Expanding the Network of Crossdated Tree-ring Chronologies for *Sequoia sempervirens*[1]

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Abstract

Crossdated tree-ring chronologies for the Arcata Community Forest (ACF) and Muir Woods National Monument (Muir Woods) expand the spatial coverage of dated coast redwood (*Sequoia sempervirens* (D. Don) Endl.) series. Crossdating relies on the common pattern of ring-width variation among tree populations, and dated chronologies have many applications, including climate analysis, growth analysis, tree age calculations, reconstructing fire histories, and archeological dating. While coast redwood poses many challenges to crossdating (e.g., ring wedging, locally-absent rings, and discontinuous rings), recent work established a network of chronologies at eight locations along the species' latitudinal distribution upon which we build. Here we used a combination of methods including coring standing live trees at multiple heights, cutting cross-sections from already exposed ends of downed trees along trail crossings, coring downed trees, and removing wedges from stumps using chainsaws. The ACF chronology is currently composed of six standing second-growth trees (1882-2015) and three stumps (1273-1714). We crossdated the stumps using existing chronologies > 36 km away as references ($r = 0.40$, $p < 0.001$, with the composite northern redwood chronology). The Muir Woods chronology is preliminary with only three trees sampled but spanned 1318-2013 and captured the oldest extent of any crossdated coast redwood south of Mendocino County. The ACF and Muir Woods chronologies showed synchrony with other chronologies in their sub-regions of the range, reflecting a shared climate signal. ACF correlated strongest with Jedediah Smith Redwoods State Park ($r = 0.47$), Prairie Creek Redwoods State Park ($r = 0.47$), and Humboldt Redwoods State Park ($r = 0.46$), and Muir Woods correlated strongest with Montgomery Woods State Natural Reserve ($r = 0.50$) and Samuel P. Taylor State Park ($r = 0.48$) (common period 1882–2009; $p < 0.001$). These chronologies add to an increasing inventory of dated redwood tree-ring series for use in research and management.

Keywords: Arcata Community Forest, coast redwood, crossdating, Muir Woods National Monument, *Sequoia sempervirens*, stumps, tree rings

Introduction

A network of crossdated tree-ring series for coast redwood (*Sequoia sempervirens* (D. Don) Endl.) was recently developed, opening up this species for detailed study utilizing accurately dated time series. Carroll et al. (2014) presented eight coast redwood ring indices spanning the latitudinal gradient of the species distribution from the northern rainforests to the warmer and drier southern forests along the Big Sur coast. These chronologies were based on an intensive within-tree sampling regime with multiple tree cores retrieved from regular height intervals along the main stem of standing redwoods in old-growth forests, where core number per tree averaged 11 and tree number per location averaged 10 but ranged from 5 to 22 (Carroll, unpublished data). Although coast redwoods can preserve millennia of tree-ring records, previous attempts at crossdating were generally limited by complex growth rings where the climatically induced ring-width patterns are difficult to decipher. Coast redwood commonly has growth rings that are discontinuous around the circumference of the stem, patterns of ring wedging, and locally absent or "missing" rings (Fritz 1940). Nevertheless, prior to Carroll et al. (2014) some success was achieved in crossdating coast redwood,

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namely Schulman's recognition of some climatically driven ring-width variation (Schulman 1940) and Brown and Swetnam's (1994) crossdated chronology near Redwood National Park (1750-1985) used for a fire history. The eight recently created redwood chronologies range from 358 to 1685 years in length with the maximum at Redwood National Park (Carroll et al. 2014).

The existing coast redwood chronologies have been the basis of several important insights. Inter-annual climate analysis revealed a latitudinal gradient of dendroclimatic response, as redwoods in southern locations exposed to warmer and drier conditions showed stronger ring-width correlations to growing season soil moisture and precipitation and a negative relationship with maximum temperature, while redwoods at the two northernmost locations expressed a positive relationship with minimum temperature (Carroll et al. 2014). Dated redwood chronologies allowed for a long-term view of size-independent wood volume growth that showed increasing tree-level productivity in the recent decades for redwoods in northern locations (Sillett et al. 2015). Dated tree-rings at regular height intervals allowed age calculations for standing redwoods using rates of trunk radius change with the oldest known standing tree being 2510 years at Redwood National Park (Sillett et al. 2015). While many redwood fire histories have relied on ring counts as crossdating can be problematic (e.g., Jones and Russell 2015), fire histories based on crossdated tree-rings are more accurate (Brown and Swetnam 1994). In this respect, crossdated redwood chronologies promise further advancement in this field, as fire scars and other indicators can be dated to a specific calendar year using known chronologies as a reference. Additional areas of research that can be furthered with crossdated tree-ring series include archeological dating of structures and artifacts, dendro-seismological investigations of earthquakes, reconstruction of disturbance histories, and isotopic analysis of wood cellulose.

While the establishment of the recent network of crossdated redwood chronologies provides a strong foundation for temporally-explicit coast redwood research, more work is needed to extend and improve these chronologies. Even though old coast redwoods can be very difficult to crossdate, each new tree adds replication to a growing database. New locations expand the spatial extent of the network, providing reference chronologies for future crossdating and data for redwood growth and climate analyses. The sampling for recent advances involved multiple increment cores taken from the stems of standing redwoods in old-growth forests (Carroll et al. 2014, Sillett et al. 2010, Sillett et al. 2015, Van Pelt et al. 2016). While labor-intensive, this methodology provided the within-tree replication necessary for crossdating and the scale of measurement needed for tree-level analyses. Here we expand tree-ring analysis of coast redwood, including sampling stumps and fallen trees. Specifically, our goals are 1) to create crossdated tree-ring chronologies for Muir Woods National Monument (Muir Woods) and the Arcata Community Forest (ACF) using cores from standing and downed trees, cross-sections from downed trees, and wedge sections from stumps and 2) to test the application of dating unknown redwood ring-width series using existing chronologies from other locations in the range.

Methods

Tree-ring series from coast redwoods were sampled at two locations representing different forest types and sub-regions of the species distribution (fig. 1). Arcata Community Forest (ACF) (40.871° N, -124.071° W) is a second-growth forest with stumps remaining from logging in the 1880s. The ACF is managed by the City of Arcata, California, and lies northeast of Humboldt Bay, ~7 km from the Pacific Ocean separated by flat bottomlands. Tree selection at ACF was driven by the goals of associated research (Coonen and Sillett 2015) while also providing a litmus for redwood crossdating and chronology extension. Muir Wood National Monument (Muir Woods) (37.895° N, -122.575° W) is an old-growth redwood forest under the management of the National Park Service that lies ~14 km north of San Francisco and ~4 km from the Pacific Ocean separated by hills of the Marin Headlands. Tree 76 at Muir Woods was intensively studied as part of the 2014 BioBlitz at the Golden Gate National Recreation Area.

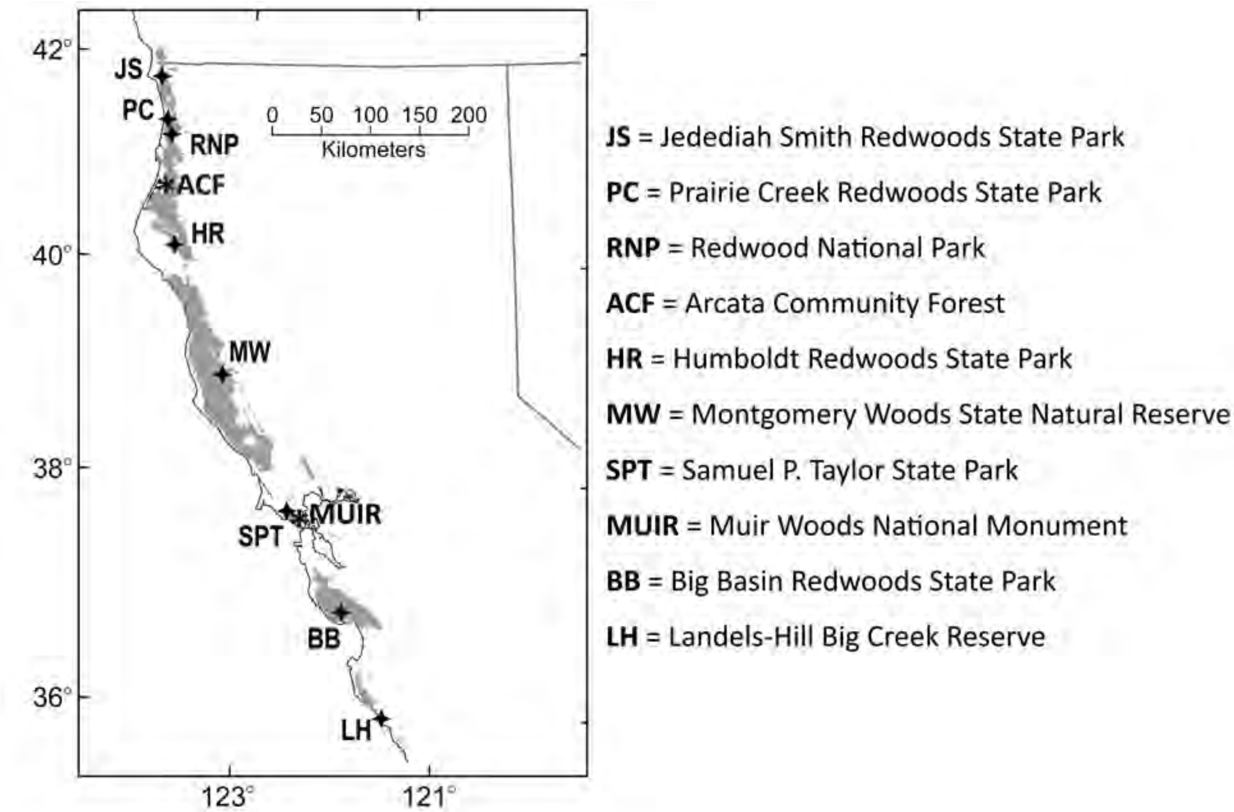

Figure 1—Map showing locations of two new (ACF and MUIR) and eight existing sampling locations. Shaded areas show native range of *Sequoia sempervirens*.

A combination of sampling strategies was implemented at both locations. Tree cores from standing live redwoods were sampled at regular height intervals (~ every 10 m) along the main trunk, accessed by climbers on free hanging ropes using 61 and 81 cm (24 and 32 inch) increment borers. Cross-sections of two recently fallen trees at Muir Woods were sampled from cut-faces where the trees crossed the trail. The Vortex tree fell on June 15, 2011, and the Solstice tree fell on December 21, 2012. The Solstice cross-section was removed at what was 11.3 m above ground level, while the height of the Vortex sample could not be determined. In addition to the cross-section, ten increment cores were taken from the downed trunk of the Solstice tree at opportunistic locations with minimal rot and easy access, ranging from 15.0 to 26.5 m above base. Three stumps at ACF were sampled by extracting wedges of wood via chainsaw. A skilled sawyer utilized angled plunge cuts to sample triangular wedges (58 to 86 cm long) at locations with the most intact wood remaining.

All samples were prepared in the lab by sanding with progressively finer sandpaper to 600 grit after increment cores were glued into wooden mounts. We scanned each sample at 1200 dpi and measured the ring widths to 0.001 mm using WinDendro software (Régent Instruments 2009). Crossdating followed the protocol established in Carroll et al. (2014) that involved a combination of visual techniques and correlation analysis on overlapping segments using Cofecha software (Holmes 1983). Each ring was cataloged according to a classification system for crossdating confidence (Carroll et al. 2014) so that complex series could be parsed into usable sections most relevant for this and ongoing research.

Crossdating followed a hierarchical flow from within trees to among trees within locations by comparing ring-width patterns. Standing live trees and fallen trees with known dates of death were anchored by the last year of growth. The stump samples had only heartwood remaining as bark and sapwood had decayed and, in addition, there were no dated temporal comparisons at ACF. So, we first created a floating chronology linking ring-width patterns among the stump samples and then compared this to the closest dated redwood chronologies and a composite northern redwood chronology to assign calendar years.

Final chronologies were generated for each tree and location to provide a standardized tree-ring index most useful for crossdating and comparison with other chronologies. First, we selected only series with high crossdating confidence ≥ 50 years in segment length. High confidence refers to annually resolved rings and can include missing rings, while moderate confidence captures sections where missing rings could have an alternative placement. An inter-annual chronology was generated for each tree using a 32-year cubic smoothing spline to remove long-term trends using ARSTAN software (Cook 1985). Then, tree-level chronologies were combined into location-specific chronologies with variance stabilized. Since there is one series per tree for stumps at ACF, the stump section was generated with one pass with the 32-year cubic smoothing spline. Although the section 1500-1392 on Stump 955 had moderate confidence in crossdating, it was included in the chronology to provide continuity as the only dated series in this section; all other stump sections were high confidence and segment length ≥ 50 years. Correlation analysis was used to compare the inter-annual variation among the network of coast redwood chronologies including Jedediah Smith Redwoods State Park (JS), Prairie Creek Redwoods State Park (PC), Redwood National Park (RNP), Humboldt Redwoods State Park (HR), Montgomery Woods State Natural Reserve (MW), Samuel P. Taylor State Park (SPT), Big Basin Redwoods State Park (BB), and Landels-Hill Big Creek Reserve (LH) (fig. 1).

Results

Portions of all redwoods sampled at ACF and Muir Woods National Monument (Muir Woods) were dated, exemplifying varying rates of crossdating success from 53.6 to 100.0 percent of available rings annually resolved (table 1). In total we analyzed 12 trees, 99 series, and 3572 rings. For the second-growth trees at ACF, we confidently dated an average of 94.4 percent of the rings for the co-dominant trees with no missing rings compared to 69.3 percent for the subordinate trees with an average of 10 missing rings. The 76 m-tall tree at Muir Woods provided a prime example of thorough dating of a standing live redwood in an old-growth forest from cores taken at multiple heights along the stem, establishing a solid base (1448-2013) for the reference chronology at Muir Woods.

Table 1—Descriptive statistics and crossdating summary for trees at Muir Woods National Monument and Arcata Community Forest

Location	Tree	Tree type	Tree height (m)	DBH (cm)	Tree age	# series	First year	Last year	# rings	% years dated (hi conf)	% years dated (mod conf)	% missing rings
ACF	11*	Live	48.8	68.8	133	13	1884	2013	130	59.6	9.4	2.0
ACF	13*	Live	52.1	77.4	134	11	1882	2013	132	79.0	10.8	0.1
ACF	19*	Live	63.9	130.0	128	10	1889	2013	125	100.0	0.0	0.2
ACF	21*	Live	62.0	175.6	138	10	1893	2013	121	100.0	0.0	1.0
ACF	873	Live	53.1	89.4	~137	12	1882	2015	134	91.2	0.0	0.4
ACF	1081	Live	57.1	139.3	~135	10	1884	2015	132	86.3	0.0	0.9
ACF	955	Stump	–	256.2 f	>485	1	1273	1757	485	68.7	22.5	0.6
ACF	984	Stump	–	174.7 f	>322	1	1429	1750	322	66.5	0.0	0.0
ACF	1147	Stump	–	280.6 f	>196	1	1610	1805	196	53.6	0.0	0.0
Muir	76	Live	76.0	249.5 f	777	17	1448	2013	566	98.3	1.7	0.7
Muir	Solstice	Fallen	–		–	12	1477	2012	536	55.8	2.5	11.0
Muir	Vortex	Fallen	–		–	1	1318	2010	693	100.0	0.0	0.0

Trees with * detailed in Coonen and Sillett (2015). First and last year based on ring counts.
At ACF, trees 11 and 13 are subordinate crown class, while trees 19, 21, 873, and 1081 are co-dominate.
DBH for stumps is estimated original heartwood size.
DBH with f denotes functional DBH, defined in Sillett et al. (2015) and Van Pelt et al. (2016).

The two downed trees at Muir Woods illustrated the different possibilities for discerning redwood tree-rings. While only one sample was acquired from the Vortex tree, it had every year present and dated from pith to last year of growth (1318-2010) with no missing rings, making it the oldest known dated piece of coast redwood in the southern portion of the range. In comparison, the Solstice tree had a cross-section and ten cores sampled, with a combined average of only 55.8 percent of the rings annually-resolved with high confidence. The cross-section provided more opportunities to find sections with visible rings, as our path extended from pith to bark with 92.7 percent crossdated and 11 accurately placed missing rings. Sections of all the Solstice cores were dated, ranging from 12.4 to 92.5 percent rings annually resolved on cores that captured 215 to 496 rings. Three cores had > 100 missing rings with a maximum of 148.

We effectively dated the three ACF stumps with between 53.6 to 68.7 percent of the years confidently placed. Notable ring width patterns allowed for the stump rings to be cross-referenced among themselves first, generating a floating chronology (table 2). We then compared the floating chronology to known chronologies and a composite northern redwood chronology (NSESE) to place exact calendar years, first using the clearest section of tree rings that dated to 1501-1713 (table 3). Although the reference chronologies were > 36 km away, relatively strong correlations provided confidence for the dates (e.g., $r = 0.40$, $p < 0.001$, composite northern redwood chronology for common period 1273 to 1714).

Table 2—Stump crossdating showing correlations of 50-year segments lagged 25 years for 1501–1713

Tree	Time span	1501–1549	1525–1574	1550–1599	1575–1624	1600–1649	1625–1674	1650–1699	1675–1713
1147	1610–1713					0.43	0.31	0.41	0.38
984	1501–1713	0.42	0.44	0.33	0.41	0.46	0.53	0.57	0.58
955	1501–1713	0.42	0.44	0.33	0.49	0.46	0.44	0.66	0.56
		0.42	0.44	0.33	0.45	0.45	0.42	0.55	0.51

Bottom row shows average segment correlation.
The preliminary stump chronology was floating and not yet dated to 1501–1714.

Table 3—Stump crossdating showing correlations with known coast redwood chronologies

	stump 955 1501–1713	stump 984 1501–1713	stump 1147 1501–1713	3 stumps 1273–1713
JS	0.40	0.18	0.35	0.31
PC	0.31	0.08	0.35	0.37
RNP	0.24	0.10	0.37	0.30
HR	0.27	0.21	0.01	0.24
NSESE	0.39	0.16	0.35	0.40

We added the two new tree-ring chronologies (ACF and Muir Woods) to the coast redwood network (fig. 2). The 1882-2015 section of the ACF chronology derived from six trees in a second-growth forest, while the 1273-1714 section derived from three stumps. The Muir Woods chronology only has three trees but extends to 1318 and has strong sample depth for Tree 76. These chronologies expand the spatial coverage of coast redwood tree-ring series (fig. 3). When compared to other tree-ring chronologies, ACF correlated strongest with Jedediah Smith Redwoods State Park, Prairie Creek Redwoods State Park, and Humboldt Redwoods State Park ($r = 0.47, 0.47, 0.46$, respectively, $p \leq 0.0001$), and Muir Woods correlated strongest with Montgomery Woods State Natural Reserve and Samuel P. Taylor State Park ($r = 0.50, 0.48$, respectively, $p \leq 0.0001$; table 4).

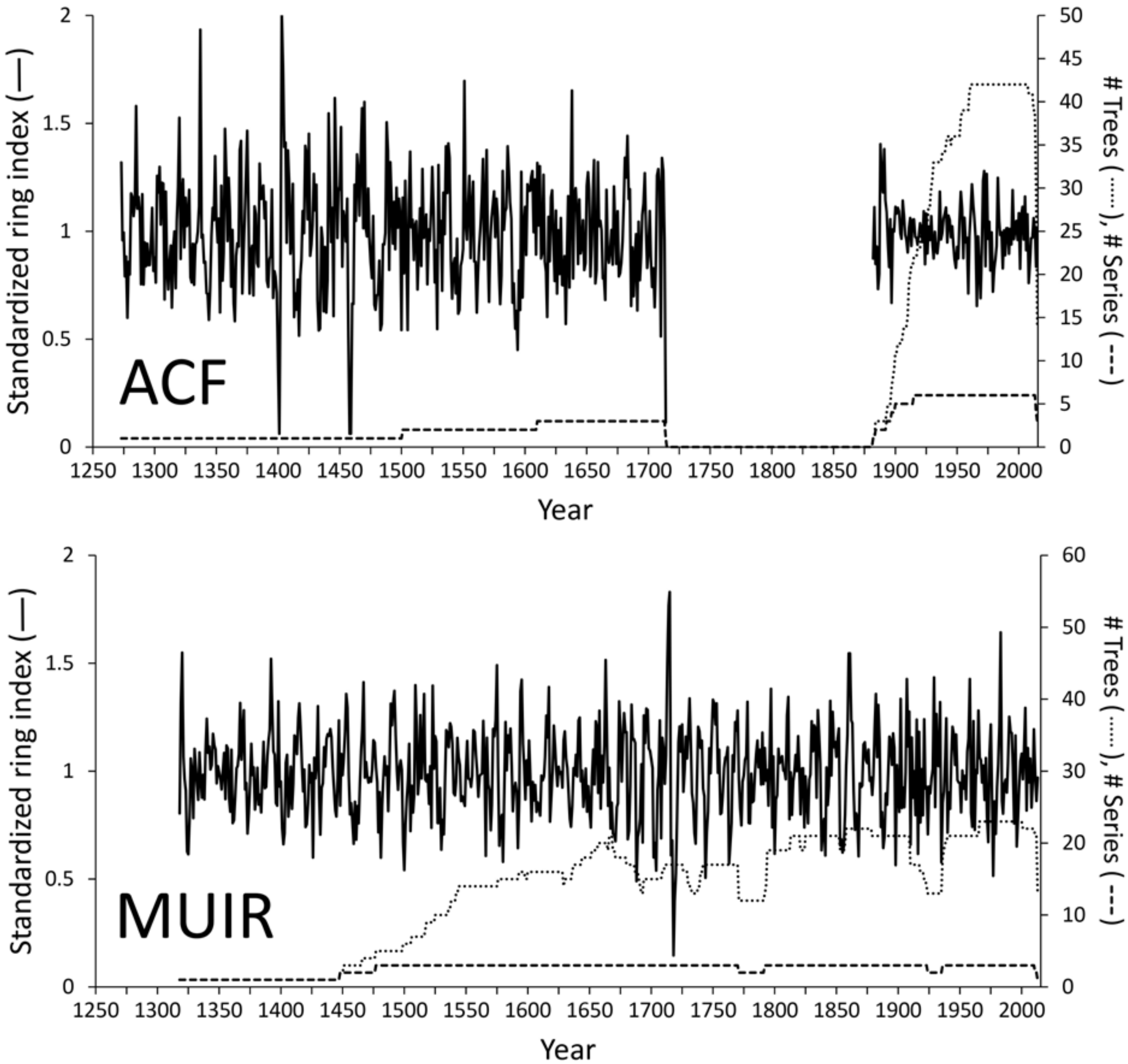

Figure 2—Standardized tree-ring chronologies and sample depths for S*equoia sempervirens* at Arcata Community Forest (ACF) and Muir Woods National Monument (MUIR).

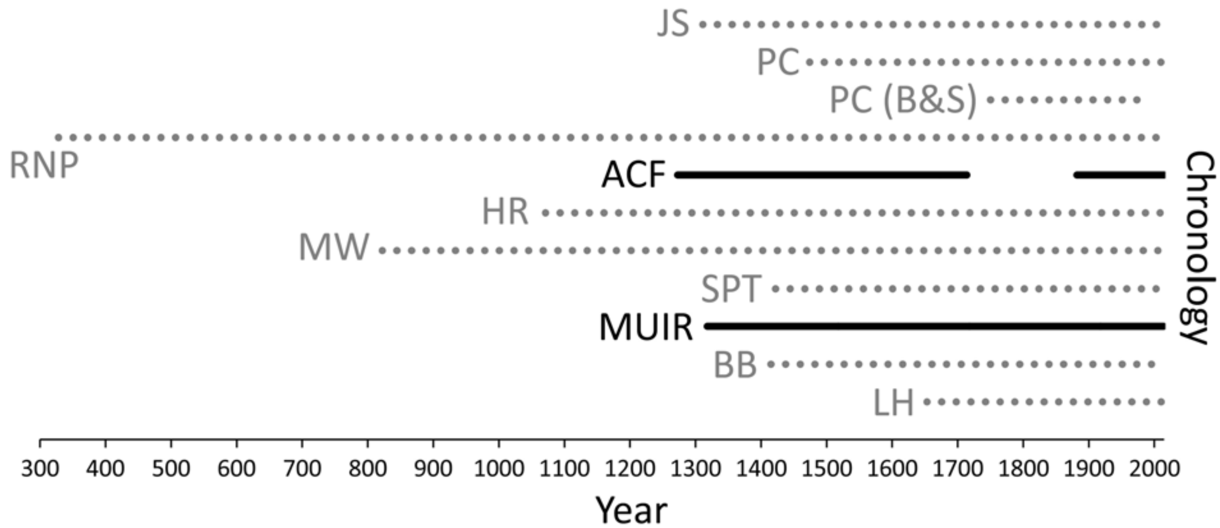

Figure 3—Lengths of crossdated chronologies for *Sequoia sempervirens* at 11 locations listed by latitude. Dashed lines indicate existing chronologies from Carroll et al. (2014) and Brown and Swetnam (1994).

Table 4—Correlations between tree-ring indices of coast redwood chronologies by latitude

	ACF	MUIR
JS	0.47	0.38
PC	0.47	0.31
RNP	0.28	0.21
HR	0.46	0.19
ACF	—	0.31
MW	0.33	0.50
SPT	0.32	0.48
MUIR	0.19	—
BB	0.30	0.43
LH	0.24	0.43

Product-moment correlations (r) for the common period 1882–2009, with statistically significant correlations at $r = 0.23$, $p < 0.01$.

Discussion

Progress continues in our effort to expand the network of crossdated coast redwood tree-ring chronologies. The new sampling had varying degrees of crossdating success, ranging from 53.6 to 100.0 percent rings dated, compared to the range of 3.7 to 100.0 percent for 76 trees in other locations (Carroll et al. 2014). Among second-growth redwoods at ACF, crossdating rates differed by crown class, where suppressed trees averaged fewer rings crossdated than unsuppressed trees (69.9 and 94.4 percent crossdated rings, respectively), similar to the results in old-growth forests (66.6 and 87.9 percent crossdated rings, respectively; Carroll et al. 2014). Suppressed trees are affected by competition from neighbors, which influences incremental growth rates (Coonen et al. 2015). Selection of trees, including crown class, can also influence climate-growth relationships (Carnwath et al. 2012) and to further clarify these influences on coast redwood, future sampling will include a broad spectrum of trees.

For old trees, crossdating remains challenging and time-consuming with variable outcomes. The Vortex tree exemplifies one end of the spectrum where one sample captured every ring for from

1318-2010 with a discernable climatically-correlated ring-width pattern. When crossdating trees at Muir Woods, ACF, and the original eight long-term study locations, perfect series such as this one provided the foundation upon which more complex crossdating was built. The Solstice tree represents a common example of redwood crossdating with variable resolution of annual rings; for this tree, sections of annually resolved rings stretched > 200 years separated by decades with no annual resolution and some cores had > 100 locally absent rings. The cross-section provided more opportunities to locate rings compared to an increment core and also accessed tree rings beyond the extent of our longest (81.3 cm; 32 inch) borer. This inner series contained the longest stretch of crossdated rings for this tree, extending 294 years from the pith. Redwood ring series obtained near pith are often more decipherable as ring widths tend to decline as trunks enlarge (Sillett et al. 2015), and tight rings (e.g., < 0.05 mm for Solstice) can be difficult to discern.

Each sampling strategy employed here has strengths and weaknesses. The most thorough method is coring standing redwoods at multiple heights along the main trunk above basal buttressing via rope climbing. This method provides the replication often needed for difficult crossdating at the tree-level, particularly for older trees, but is labor-intensive and requires specialized training. Downed trees and stumps are more easily accessed, but tree selection is limited. Downed trees can be difficult to core as decaying wood can easily jam the borer. While sampling the Solstice tree, our borer jammed with decayed material on several occasions, even though the tree had been on the ground less than two years. Opportunistic sampling of cross-sections of cut faces along road or trail crossings allows for a more complete view of annual rings at a given height than increment cores, and, while limited in selection, can be useful for chronology extension and material acquisition for isotopic analysis. Sampling stumps required a more technical chainsaw cut than the cross-sections.

Utilizing various methods of obtaining tree-ring series from live and dead trees is important as we aim to extend coast redwood chronologies both spatially and temporally, including dating series beyond the oldest material accessible by increment core from living trees. We are building coast redwood chronologies in a manner similar to the multi-millennia giant sequoia chronologies, combining samples from living trees, fallen trees, and stumps (Brown et al. 1992, Douglass 1919). As with giant sequoia (*Sequoiadendron giganteum* (Lindl.) Buchholz), decay-resistant heartwood allows wood to persist many years after tree death.

Crossdating the ACF stumps offered a case study in the effectiveness of dating redwoods with chronologies from distant forests. Dating remnant material using references > 36 km away is a promising example of crossdating in a forest with no living comparable references. However, the nature of coast redwood suggests that success will be variable (Brown and Swetnam 1994, Carroll et al. 2014, Fritz 1940). Preliminary results from a more intensive effort to crossdate downed logs with two increment cores per log revealed comparably low crossdating rates; for example, of 24 downed logs at Humboldt Redwoods State Park, five were dated with high confidence and three were dated with moderate confidence when compared to a reference chronology < 10 km away (Carroll, unpublished data). In general, the correlation of coast redwood chronologies is stratified by distance with differences between the sub-regions of the range, as exemplified by this study (table 4) and Carroll et al. (2014). A notable example was the use of the 1580 as a marker year for the Muir Woods chronology, the year 1580 has the smallest ring width in many giant sequoia chronologies but not northern coast redwood chronologies (Brown et al. 1992, Carroll et al. 2014).

The ACF and Muir Woods ring indices add to the largest archive of crossdated coast redwood tree rings, stored and cataloged at Humboldt State University with a current tally of 354 trees, 2564 series, and 419,024 rings. All samples are curated understanding the value of these resources for further research, especially given the investment in acquiring and dating redwood samples and as new techniques are developed (Creasman 2011). This work at ACF and Muir Woods adds to the network of crossdated tree-ring chronologies initiated with eight long-term research and monitoring plots in old-growth redwood forests under Save the Redwoods League's *Redwoods and Climate Change Initiative*. While tree number is low compared to many dendrochronological studies, each tree adds value given the often complex nature of crossdating this species. More trees will be sampled at ACF in 2017 to enhance this chronology and study the impact of tree crown manipulations on growth (Sillett, unpublished data). We are actively adding chronologies for investigations of growth and climate at new locations, including redwoods sampled in old-growth forests on the eastern extent of the redwood distribution in Napa County, at the Redwood Experimental Forest near the mouth of the Klamath River, and in the Santa Cruz Mountains (Carroll and Sillett, unpublished data).

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