during the 2014 field season. These are being processed alongside the Interior West cores and will be added to the database and archive. Researchers at the Laboratory of Tree-Ring Research at the University of Arizona have expressed interest in analyzing areas where FIA has obtained cores but not read them; in this collaborative effort, we have made the cores available for processing, and the resulting data will be contributed to the FIA database. In addition to producing the raw material for analysis, partnerships can be used to advance analysis methodology. For example, X-ray densitometry and neutron imaging can provide information on growth variation within a growing season and over the life of a tree (e.g., Mannes et al. 2007), but these methods are expensive and require highly specialized equipment and procedures. Reflected light methods offer an alternative approach to measuring wood density (Sheppard et al. 1996), with blue light reflectance effectively separating earlywood and latewood in conifers (McCarroll et al. 2002). We are currently exploring the effectiveness of the blue light approach in partnership with the University of Nevada, Reno.

The final goal of the project will be to publish and maintain a tree-ring archive that is compatible with and an extension of the national FIA database. Researchers can take advantage of the fact that FIA cores are collected over a much larger sampling footprint than any individual research effort could accomplish. Access to raw ring-width data will provide maximum flexibility for analysis, and the availability of stand-level data with repeat measurements will permit analyses that are not possible with other dendrochronological data sets. Prototype data structures, using climate station and gridded tree-ring data, have been developed for climatic studies (DeRose et al. 2013).[1] A database version that is compatible with the public FIA database is currently under development.

Conclusions

This ongoing project has resulted in the successful measurement of more than 14,000 increment cores collected during FIA's periodic inventory. Approximately 10% of those cores have been crossdated and subject to quality control, providing time series with annual resolution. In addition, more than 2,000 increment cores collected since 2010 as part of the annual inventory have been measured. The protocol described here could be applied to other FIA programs. Although the FIA tree-ring data do not have the replication or temporal length of ITRDB chronologies, results from initial analyses suggest that these concerns can be at least partially resolved with minor modifications to the sampling approach or by combining data sources. Although the FIA sample design was not optimized specifically to produce a gridded tree-ring data set, increment cores collected on the grid offer substantial research potential. For example, the FIA tree-ring data are largely distributed over areas where weather monitoring is either sparse or nonexistent. In the Interior West, it is precisely these mountainous regions that are the most critical for water resources in snow-driven hydrologic systems. If the coupling of climate variability and tree-ring data is demonstrated, then high spatial resolution climate variables over these mountain regions can be created. Furthermore, the FIA tree-ring grid could provide the dendroclimatology community with a "tree-ring atlas" to be used as part of the survey/planning process before field reconnaissance to inform future sampling efforts. Future enhancement of the data set needs to be defined explicitly, because, as multiple cycles of annual data are measured, reliance on increment cores will go away. To take advantage of the multiple possible ways to use increment core data from the FIA inventory, researchers first need to recognize the potential and then champion its collection.

Endnote

1. See also cliserv.jql.usu.edu/FIAdata/.

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