Save The Redwoods League®

PAST, PRESENT AND FUTURE OF REDWOODS:

A Redwood Ecology and Climate Symposium

August 14, 2013

Photo by Anthony Ambrose

Symposium Generously Sponsored by

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We are grateful to the many individuals, foundations, and League donors who have provided generous support to make this research collaboration possible. We appreciate the gift-in-kind support for the research provided by Green Diamond Resources Co.

The highest known giant sequoia leaves (96.29 m in Giant Forest in 2012). Photo by Stephen C. Sillett

Symposium Program

9:00am **Keynote Talks – *Goldman Theater***

Welcome by Jim Larson, Save the Redwoods League
Introduction by Emily Burns, Save the Redwoods League
California Climate Trends by Healy Hamilton, Marine Conservation Institute
Decoding Millennium-old Tree Rings by Allyson Carroll, Humboldt State University

10:50am **Break – *20 minutes***

11:10am **Keynote Talks – *Goldman Theater***

Phenomenal Redwood Growth by Stephen Sillett, Humboldt State University
Redwoods and Climate Change Initiative Remarks by Ken Fisher, Fisher Investments

12:20pm **Lunch – *Hazel Wolf Gallery & Terrace (second floor patio)***
Poster Session – *Kinzie Conference Room*

1:30pm **Keynote Talks – *Goldman Theater***

Recognition of Bill Hayward and Hayward Family Foundation by Harry Pollack, Save the Redwoods League
Seedling Responses to Drought by Anthony Ambrose, UC Berkeley
Chemical Signal of Climate and Physiology in Redwoods by Todd Dawson, UC Berkeley

3:00pm **Break – *20 minutes***

3:20pm **Keynote Talks – *Goldman Theater***

Mighty Forest Footprints by Robert Van Pelt, Humboldt State University
Why We Must Study Forests by Jerry Franklin, University of Washington
Closing Remarks by Emily Burns, Save the Redwoods League

5:00pm **Reception until 6:00pm – *Hazel Wolf Gallery***
Poster Session – *Kinzie Conference Room*

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Research Abstracts – Keynote Talks

Current and future trends in coast redwood climate

Healy Hamilton, Marine Conservation Institute

Today, coast redwood forests occupy a relatively cool, moist, and narrow sliver of coastal California. This limited distribution suggests that coast redwood forests have a narrow envelope of climatic conditions within which they can compete. Global climate change may alter the range of conditions for temperature and moisture that support healthy coast redwood forests. As part of the RCCI, we used several approaches to identify areas of high climate stability and change across the range of coast redwoods, both now and into the future. We investigated contemporary patterns of significant climate change in the coast redwood region, and predicted where those changes may be greatest in the century ahead. Using 115 years of weather station data, we compared seasonal temperature and precipitation trends in recent decades against a 20th century baseline. We found significant changes in climate patterns are already occurring across the coast redwood range. Increases in summer minimum temperatures (warmer summer nights) were identified as the most salient current trend in coast redwood forests. Total precipitation has not yet significantly changed, but remains highly variable year-to-year. The southernmost portion of redwood forest in Santa Cruz County is already experiencing minimum temperature increases in all four seasons, while redwood forests in Humboldt and Del Norte Counties are currently demonstrating climate stability.

To investigate how climate might change throughout the coast redwoods range in the future, we used a climate analogue approach. We determined historical occurrences of anomalous weather years, including individual years of extreme heat, cold, rainfall, drought, and combinations thereof. These past conditions were used as input into species distribution models, to map the distribution of coast redwood bioclimate under conditions that may approach future climates. The results suggest patterns of stability and change similar to observed trends. Under a wide range of potential future climate conditions, almost the entire distribution of Humboldt and Del Norte County redwood forest climate remains stable. The most severe departures from normal conditions occur in Santa Cruz and Monterey County redwood forest under futures that are warmer and drier. While we do not yet know how coast redwood forests and their many associated species will respond to these current or projected climate changes, our results suggest where the most severe changes are likely to occur. These findings can direct future field-based monitoring of coast redwood trees in these climate-risk zones. Citizen science participation to refine coast redwood distribution at fine spatial scales, particularly at the edges of their range, could significantly improve our understanding of the climate tolerance of coast redwoods.

Millennium-scale cross-dating of *Sequoiadendron giganteum* and *Sequoia sempervirens*

Allyson L. Carroll, Humboldt State University

Through RCCI, we created tree ring records from both *Sequoiadendron giganteum* (SEGI) and *Sequoia sempervirens* (SESE) dating back over 1000 years. This dendrochronological study (*i.e.*, analysis of tree rings) created a baseline, or ruler, upon which researchers can study tree growth, climate, fire history, and even date archeological structures. Here we present and compare cross-dated chronologies for SEGI and SESE at sites spanning their native ranges in California using samples collected at multiple heights along trunks of standing trees. This work represented the most successful and comprehensive cross-dating effort for SESE with 8 sites, 76 trees, 864 radii (*i.e.*, rings measured from the oldest wood to the youngest), and 250,530 growth rings encompassing the years 328 to 2012 AD. We also contributed to the catalog of work on SEGI that was originally started by the pioneer of dendrochronology, A.E. Douglass, in the early 1900s by adding chronologies from 6 sites, 44 trees, 602 radii, and 233,182 growth rings encompassing the years 474 to 2012 AD. SEGI yielded very obvious ring patterns, while SESE rings were more difficult to cross-date. For both species, site-level chronologies were created for cross-dating and reflected reliable marker years (*i.e.*, consistent narrow or large rings or patterns thereof). SEGI site-level chronologies generally showed common synchrony while SESE site synchrony grouped along the north-south gradient. For SESE, common signals occurred within northern and southern chronologies with mid-range sites providing a bridge for cross-dating. The southernmost SESE sites (Landels-Hill Big Creek Reserve and Big Basin) generally correlated more strongly with the SEGI sites than the northern SESE sites. Landels-Hill Big Creek Reserve captured the strongest drought signal of all sites. All SESE and SEGI chronologies shared some marker years that were often strong regional drought events, such as the one reflected in the narrow ring width for 1924. Many other notable marker years (*e.g.*, fire signals at Landels-Hill and Montgomery Woods, 1739 growth reduction for northern SESE, 1580 missing ring for SEGI) emerged from this work and are related to past environmental and climatic events, underscoring the many applications of cross-dated chronologies.

Separating effects of tree size and age on trunk growth in California redwoods

Stephen C. Sillett, Humboldt State University

Sequoia sempervirens (SESE) and *Sequoiadendron giganteum* (SEGI) are the tallest and largest trees with incredible capacity to sequester carbon in decay-resistant wood and fire-resistant bark, yet little is known about how crown structure, growth rates, and allocation of aboveground wood production change as they age. We climbed, mapped, and sampled trees representing the full size and age ranges of both species within 16 RCCI plots and nearby old-growth forests. A total of 137 trees were mapped, which involved intensive measurements of main trunks and appendages. A 3-D model based on the complete set of measurements was used to error-check each tree's data prior to final calculations of all aboveground quantities. From nearly 20 thousand mapped branches, we dissected 257 spanning the range of heights and diameters to develop predictive equations. Applying these to the complete inventory of branches yielded accurate whole-tree estimates of leaves as well as bark, cambium, sapwood, and heartwood on branches. A total of 1462 increment cores (*i.e.*, thin cylindrical samples) encompassing

458,213 annual rings were collected at multiple heights on trunks to estimate minimum tree ages and to quantify bark, cambium, sapwood, heartwood, and annual growth of trunks. To be comprehensive, we measured numerous superlative trees, including the tallest known of each species (SESE = 115.72 m, SEGI = 96.29 m). The largest SESE was at least 1450 years old and had 424 Mg dry mass, 1103 m^3 total volume, 5467 m^2 cambium area, 9549 m^2 leaf area, and 1.12 billion leaves. A 2520-year-old tree became the oldest SESE known (by 300 years). The largest SEGI was at least 3240 years old and had 550 Mg dry mass, 1512 m^3 total volume, 5978 m^2 cambium area, 6726 m^2 leaf area, and 1.94 billion leaves. The 137-tree dataset enabled us to develop equations for accurately predicting aboveground quantities of any redwood in an old-growth forest using simple measurements obtainable from the ground (*e.g.*, trunk diameter at breast height, crown volume), which will be critical for future research and long-term monitoring. Annual ring width declined with age in both species, averaging 1 mm in SESE by 1700 years and SEGI by 1000 years. Despite declining ring widths, annual rates of main trunk wood volume growth increased with size through old age in both species. The fastest growing tree was a 108.6-m-tall, 1180-year-old SESE whose main trunk produced 1.61 m^3 of wood annually during the last decade. Rates of heartwood production also increased with age in both species, averaging 90% of the annual wood volume increment in SESE by 1100 years and SEGI by 1600 years. Mass growth of SESE and SEGI was comparable for the first 650 years when aboveground dry mass of both species averaged 50 Mg, but by 1000 and 2000 years an average SEGI had accumulated only 89% and 75% of an average SESE's dry mass (106 and 348 Mg, respectively). In both species, tree size and crown structure were much stronger determinants of trunk growth than age *per se*, and trees retained high annual rates of carbon sequestration through old age. Regardless of tree age, annual rates of wood production increased during the last century in both species, and the pace of increase was unprecedented in our tree-ring record. Only one tree of each species (both relatively small) exhibited a significant decline in wood production during the last century, whereas declining growth following disturbance (*e.g.*, fire) was more frequent in prior centuries. Aside from the obvious effect of size (*i.e.*, larger trees have more leaves to photosynthesize), causes for increasing rates of wood production during the last century may reflect climate change or other anthropogenic effects (*e.g.*, fire suppression).

Redwood seedling responses to drought

Anthony Ambrose, UC Berkeley

Increasing drought severity and duration associated with climate change may significantly impact coast redwood and giant sequoia trees in the coming decades, especially young seedlings given their small stature and limited rooting depth. As part of the Redwoods and Climate Change Initiative, we studied the impact of drought on coast redwood and giant sequoia seedlings originating from seed stocks obtained from different geographic locations throughout each species' range (north, central, and south provenances). We imposed a 6-week period of severe soil water deficit followed by a 2-week period of re-watering in a controlled greenhouse experiment in order to assess how the two species, and different sampled provenances of those species, respond to drought. The single drought event had a significant effect on seedling growth and physiology, but most water-stressed seedlings of both species largely recovered their physiological functioning by the end of the 2-week recovery period. Importantly, the experiment revealed that seedlings of the two species exhibited contrasting drought-response strategies. Compared to coast redwood, giant sequoia seedlings showed higher leaf photosynthesis and transpiration rates, greater control over plant water status, and a lower degree of stem water transport impairment due to drought, as well as lower relative growth rates and lower growth sensitivity to drought. Drought-stressed coast redwood seedlings had 40% lower average relative growth rates compared to well-watered control seedlings over the entire experiment, while drought-stressed giant sequoia seedlings had 13% lower average relative growth rates compared to control seedlings. Drought-stressed coast redwood seedlings had 80% lower average photosynthesis rates and 88% lower average transpiration rates than control seedlings at the time of maximum drought, compared to 61% lower average photosynthesis rates and 85% lower average transpiration rates in drought-stressed versus control giant sequoia seedlings. Drought had a substantially greater effect on plant water status in coast redwoods than giant sequoias, with 298% lower average daytime shoot water potential in drought-stressed coast redwood seedlings compared to controls at the time of maximum drought versus 157% lower average daytime shoot water potentials in drought-stressed giant sequoia seedlings compared to controls. The greater water stress levels experienced in coast redwoods was associated with significantly greater levels of stem embolism (i.e., air bubbles in water-conducting wood cells which prevent further movement of water in the affected cells) compared to giant sequoia seedlings. The two species showed contrasting whole-plant biomass allocation patterns independent of drought-effects, with a greater proportion of total plant biomass allocated to roots in giant sequoia and a greater proportion of total plant biomass allocated to stems in coast redwood. Notably, there were only minor response differences among the different provenances we tested, indicating that seed source location may not substantially influence drought effects in either species. Both species appear to have a threshold response to drought where seedling growth and physiology become significantly impaired as soil moisture levels decline to less than about 10-15% and plant water potentials decline to less than about -1.5 MPa. These results suggest that despite important species-level differences, both coast redwood and giant sequoia seedlings may experience significant levels of water stress and as a result reduced physiological performance and growth under drier and warmer conditions projected for California in the near future.

Chemical signals of climate and physiology in redwoods

Todd Dawson, UC Berkeley

It is well established that the chemical components (e.g., carbon and oxygen) that comprise the leaves and wood of any tree provide signals about tree function and climate. Through the Redwoods and Climate Change Initiative, we used chemical signals in the leaves and wood of redwoods to extend what was learned from our measurements of physiology and tree ring sizes to explore how redwood trees have responded to environmental variation and change in both space and time. Analyses of leaf stable carbon isotope ratios for both coast redwood and giant sequoia from throughout their geographical ranges show species-level differences and a marked gradient with tree height but only minor differences among populations within each species. The vertical gradient is best explained by tree response to changes in both microenvironment and physiology that are known to change with tree height. In contrast, leaf stable oxygen isotope ratios for both species showed no clear trend with tree height but very clear and marked differences between populations with giant sequoia displaying a generally stronger inferred leaf-level response to the higher summer evaporative conditions present in the Sierra Nevada Mountains as compared to the coast. Both species showed population-level differences in oxygen isotope ratios with the driest and warmest sites most distinct from the others. Detailed analyses of the stable carbon and oxygen isotope ratios in individual (annual) tree rings were also used to explore how climate and tree response to climate was recorded for both redwood species. Wood processed from two periods in a single year (spring and summer) and for each year over a 21-year continuous record where climate data for each location was recorded revealed unique (local) climatic conditions and tree responses to climate for each species and population. Isotope variation was most pronounced in the tree ring record and corresponded to (1) drought (e.g. 1976/1977), (2) above-average temperatures, (3) growing season evaporative conditions, and (4) above-average precipitation (e.g., 1982-1985). Isotope variation also appeared to be influenced by tree size and microsite conditions (e.g., streamside versus upslope locations). Having established the climate-physiology-isotope associations now allows us to develop a robust calibration for looking at periods when and places where climate records do not exist. One very strong relationship across both species was how carbon and oxygen isotopes co-varied; based on a physiological model and real calibrations we can infer that during dry and also warm periods trees appear to first down-regulate their water use and secondly their carbon fixation and that high evaporative conditions drive some of the most marked changes in both variables. These new isotope data are permitting us to reconstruct the responses of redwoods to past and current environments like no other set of information can. Moreover, our analyses can be extended with the use of models to provide well-grounded predictions of redwood responses to future change as well. This information could also be useful for guiding future efforts to conserve and protect redwoods under the novel changes they have been experiencing since human impacts have increased.

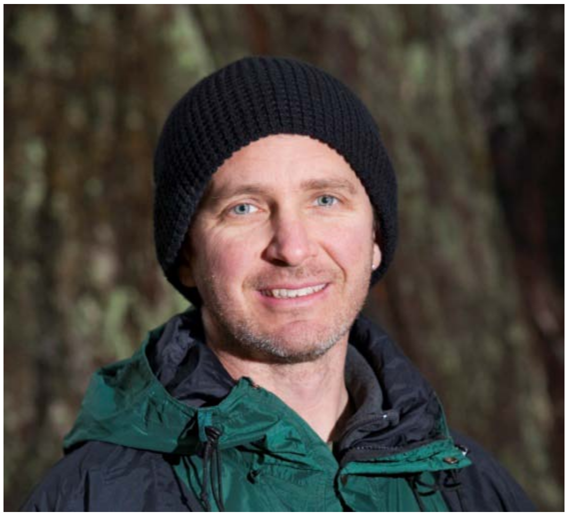
Establishment of long-term reference plots in old forests of both California redwood species, including a detailed mass, carbon, and structural analysis of coast redwood.

Robert Van Pelt, Humboldt State University

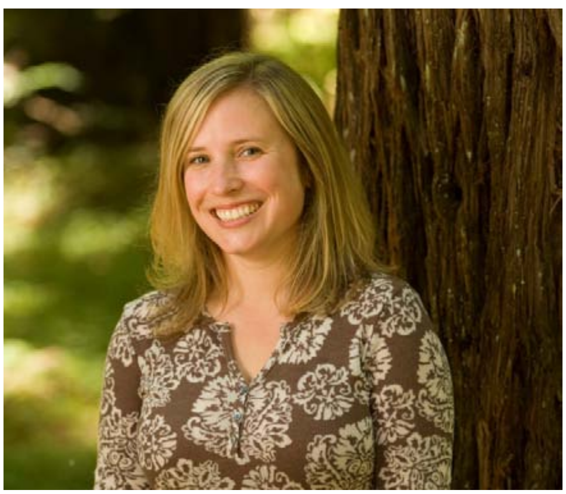
The largest single effort to monitor old-forest responses to a changing environment throughout the ranges of both *Sequoia sempervirens* (SESE) and *Sequoiadendron giganteum* (SEGI) began as a Save the Redwoods League-funded project in 2009. At the core of this unprecedented leaf-to-landscape effort was the establishment of 16, 1-hectare (2.5-acre) plots distributed throughout the species' latitudinal ranges in which we took detailed measurements on forest structure and composition as a baseline to track changes over time. In each plot we conducted an inventory of all aboveground plant material by species, live and dead, at a resolution never before attempted. This involved measuring a tagged population of more than 6000 trees, a subsample for shrubs of more than 5200 individuals, and more than 1300 vegetation plots for estimates of seedlings and herbaceous vegetation. For the needed resolution on the two redwood species, more than 100 trees of all sizes and vigor were climbed and mapped to develop relationships for the stand-level quantification of biomass (leaf, bark, sapwood, heartwood, dead wood) and surface areas (leaf, bark, cambium). So far for the 11 SESE plots, similar biomass relationships have been developed for each species of tree, shrub, fern, herb, and woody debris that occurs in these forests. In addition, massive accumulations of dead wood, particularly in rain forests of Del Norte and Humboldt Counties, forced us to adopt a new classification system for coarse woody debris. We found that above-ground biomass in the northernmost SESE plots was the highest ever recorded, and the dead wood component was 2–3 times what had been previously reported in these or other forests. Stand basal area for live SESE exceeded 400 m^2 ha^{-1} in one plot, and stand totals of 300–400 m^2 ha^{-1} occurred in six others. When living vegetation was combined with standing dead and downed logs, the aboveground portion represented oven dry masses of 3500–5000 Mg ha^{-1} (Mg ha^{-1} = metric tons per hectare). Up to 25% of the total biomass was dead wood in the form of snags and logs. The largest component masses in SESE forests were wood and bark of live trees and the decaying wood of dead trees. Carbon content varied only slightly among these components (*i.e.*, 45–53%), so roughly half of the total forest mass was carbon, and by far the bulk of this was bound up in decay-resistant heartwood. Five of the northern plots had > 25 Mg ha^{-1} of leaf dry mass, which is a global record, as is the accompanying 15–17 Leaf Area Index (m^2 of projected leaf area per m^2 of ground area). Long-term changes in these forests will be detected by annual surveys of growth and mortality, remeasurement twice per decade, the establishment of smaller plots in other landscape positions, and the linking of the ground-based research to LiDAR and other remote sensing techniques to allow detection of landscape-level change.

Robert Van Pelt shown here obtaining ground-level measurements in the lush understory of Jedediah Smith Redwoods State Park. Photo by Anthony Ambrose.

Speaker Biographies

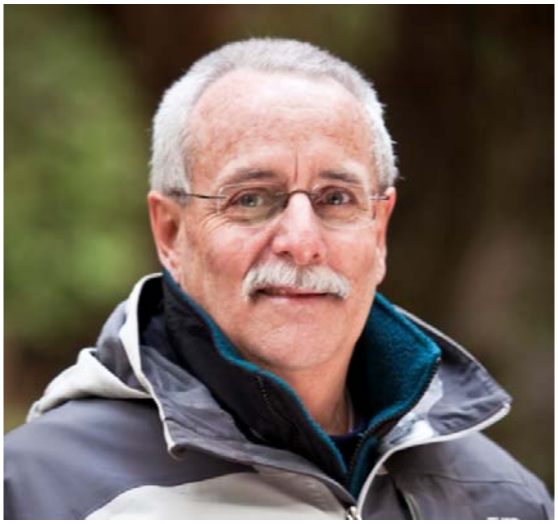


Anthony Ambrose, PhD is a lead research scientist for the Redwoods and Climate Change Initiative and has been studying redwood forest canopy ecology since 1997. Ambrose's Master's thesis at Humboldt State University quantified the effects of canopy soil on microclimates in coast redwood trees, demonstrating that arboreal soil accumulations can store thousands of liters of water within a single tree crown and contribute to the maintenance of redwood forest canopy biodiversity. His PhD dissertation at UC Berkeley focused on coast redwood and giant sequoia physiology. Ambrose's dissertation showed that the combination of soil and atmospheric drought caused 72% lower carbon assimilation in giant sequoia and 82% lower carbon assimilation in coast redwood saplings in greenhouse experiments. His research also revealed redwoods' environmental sensitivity changes with the height of the tree, suggesting that the effects of climate change will differ among trees of different sizes and ages.

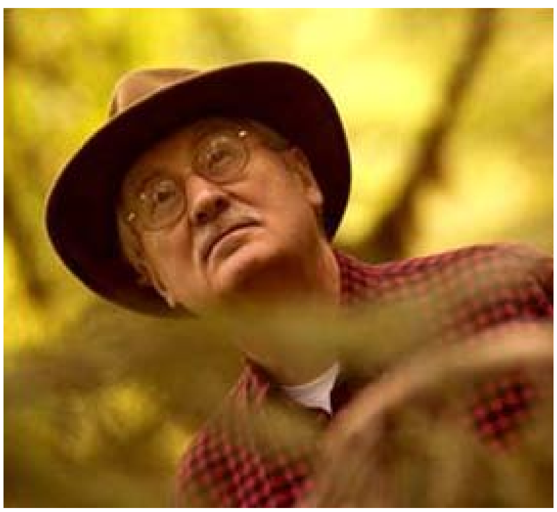


Emily Burns, PhD is the science director for Save the Redwoods League and directs the Redwoods and Climate Change Initiative (RCCI). Burns joined the League's staff in 2010 after studying redwood forest ecology for seven years. Burns received her PhD from UC Berkeley after studying climate impacts on coast redwood forest understory plants. She conducted research as a postdoctoral scholar at UC Santa Cruz on the drought tolerance of redwood forest ferns and in 2009 worked with Chabot Space & Science Center to initiate a citizen science research project called Fern Watch that uses sword fern as an indicator species of climate change in the coast redwood forest. This project engages volunteers to collect important data needed to understand climate change impacts on local flora. Burns is proud that the League supports RCCI because she knows this research is vital for making informed decisions about how to conserve the redwoods as the environment changes.

Allyson Carroll, MS is a dendrochronologist currently working with coast redwoods and giant sequoias through the Fisher Lab at Humboldt State University, chaired by Dr. Stephen Sillett. She completed her undergraduate degree at Duke University and her Master of Science degree at Humboldt State University. Carroll learned the basics of dendrochronology at the Tree Ring Lab at Columbia University's Lamont-Doherty Earth Observatory. She has been researching redwoods for five years and is proud to contribute the most successful and comprehensively cross-dated coast redwood chronologies to date, which can be used as a baseline for many applications. The Redwoods and Climate Change Initiative enabled this and other foundational research for the superlative coast redwood and giant sequoia forests.

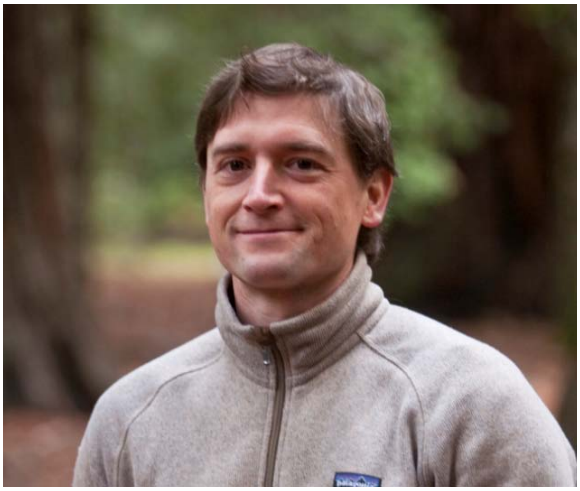


Todd Dawson, PhD is a Professor of Environmental Biology in the Departments of Integrative Biology and Environmental Science, Policy & Management at UC Berkeley and is the Director of UC Berkeley's Center for Stable Isotope Biogeochemistry. His research is focused on ecology, physiology, and biochemistry of plants. The RCCI research has afforded Dawson and his team the opportunity to conduct innovative and necessary research on how past, present and future environments and environmental changes have, are, and will impact redwood trees and forests. The outcomes of their RCCI research have helped advance fundamental scientific understanding about the biology of redwoods in a changing world while also providing data needed for informing the future protection, conservation, and management of redwood ecosystems. Dawson began redwood research as an undergraduate student at UC Santa Cruz in 1980 helping Professor Jean Langenheim in the broad area of chemical ecology. He returned to working on the ecology and physiology of redwoods as an assistant professor in 1990 and has worked on many facets of redwood tree biology and redwood forest science since. Dawson and his students, post-docs, and collaborators have published numerous peer-reviewed papers, with several others either in press, in review or in the works.

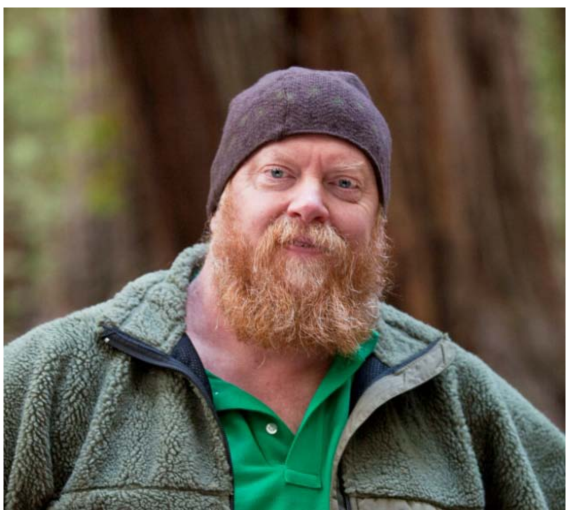


Jerry Franklin, PhD is a Professor of Ecosystem Analysis at the School of Environmental and Forest Sciences at the University of Washington. He has worked and conducted research in the forests of the Pacific Northwest for over 50 years and has become known as the 'father of new forestry' for his holistic approach to forest management that recognizes the importance and role of all the inhabitants of the forests, and aligns timber harvests with the scale and character of natural disturbances. Franklin has been a longtime leader in the field of forest science, serving on the Board of Governors of the Nature Conservancy, as the Director of Ecosystem Studies for the National Science Foundation, and as President of the Ecological Society of America. In response to the conflict over the northern spotted owl, Franklin was a member of the 'Gang of Four', a team of scientists tasked with balancing the needs of old-growth dependent species with the economic necessities of commercial timber harvesting. The result was the Pacific Northwest Forest Plan, the world's first large-scale, ecologically-based forest plan and the model for much current landscape-level ecosystem planning. Franklin served as co-chair of the Climate Change Task Force which was instrumental in launching RCCI in 2009.

Healy Hamilton, PhD is an independent biodiversity scientist with broad interests in the evolution and conservation of the diversity of life. Dr. Hamilton received her graduate training at Yale and UC Berkeley. She is a former Fulbright scholar and a Switzer fellow. In November she will start work as Chief Scientist at Natureserve. Her current research focus is on ecological forecasting. Her lab analyzes spatial information about climate and environment to improve our ability to understand and adapt to the effects of global change on biodiversity. She has been formally collaborating with the League since 2010 to investigate how changes in climate could affect the distribution of redwoods. The RCCI is currently her favorite research project because of its potential to create a positive feedback loop among field observations, computer modeling, and conservation actions.



Stephen C. Sillett, PhD is the Professor and Kenneth L. Fisher Chair in Redwood Forest Ecology, Department of Forestry and Wildland Resources at Humboldt State University. His primary focus is research, especially in tall forests. He also teaches an upper-division Silvics course for Forestry majors and advises graduate students. He has been climbing redwoods and other tall trees for research purposes since 1989. Sillett considers the Redwoods and Climate Change Initiative to be the first comprehensive investigation comparing *Sequoia sempervirens* (coast redwoods) and *Sequoiadendron gigenteum* (giant sequoias) across their geographic distributions in California. Sillett and the team's direct measurements provide the first accurate age estimates for standing trees in old-growth forests, a quantitative assessment of annual wood production rates over the past millennium, and powerful equations to predict aboveground tree biomass and structure using only ground-based measurements. Sillett deems the first four years of the initiative the "golden age of redwood exploration."



Robert Van Pelt, PhD is currently on the research and teaching faculty at Humboldt State University, where he is part of the Institute for Redwood Ecology. He transferred from the University of Washington in 2009, where he received both his MS and PhD. For the past 25 years he has studied old-growth forests across North America, particularly in California and the Pacific Northwest, during the course of which he organized and led large field crews. Currently, he is involved in canopy research on the structure and physiology of the world's tallest trees: coast redwood, giant sequoia, Douglas fir, Sitka spruce, and mountain ash in Australia. He has been studying the two species of California's redwood extensively since the mid 1990s, first publishing on them in 2000. His dual fascination with trees and with facts and figures ultimately led him to write *Forest Giants of the Pacific Coast* (2001), which chronicles in detail the largest trees in western North America. He was a scientific consultant for a congressionally-mandated study of state forests in Washington, and wrote two books which are currently being used in Washington state forest management. These books were but one output from a four-year effort in defining what old-growth and pre-EuroAmerican settlement forests are throughout the state. This has led to a major shift in how state forests are managed in both eastern and western Washington. For Van Pelt, RCCI represents the largest and most significant scientific study of the California redwoods ever attempted. As primary architect of the RCCI study design, Van Pelt has a passionate interest in seeing the scientific vision fulfilled. The first four years were the largest undertaking he had ever been involved with, but the efficiency of design combined with a large crew of very talented individuals has led to very extensive high-quality data sets, which are currently being analyzed.

Poster 1

Inter-annual climate-radial growth relationships and regional synchrony of *Sequoia sempervirens* and *Sequoiadendron giganteum* tree-ring series

Allyson L. Carroll, Stephen C. Sillett, and Russell D. Kramer, Humboldt State University

Through RCCI we investigated inter-annual climate sensitivities and regional synchrony of cross-dated chronologies of *Sequoia sempervirens* (SESE) and *Sequoiadendron giganteum* (SEGI) from sites across their native ranges. We described relationships between high-frequency radial growth variation and monthly climate variables of Palmer Drought Severity Index (PDSI), precipitation, maximum temperature, and minimum temperature for the period from 1895 to present using correlation and principal components analyses. For SESE, summer soil moisture (PDSI) correlated with radial growth, and this relationship extended into the spring months for southern sites. Also, southern sites were more limited by maximum temperatures than northern sites. In the case of SEGI, we confirmed the findings of Hughes *et al.* (1989, 1992) that rather than tracking a strong signal for temperature or precipitation, SEGI's smallest rings recorded extreme events. In addition to seeing this relationship expressed in summer PDSI correlations, we showed that June temperature also captured the association of drought with SEGI radial growth. The strongest relationship among all sites was between growing season soil moisture and growth at the southernmost SESE site, Landels-Hill Big Creek Reserve. In fact, SESE growth at Landels-Hill showed a strong relationship with state and regional drought. Examination of relationships between the high-frequency tree ring chronologies revealed that SEGI chronologies were highly associated with each other while the SESE chronologies separated more distinctly into northern and southern signals. While fog data were sparse and complex, inter-annual growth for northern SESE showed a negative correlation with summer "airport fog" (*i.e.*, 400 m ceiling height, Johnstone & Dawson 2010), which we considered a surrogate for cloudiness in low elevation forests. SESE growth in low elevation forests increased with decreasing summer cloudiness (see RCCI, Sillett et al., "Annual rates of trunk wood production in old-growth redwood forests since 1750). The relationship between summer cloudiness and inter-annual growth generally weakened towards the southern end of the SESE range.

Poster 2

Annual rates of trunk wood production in old-growth redwood forests since 1750

Stephen C. Sillett, Robert Van Pelt, Russell D. Kramer, and Allyson L Carroll, Humboldt State University

Old-growth forests dominated by *Sequoia sempervirens* (SESE) and *Sequoiadendron giganteum* (SEGI) contain world-record biomass and store large quantities of carbon in trees with decay-resistant wood and fire-resistant bark, yet little is known about how annual growth rates vary in response to climate. As a first step toward understanding this relationship, we quantified wood production in SESE and SEGI trees from 16 RCCI plots and nearby old-growth forests.

Increment cores (*i.e.*, thin cylindrical wood samples) were collected at multiple heights on main trunks of 106 trees, and dendrochronology was used to cross-date annual rings, whose widths were measured to the nearest micron. The mapped taper of each tree's trunk was combined with predicted bark radii and measured ring widths to determine wood radii backwards in time and to calculate wood volumes for each year. Wood volume growth was determined by subtracting preceding-year volumes from subsequent volumes. Each tree's growth history was taken as far back as cross-dated rings allowed. The longest whole-trunk records extended back to 1179 and 781 AD for SESE and SEGI, respectively. By 1750 AD, only 50 trees remained in the dataset, and replication was too low at most sites to continue further. Because rates of wood volume growth increased through old age in both species, we derived a size-detrended rate of wood production that did not increase merely because trunks enlarged over time. Despite a high degree of inter-annual variation in wood production corresponding to high-frequency climatic fluctuations, several longer-term trends were evident. Following a period of relatively rapid growth in the 1940s, growth was depressed in the 1950s and 1960s, surged in the 1970s, and has remained high in the 4 northernmost SESE forests (Jedediah Smith RSP, Prairie Creek RSP, Redwood NP, Humboldt Redwoods SP). Wood production since the surge in 3 of these forests (all but Prairie Creek RSP) was higher than at any time on record. No such growth surge was evident in SESE forests farther south except Samuel P. Taylor SP, though a trend of increasing growth during the 20th century was evident in all but the southernmost SESE forest (Landels-Hill Big Creek Reserve). Compared to SESE, there was less inter-annual variation in SEGI growth. A trend of increasing wood production during the 20th century was evident in all SEGI forests except Whitaker Forest, which was partially logged starting about 1870. Growth at Whitaker Forest surged following logging, returning to pre-logging rates by about 1910. Two other SEGI forests exhibited less pronounced growth surges, Mountain Home State Forest in the 1870s and Freeman Creek Grove in the 1880s. Overall, wood production of SESE forests was consistently higher than that of SEGI forests, except for the 1880s and late 1950s. Temporary release from competition following partial logging likely contributed to unusually high rates of SEGI wood production in the late 19th century. Heavy logging and slash burning of northern SESE forests might have contributed to unusually low rates of growth in the mid-20th century by obscuring sunlight. Gradually increasing rates of SEGI wood production during the 20th century could reflect extended growing seasons accompanying global warming. Declining cloud cover during the late 20th century probably contributed to the growth surge in northern SESE forests by increasing light availability. These possibilities and others (*e.g.*, CO_2 fertilization) warrant further investigation.

Poster 3

Structural development of redwood branches and its effects on wood growth

Russell D. Kramer and Stephen C. Sillett, Humboldt State University

The heaviest forests in the world are those dominated by *Sequoia sempervirens* (SESE) and *Sequoiadendron giganteum* (SEGI). Branch contributions to above-ground mass growth are initially 10% and increase to 35% in the largest trees. Recent measurements of all branches from SESE and SEGI trees through the RCCI provide a new source of knowledge for within-tree carbon dynamics and branch structure. This study adds a finer scale of resolution to what we know about wood production and is important because branches represent a significant portion of redwood above-ground biomass. We dissected 31 branches from 8 SESE and 7 SEGI trees to identify the structural determinants of branch wood volume growth and develop a conceptual model of branch development. Branch heights ranged from 15.6–104.5 m, diameters from 3.4–13.6 cm, ages from 11–258 years, and wood production from 3.4–80.3 cm^3 per year. The ratio of energetically expensive cambium to energy-supplying leaf area did not change with size or age but increased with height and light availability. The ratio of expensive heartwood depositional area to supplying leaf area increased with both size and age. Branch size, light availability, species, and heartwood area explained 87.5% of the variation in wood volume growth. After accounting for the positive effects of size and light, wood volume growth declined with both heartwood depositional area and age, but the age effect was trivial in comparison. These results suggest that age-related declines in wood volume growth may be caused by expansion of the heartwood sink, not age *per se*. The oldest branch (258 years) was also 57% heartwood by volume and produced the least wood relative to its size of any branch. Additionally, the negative heartwood effect is twice as strong in SEGI. Cone production correlated with reduced wood volume growth in SEGI branches after accounting for size and light availability even though the cones are long-lived and photosynthetic. The most fecund (i.e had the most cones) SEGI branch had 48% of its mass and 26% of its photosynthetic area in cones, and 1/3 of the measured SEGI branches had > 30% of their mass in green cones. A reduction in growth with heavy reproductive output implies branches are not limited by their ability to support cones, but rather by their ability to provide for them. Thus, branch wood production in both species may be limited by competing internal carbohydrate sinks. We developed a conceptual model for branch development, based on a feedback system, where branch growth and structure interact to produce an array of appendage types, including limbs bearing reiterated trunks.

Poster 4

Establishing baseline reference conditions for old-growth redwood forests

Robert Van Pelt[1], Stephen C. Sillett[1], and Bill Kruse[2]

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The largest single effort to monitor old-forest responses to a changing environment throughout the ranges of *Sequoia sempervirens* (SESE) and *Sequoiadendron giganteum* (SEGI) began as a Save the Redwoods League-funded project in 2009. At the core of this unprecedented effort are 16 plots distributed throughout the ranges of both species in which we measured above-ground biomass, forest structure, and species composition. Eleven plots span the range of SESE from within a few kilometers of Oregon to south of Big Sur (670 km), and 5 plots span the more limited range of SEGI from Calaveras to the easternmost and one of the southernmost SEGI groves – Freeman Creek (279 km). Within each plot, a wide variety of techniques were used to obtain accurate stand-level estimates of biomass (leaf, bark, sapwood, heartwood, dead wood) and surface areas (leaf, bark, cambium) for each species of tree, shrub, fern, herb, and woody debris. This poster highlights the various methods we used to achieve this goal. Plots were all one hectare, scaled to be 10:1, or 316.23 x 31.623 m. Within the entire plot, complete inventories were made of all live trees > 5 cm DBH, all dead trees > 5 cm and taller than 0.5 m, and all downed wood > 30 cm diameter. Each live tree was identified to species, mapped for its X–Y position within the plot, and marked with an aluminum tag and nail (rain forests) or stainless steel tag and nail (all other plots) at 1.4 m or often higher with very large trees or tree clusters. Measurements of height, height to crown base, 4–8 crown radii, diameter at the nail, and nail height were collected for each tree. Trees not yet tagged, shrubs, ferns, herbaceous vegetation, and fine woody material was subsampled, most often using the 316 m plot centerline as a transect. The large and often irregular shapes of tree bases or tree clusters required detailed mapping to get the aboveground resolution needed for this study. One of a few different mapping methods were employed for all non-round tree bases, depending on circumstances. Tree mapping was done first, so that hard copy maps could be error-checked in the field and updated while performing the various plot-level tasks. Maps were error-checked a minimum of three times by the time plot installation was completed. Converting the relative plot coordinate system into real-Earth coordinates was a multi-stage process involving the comparisons of three data sets collected both from ground work and LiDAR-based estimates. The first was a comparison of a detailed DEM (Digital Elevation Model) prepared from ground sampling using lasers to the LiDAR-generated DEM. The second comparison involved using tree crown maps based on the stem map and measured crown radii with the LiDAR CHM (Canopy Height Model). The third comparison used mapped log positions with any large diameter logs detected while creating the LiDAR DEM. Once these three datasets had been linked, a minimizing algorithm was used to lock in the four plot corners (final error was 0.2–0.4 m).

Poster 5

Redwoods, lasers, optics, and bytes: computational remote sensing for the RCCI from trees to the landscape

Bill Kruse, Kruse Imaging

How has remote sensing currently contributed to the Redwoods and Climate Change Initiative? Further, how can we scale the detailed ground truth measurements made by the Initiative's scientists in the long-term reference and smaller satellite plots to the forest and ultimately the landscape? LiDAR, multi-spectral, and hyper-spectral remotely sensed data sets contain a wealth of quantitative information about coast redwoods, their forests, and their topographic environment. Computational remote sensing is being used to mine this data for useful information about the RCCI's signature trees, plots, and the surrounding landscape. LiDAR is used to measure forests from an aircraft. It consists of a pulsed, near-infrared laser scanner that is able to measure the location of reflections from each laser pulse with the help of GPS and inertial navigation. Each reflected point contributes to a point cloud that can be analyzed to measure tree and forest 3D structure. Multi-spectral data is like 2D color digital photos but with less than ten additional spectral bands for analysis. General categories of vegetation and materials can be identified at relatively high ground resolution. Hyper-spectral data also produces 2D imagery but provides many more spectral bands for analysis. This enables more detailed differentiation of vegetation species and materials categories than multi-spectral data can but at the cost of lower ground resolution and higher processing requirements. Used together, these three complimentary remote sensing data resources work together to improve the analysis of our forest's health and change.
RCCI's Phase I utilized LiDAR data, containing 3D forest structure information, to support work in 12 of the 16 long-term reference plots. This data was processed using custom developed workflows, to identify location, height, and crown volume of individual trees and used to create

high resolution ground, canopy surface, and canopy height raster maps at sub-meter geographic accuracy. All of the 12 long-term reference plot locations were selected and finalized with the help of the newly created LiDAR canopy height maps. An ArcGIS geodatabase of all newly-created LiDAR-derived data layers and selected supporting GIS layers was assembled for each LiDAR-supported RCCI Phase I plot to provide a permanent geographic data reference archive. RCCI's Phase II has access to a selection of optical data sets that can be utilized to compliment the LiDAR-derived geographic data layers. Color, near-infrared and hyperspectral imagery with 128 bands of spectral information, where available, can be used with LiDAR primarily to differentiate and identify vegetation types in the plots and surrounding areas. New LiDAR processing software currently being developed can also be used to automatically isolate individual trees and subcanopy vegetation from the LiDAR point clouds, allowing the identification of specific crown structures which are essential for accurate stand-to-landscape scaling. These derived information products provide a scalable plot-to-landscape context to the Initiative's active multi-disciplinary research programs. Calibration and validation of the computed products is provided by the detailed hands-on measurements in signature trees, the existing large old-growth reference plots, as well as the increasingly important smaller and more widely distributed satellite plots.

Poster 6

Monitoring microclimate in the redwoods

Wendy Baxter, Anthony Ambrose, Chris Wong, Cameron Williams, Rikke Næsborg, and Todd Dawson, UC Berkeley

As part of the project goal to provide detailed climate information for the Redwood and Climate Change Initiative plots, microclimate monitoring systems were installed at the treetop and ground level at three coast redwood (*Sequoia sempervirens*) and three giant sequoia (*Sequoiadendron giganteum*) study sites. The information supports more detailed research conducted at specific sites that goes beyond what can be obtained from regional scale satellite or weather data. Measurements are continuously recorded every 30 minutes on key climatic variables, enabling not only species and site-level comparisons but also treetop and ground-level characterizations. Treetop environmental conditions experienced throughout the range of both species are driven mainly by latitude, distance from coast, elevation, and microsite topography. For the coast redwood sites, the first year of data highlight the importance of the summer coastal fog influence at Landels Hill-Big Creek Reserve (LHBCR) and Jedediah Smith Redwoods State Park (JSRSP) in moderating temperatures and vapor pressure deficits (VPDs). Montgomery Woods State Natural Reserve (MWSNR), which is farther inland, experiences higher summer temperatures and VPDs, but during the autumn and winter experiences conditions more similar to those at JSRSP. As the autumn sets in, LHBCR becomes the warmest site but has relatively stable temperatures throughout the year, as does JSRSP. As the northernmost site, JSRSP receives the most precipitation. However MWSNR consistently has the highest soil moisture, presumably due to an elevated water table resulting from an ancient landslide downstream of the site. The range of temperatures and VPDs experienced at the giant sequoia sites is greater than that at the coast redwood sites. However, all three giant sequoia sites follow very similar seasonal patterns, unlike the coast redwood sites. Calaveras Big Trees State Park (CBTSP) is consistently the warmest and experiences the highest VPDs. Although it is the northernmost giant sequoia site, its lower elevation is most likely responsible for these trends. The difference between treetop and ground conditions is greatest at CBTSP, with the treetop experiencing higher temperatures and VPDs. Freeman Creek Grove (FCG) generally receives less precipitation, which is also reflected by lower soil moisture. CBTSP received the most precipitation during the first year of measurements. In the context of climate change, increasing temperatures, decreasing fog and reduced snowpack may play important roles in seedling establishment and overall water-status of mature trees. Continued monitoring will facilitate characterization of inter-annual and long-term trends in environmental conditions, further clarify site-level differences, and may be important in detecting future climatic changes at each site. These data have been essential to the physiological and isotopic research conducted at these sites, but have many other potential future applications and will be available to other researchers and land management agencies. A possible expansion of the network is being considered.

Poster 7

Within-crown and whole-tree water use patterns in giant sequoia trees

Anthony Ambrose[1], Stephen Sillett[2], Todd Dawson[1], Stephen Burgess[3], George Koch[4], Robert Van Pelt[2], Wendy Baxter[1], Cameron Williams[1], Rikke Næsborg[1], Marie Antoine[2], Jim Spickler[2], Russell Kramer[2], and Chris Wong[1]

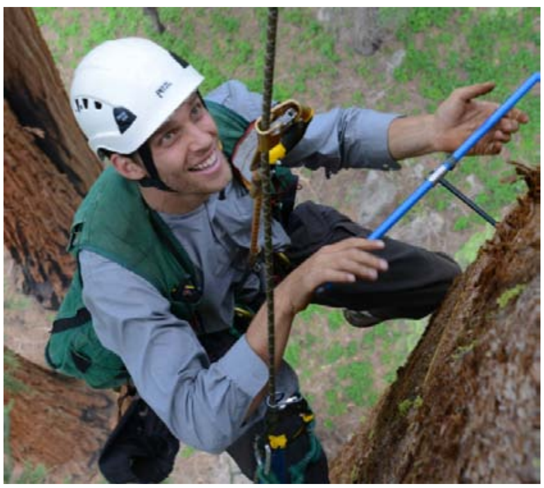
[1]UC Berkeley, [2]Humboldt State University, [3]University of Western Australia, [4]Northern Arizona University

Giant sequoia (*Sequoiadendron giganteum*) trees are the largest and among the oldest living organisms on Earth, with many individuals possessing massive and complex crowns. Spatial and temporal variability in climatic factors interact with changes in tree structure and water status throughout individual crowns to determine water and carbon exchange rates at leaf, branch, and whole-tree scales. We measured sap flow rates throughout the crowns of 3 large *Sequoiadendron* trees growing at UC Berkeley's Whitaker Forest Research Station to characterize within-crown and whole-tree water-use patterns and to examine the relative influence of structural and environmental factors in driving these patterns. Sap flow was measured in individual branches located on opposite sides of each tree crown in lower, middle, and treetop locations, and at the tree base, live crown base, and treetop in the main trunk of each tree. Branch xylem water potential (i.e., water status) and environmental variables such as vapor pressure deficit and solar radiation patterns were also characterized at each sapflow measurement location to account for the effects of highly variable environmental conditions throughout each crown. Each tree was also crown-mapped and a sub-set of branches dissected to provide detailed tree structural information, including branch and trunk sapwood and leaf area. Environmental conditions at different crown positions in each tree were highly variable. Diurnal patterns of solar radiation, atmospheric vapor pressure deficit (VPD) and xylem water potential varied considerably among branches and reflected the interacting influence of both height and the daily trajectory of solar radiation exposure at each branch. In general, branches on the eastern side of each tree experienced greater solar radiation levels, higher VPD, and lower water potentials in the first half of the day, while branches on the western side of each tree experienced these conditions in the second half of the day. Sap flow in all branches, expressed as mean stomatal conductance rates, also showed considerable variability throughout the day and followed similar diurnal patterns as environmental conditions. Despite increasing levels of water stress with increasing height, branches in the upper crown generally exhibited greater stomatal conductance rates than branches in the lower crown for much of the day, suggesting that foliage in upper and outer crown positions is responsible for the majority of water use and consequently carbon gain at the whole-tree scale. Branch stomatal conductance rates were significantly correlated with solar radiation, VPD, and xylem water potential at all crown locations, although the strength of the correlations increased with height (r^2 = 0.28-0.50 for solar radiation, 0.25-0.39 for VPD, and 0.14-0.51 for water potential). We estimate that sapflow through the base of the main trunk of large individual *Sequoiadendron* trees can exceed 2,000 liters of water per day during the summer, substantially more than any other tree species reported in the literature. Whole-tree sapflow rates also appeared to be influenced by the spatial distribution of trees and the consequent effect on solar radiation exposure of individual tree crowns as well as the vertical distribution of leaf area. These findings suggest that entire *Sequoiadendron* groves require enormous quantities of water, and raises concerns that tree and forest structure and function might be compromised with increasing drought conditions predicted for the Sierra Nevada Mountains in the future.

Wendy Baxter is shown here installing infrastructure and probesets for measuring trunk sap flow rates at the crown base of a 90.7m-tall, 1200-year-old *Sequoiadendron giganteum* at Whitaker Forest Research Station. Photo by Anthony Ambrose.

Poster Presenter Biographies

Wendy Baxter, MS is a Research Assistant in the Department of Integrative Biology and Center for Stable Isotope Biogeochemistry at UC Berkeley. Baxter studied Natural Resources at Cornell University and went on to complete her Master's degree at Wageningen University in the Netherlands. Her Master's thesis explored the relationship between climate change and butterfly abundances in the Netherlands and demonstrated the importance of taking into account specific life stages that may be more sensitive to climatic conditions. Her research showed that average temperature and total precipitation correlated most strongly with the abundances of the majority of species studied. She has been a research assistant at UC Berkeley working on the Redwoods and Climate Change Initiative since 2010.



Russell Kramer, MS is a recent graduate from the Master's degree program at Humboldt State University, where he studied under Dr. Stephen Sillett and has been conducting research with Sillett's team for the last three years. Throughout this time Kramer has been affiliated with the Redwoods and Climate Change Initiative; assisting in arboreal data collection, data management, data analysis, and the production of articles for publication in peer-reviewed journals. Kramer started working with redwood dendrochronology in 2006 as an undergraduate assistant in Dr. Sillett's lab. After a three-year hiatus, he was lured back to the redwoods to pursue a Master of Science degree and to participate in one of the most exciting areas of research available: studying old-growth redwood forests. Researching how some of the largest, tallest and oldest organisms grow in the face of a changing climate is critically important because these trees dictate the structure of the forests they inhabit. Forest structure in turn shapes how redwood stands will look, feel and perform into the future.

Bill Kruse is the Principal at Kruse Imaging and develops LiDAR, hyperspectral and remote sensing data-derived intelligence products to support environmental collaborations that strive to answer research questions and inform ecological decision making. This leverages experience acquired during a problem-solving career in remote sensing software development, airborne mapping and systems engineering. Kruse is engaged in working collaborations with scientists, professors and graduate students at the Institute for Redwood Ecology at Humboldt State University and at San Francisco State University's Romberg Tiburon Center for Environmental Studies. Kruse began applying his professional knowledge directly to redwoods in 2007, after discovering a wealth of information hidden in a unique and special LiDAR data set covering old-growth redwood parks in Northern California. The RCCI research contributes to the long-term understanding of our climate, the role redwoods are playing, and advances the state-of-the-art for multidisciplinary and multiscale forest measurements. The work is producing valuable calibration data for quantitative remote sensing models that support cost-effective characterization of forests at scales from individual trees to landscapes.

Glossary

Azimuthal—Referring to the direction or orientation of an object relative to north, usually measured in degrees

Annual ring—One year's growth of wood produced by the cambium and measured for thickness

Bark—Consists of two layers produced by cambium: a dead outer protective layer and a living inner layer that transports sugars from leaves to roots

Basal area—The area of ground occupied by the cross-section of tree trunks and stems

Biomass—Organic material comprising a plant body

Cambium—Living cell layer beneath bark that produces bark from its outer surface and wood from its inner surface

CHM—Canopy height model

Cross-dating—The precise dating of annual growth rings based on the common patterns of ring widths over a population of trees

Dendrochronology—The dating and study of annual rings in trees

DBH—Diameter at breast height; a standardized measurement of tree trunk width taken at 1.37m above ground (or 4.5 feet)

DEM—Digital elevation model

Embolism—Development of air bubbles within the water-conducting xylem cells of a plant, thus preventing further water movement within those cells

Growth ring—A layer of wood produced during a tree's growing season

Heartwood—Completely dead layer of wood beneath sapwood that contains toxic chemicals resistant to decay

Inter-annual (high-frequency)—Occurring between years (from one year to the next) as opposed to a long-term trend (low-frequency)

LAI—Leaf area index; the one-sided leaf area per unit ground

LiDAR—Light Detection and Ranging; a type of remotely sensed spatial data

Marker years—Consistently narrow or large growth rings, or patterns thereof, used for cross-dating

Photosynthesis—Process in which light energy from the sun is used to convert CO_2 from the air into organic compounds in a plant

PDSI—Palmer Drought Severity Index; a widely used index reflecting drought severity, or soil moisture

Provenance—Geographic origin or source location of plant seeds

Radii—A series of growth rings spanning from the oldest rings to the youngest, capturing a cross-sectional view of tree growth

Sap flow—The movement of water through a plant

Sapwood—Partially living layer of wood beneath cambium that transports water from roots to leaves

SEGI—Abbreviation for *Sequoiadendron giganteum* (giant sequoia)

SESE—Abbreviation for *Sequoia sempervirens* (coast redwood)

Stable Carbon isotope ratio— The ratio of naturally occurring carbon-13 to carbon-12 atoms within a compound

Stable Oxygen isotope ratio—The ratio of naturally occurring oxygen-18 to oxygen-16 atoms within a compound

Transpiration—Water loss from plant leaves due to evaporation through tiny pores in the leaf called stomata

VPD—Vapor pressure deficit

Water deficit—Reduction in the amount of soil water available for uptake by plant roots

Water potential—Chemical potential of water in soils, plants, and the atmosphere

Xylem— the woody cellular system of higher plants responsible for conduction of water and dissolved minerals as well as support and food storage

Units

1 ha (hectare) = 2.47 acres
1 m (meter) = 3.28084 feet
1 m^2 (square meter) = 10.76 square feet
1 m^3 (cubic meter) = 35.31 cubic feet or 423.8 board feet
1 Mg (metric ton) = 2205 pounds

Acknowledgements

A warm thank you to the many individuals who contributed to the collection, analysis, and synthesis of Redwoods and Climate Change Initiative data:

Scott Altenhoff
Otto Alvarez
Marie Antoine
Chris Atkins
Stephanie Auer
Awista Ayuby
Wakana Azuma
Will Blozan
Nolan Bowman
Paul Brooks
Aldo Compagnoni
Ethan Coonan
Christopher Earle
Miguel Fernandez
James Freund
Tom Greenwood
Keala Hagman
Frisco Holwerda
Hiroaki Ishii
Bryan Kotwica
Dan Krauss
Lara Kueppers
Cindy Looy
Sky Lovill
Stefania Mambelli
Cameron Musser
Rikke Naesborg
Tara Najim
Marty Reed
Giacomo Renzullo
Marina Rizkalla
Barbara Rotz
Kalia Scarla
Tobe Sherrill
Jim Spickler
Steven Voelker
Cameron Williams
Chris Wong
Rob York
Forest Measurements and Silvics classes at Humboldt State University

We thank our Redwoods and Climate Change Initiative Advisors for providing leadership support to Save the Redwoods League during the launch of this unprecedented research program:

Philippe Cohen
Bob Connick
Bill Croft
Ted Driscoll
Justin Faggioli
Mary Firestone
Ken Fisher
Jerry Franklin
Alex Glazer
Mike Helms
Betsy Herbert
Reed Holderman
Bill Libby
Peggy Light
Ralph Osterling
Kim Rodrigues
Roger Samuelsen
Jim Sergi
Denzil Verardo
David Wake

This research would not have been possible without access to the forest plots provided by CAL FIRE, California State Parks, National Parks, US Forest Service, and the University of California Natural Reserve System. Additional support for this research was provided by City of Arcata.

Sequoiadendron in Giant Forest. Main trunks of tall *Sequoiadendron* are often free of branches for 50 m or more, especially when they stand close together. Photo by Stephen Sillett.

Notes

Notes

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