LTER: Long-Term Ecological Research at the H.J. Andrews Experimental Forest (LTER8)

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PROJECT SUMMARY

Overview. The Andrews Forest LTER program is an integrated, interdisciplinary, 40-yr LTER program of research, education, and outreach dedicated to understanding how forest mountain ecosystems function, as driven by social and ecological processes. Andrews Forest research addresses fundamental ecological questions informed by ecological theory and social challenges. Andrews Forest LTER research integrates many approaches to research including long-term measurements, experiments, analyses, and modeling.

Intellectual merit. In the eighth cycle of the Andrews Forest LTER program (LTER8: 2020-2026) the program will continue to be guided by a central question, “How do climate, natural disturbance, and land use as influenced by values and decisions interact with biodiversity, hydrology, and carbon and nutrient dynamics?” Recent analyses and syntheses of Andrews Forest long-term studies identified knowledge gaps requiring further research and data collection. In particular, we have discovered that microclimate conditions are highly spatially heterogeneous, and driven by fine-scale features such as forest canopy structure and fine-scale topography. Also, preliminary results indicate that the influence of warming temperatures on biodiversity may be strongly mediated by interactions among species. In response, LTER8 investigates the theme of “interactions,” focusing on four interaction types, which represent uncertainties in predictions of change: (1) how forests modulate the expression of regional climate to create local microclimate patterns in mountains; (2) how microclimate and legacies of land use and disturbance influence populations, communities and ecosystem processes; (3) how species interactions amplify or reduce responses to microclimate; and (4) how values filter the use of science in land use decisions. LTER8 also expands on the ecological concept of microclimate, derived from analyses of long-term data, and defined as fine-scale temporal and spatial variation of temperature and moisture in, and under the forest canopy and across the forest landscape. LTER8 also establishes several new studies to examine how climate stress effects may propagate across levels of ecological organization, including responses of tree canopy physiology and microbiomes to heat and moisture stress; cascading consequences for disturbance susceptibility, mortality, and forest productivity; altered seed production cycles and effects on mammals and top predators. A new integrated cross-taxa mechanistic experiment will elucidate how biotic interactions – particularly competition and facilitation – might amplify or dampen species responses to a changing climate. Finally, work on conservation ethics will examine how values affect the ways science is used in land-use decisions.

Broader impacts. The Andrews Forest LTER will continue collaborative experiments, demonstrations, field discussions, workshops, and seminars to connect our science to forest management and policy. The Andrews Forest LTER will also conduct a variety of STEM development activities for K-12, undergraduate and graduate students, teachers, and the public. Andrews Forest Schoolyard LTER will continue the successful model of engaging Oregon K-12 teachers in Andrews Forest science and professional development opportunities; working with teachers extends our impact on K-12 education exponentially. Site-based education programs will give ca. 400 middle and high school students per year opportunities for hands-on inquiry at the Andrews Forest. As a research community comprising 42% women and underrepresented groups, the Andrews Forest LTER program will contribute to diversity and inclusion efforts. REU students, including students from disciplinarily diverse and traditionally underrepresented backgrounds, will conduct supervised research with mentors, and design and implement individual research projects. The Andrews Forest LTER program will continue to engage the public through international, national, and regional media, tours, classes, and on-site programs (~1500 people/yr), the interactive Discovery Trail, and social media interactions (newsletter, website, Facebook, and Twitter). The arts and humanities program (LTEReflections) will host several dozen public events and gatherings and ~50 residencies for writers, musicians, and humanities scholars, leading to Andrews Forest-inspired writing, music, and art. The program anticipates that science conducted at the Andrews Forest will continue to inform forest policy – which will be particularly important given ongoing revisions to regional federal forest management plans.

1.0 RESULTS FROM PRIOR SUPPORT

The Andrews Forest LTER has long been a dynamic and integrated program of research, education, and outreach focused on understanding the functioning and societal role of mountain forest ecosystems in the Pacific Northwest. We collaborate with a broad and diverse community of university and federal scientists, students, and land managers to support ecosystem science, education, natural resource management, and the arts and humanities. The program has its roots at the HJ Andrews Experimental Forest (Fig. 1) (hereafter the Andrews Forest), established in 1948 by the U.S. Forest Service. In the 1950s and 1960s, Forest Service researchers focused on timber and watershed management. In the late 1960s, university scientists became active at the site and research began focusing on forest ecosystems, especially old-growth forests. The Andrews Forest became a charter member of the LTER program in 1980. Long-term measurement programs began in experimental sites and watersheds with a focus on questions about climate, streamflow, water quality, vegetation succession, biogeochemical cycling, and effects of forest management. In our 70-year history, research has interacted within a continually-evolving context of changes in the environment, in science, and in society (Fig. 2). Research on old-growth forests and streams in the 1970s and 1980s contributed to the concept of forest fragmentation, the river continuum concept, and the emerging field of landscape ecology, setting the stage for a 1990s shift in federal forest policy from conversion to conservation of old-growth forests. Andrews Forest research continues to help guide forest management and assessment of effects of environmental change.

Our understanding of the ecosystem has developed over seven LTER cycles (Fig. 2). **LTER1-2** focused on establishing long-term measurements and research on fundamental ecosystem structure and processes. **LTER3-7** were guided by a central question: *How do land use, natural disturbances, and climate change affect three key ecosystem properties: carbon and nutrient dynamics, biodiversity, and hydrology?* (Fig. 3). LTER cycles have also adopted themes: **LTER3,** process-based understanding of landscape dynamics; **LTER4,** effects of early succession and species attributes on ecosystem dynamics; **LTER5,** synchronous temporal behaviors and drivers of biogeochemical cycling in small watersheds; and **LTER6,** complex topography and its influence on ecosystem components. **LTER7** focused on the causes and consequences of connectivity in our landscape. Ten significant publications from LTER7 are highlighted in **bold** when they first appear in the text.

CLIMATE. In LTER7 we examined drivers and consequences of climate processes in the forested mountain landscape (Black et al. 2014). Cold air drainage and pooling decouple portions of the forest landscape from the regional climate, especially at night and in the winter (Johnson 2015, Freundorfer 2017, Singh 2017, Malek 2019, Rupp et al. in review). Long-term, under-canopy air temperature trends indicate that the moderating influence of cold air drainage and pooling on climate warming in forested mountain landscapes is seasonally variable (Fig. 4-c, Honzakova 2017, Jones et al. in review). Old-growth forests appear to insulate understory microclimates against extreme maximum temperatures during portions of the growing season (**Frey et al. 2016b**). Here, we define 'microclimate' as climate conditions measured at fine spatial scales under the forest canopy. We have quantified microclimate over 10 years using under-canopy temperature dataloggers positioned 1.3 m above the forest floor, and distributed across the entire HJ Andrews watershed at 184 sites. The combination of elevation, microtopography, and forest structure results in a highly spatially-heterogeneous thermal landscape (Fig. 5). This spatial heterogeneity differs substantially from many previous conceptualizations of climate in mountain landscapes that tend to describe temperature as driven primarily by elevation (Rahbeck et al. 2019). Our long-term climate studies prompt the question, in LTER8, of how species' populations and whole communities will respond to such thermal heterogeneity, especially under a changing climate.

NATURAL DISTURBANCE AND LAND USE. In LTER7 we studied how natural disturbance and land use create and maintain heterogeneity in terrestrial and aquatic components of forested mountain ecosystems. Disturbance and land-use legacies (Fig. 4-a, Fig. 5-b) shape long-term ecological patterns and processes, such as the distribution of forest structure and biomass (Zald et al. 2016, Bell et al. 2017, Harmon and Pabst 2019), the development of early seral habitat (Fischer et al. 2016, Cook and Halpern 2018, Tepley et al. 2018, Chang et al. 2019), longer-term forest development (Seidl et al. 2014), nutrient dynamics (Perakis et al. 2015), and grassland restoration effects on meadow community dynamics (Halpern et al. 2014, 2016, 2019). Disturbances interact with landforms and geology to affect in-stream wood and sediment (O'Connor et al. 2014, Bywater-Reyes et al. 2018, Safeeq et al. 2020). Past disturbance, which is reflected in forest structure, affects forest responses to new disturbances (Shaw and Agne 2017, Tepley et al. 2018). Addressing social-ecological processes and feedbacks contributed to our understanding of disturbance ecology across LTERs (**Gaiser et al. 2020**). In LTER8 we will explore how interactions between disturbance and land-use legacies, climate, and landforms influence ecosystem pattern and process.

HYDROLOGY. In LTER7 we examined the roles of snow, forests, and landforms on water storage and streamflow connectivity, and implications of climate and forest change for regional water resources management. Regional climate oscillations (Fig. 4-b) dominate streamflow responses (Burt et al. 2015) and drive variation in snowpack (Kostadinov and Lookingbill 2015, Sproles et al. 2017). Protracted rain coupled with existing snow can produce extreme floods (Jennings and Jones 2015). Old-growth forest canopy structure and epiphytes influence interception (Allen et al. 2015b, Heffernan 2017, Pypker et al. 2017). Soil water storage varies with climate (based on the RHESSys model, Garcia 2014) and past disturbance (Nijzink et al. 2016). Hydrologic and geomorphic variables predict surface streamflow connectivity and hyporheic flow at the stream reach (Ward et al. 2016, Ward et al. 2017, Schmadel et al. 2017) and network scales (Ward et al. 2018a). Cross-site syntheses demonstrated consistent forest influences across ecosystems (Creed et al. 2014, Jones et al. 2017, Zhang et al. 2017) and the essential role of forest-water connections for UN Sustainable Development Goals (Creed and van Noordwijk 2018). Long-term paired-watershed experiments reveal that conversion of forests from old-growth to second-growth has reduced streamflow in late summer (**Perry and Jones 2017**). During drought years geologic and geomorphic features control summer baseflow (Segura et al. 2019). In LTER8 we will examine how changes in precipitation timing and form influence water storage, availability, and hydrologic drought.

CARBON AND NUTRIENT DYNAMICS. Old-growth forests in and around the Andrews Forest have massive carbon (C) stores relative to other forest ecosystems, including total ecosystem C (800 to 900 Mg C ha^{-1}) and down wood C (100 to 115 Mg C ha^{-1}) (Harmon and Campbell 2017, Campbell et al. 2019) (Fig. 6). These forests can be managed to store carbon and provide habitat for some species, but carbon storage competes with timber production and habitat for other species (Kline at al. 2016, Harmon 2019). Many stream ecosystem processes export carbon: CO_2 evasion from the surface of small streams was surprisingly high (Dosch 2014), and microbial decomposition of organic matter in the hyporheic zone was a substantial source of dissolved inorganic carbon into the stream (Corson-Rikert et al. 2016, Brandes 2017). Although annual C exported from a small stream was <6% of terrestrial net ecosystem productivity, the annual fluxes were comparable to those from larger rivers around the world (**Argerich et al. 2016**). Fifty-year legacies of forest harvest controlled dissolved organic carbon (DOC) export in small watersheds (Lajtha and Jones 2018), while seasonal variation in microbial- vs. plant- or soil-based C sources influenced DOC quality (Lee and Lajtha 2016) and carbon in suspended sediment in streams (Guerrero-Bolaño 2018). Future projected high summer temperature and reduced summer precipitation may drive decreases in foliar biomass, with negligible responses to increasing atmospheric CO_2 and negligible effects on nitrogen dynamics (Dong et al. 2019). In LTER8 we will examine how C cycling processes in old-growth forests, second-growth forests, and streams respond to climate warming, intensified summer drought, and altered disturbances.

VEGETATION DYNAMICS. LTER7 vegetation research based on long-term tree measurements implies that interactions between biotic and abiotic conditions are important drivers of both spatial and temporal variation in tree demography and forest dynamics (Fig. 6). Tree- and population-level growth and mortality responded to interactive effects of climate and competitors (Ford et al. 2017) or parasitic plants (Bell et al. 2020). Variation in mortality can contribute to the development of structural and compositional complexity (Larson et al. 2015) and to trends in ecosystem biomass diverging from theoretical predictions (**Harmon and Pabst 2015**). Individual tree growth rates were synchronized with climate variability for slow-growing trees in second-growth forests, but desynchronized among older or widely-separated forest stands (Woolley et al. 2015). In LTER8 we will examine how interactions between trees (competition) and communities of beneficial or antagonistic species mediate vegetation responses to climate from tree- to landscape-levels.

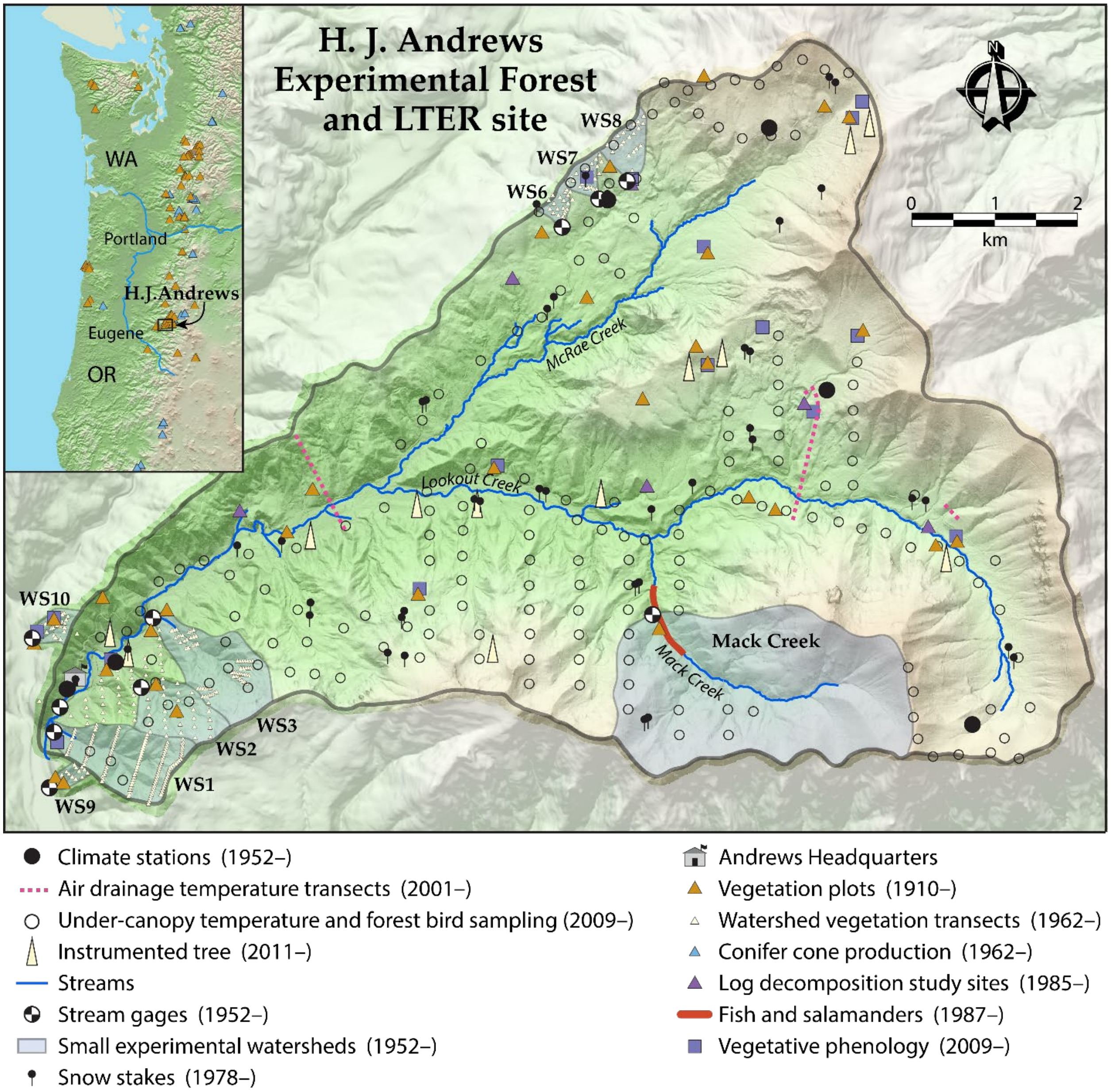


Figure 1. The Andrews Forest LTER is a 64 km^2 drainage basin in the western Cascade mountains of Oregon, ranging from 400 to over 1600 m, dominated by conifer forest. Long-term climate studies include 6 climate stations (MS001, *see list of datasets in supplementary documents*), soil and air temperature in old-growth vegetation reference stands (MS005), a distributed temperature sensor network (MS045), air drainage transects (MS036), 11 vertically instrumented trees (MV005, MV008), snow stakes (MS007). Long-term disturbance and land use studies include a regional network of 140 permanent vegetation study plots (TV010) and vegetation transects (TP041, TP073, TP114, TP115) in second-growth and old-growth forest. Long-term hydrology and carbon and nutrient studies include streamflow, precipitation chemistry and streamflow chemistry at 10 gaged streams and three paired watershed experiments (HF004, CP002, CF002) and a 200-year log decomposition experiment (TD014, TD017). Long-term biodiversity studies include fish and salamanders (AS006), regional conifer seed production (TV019), forest birds (SA024), and phenology (TV075).

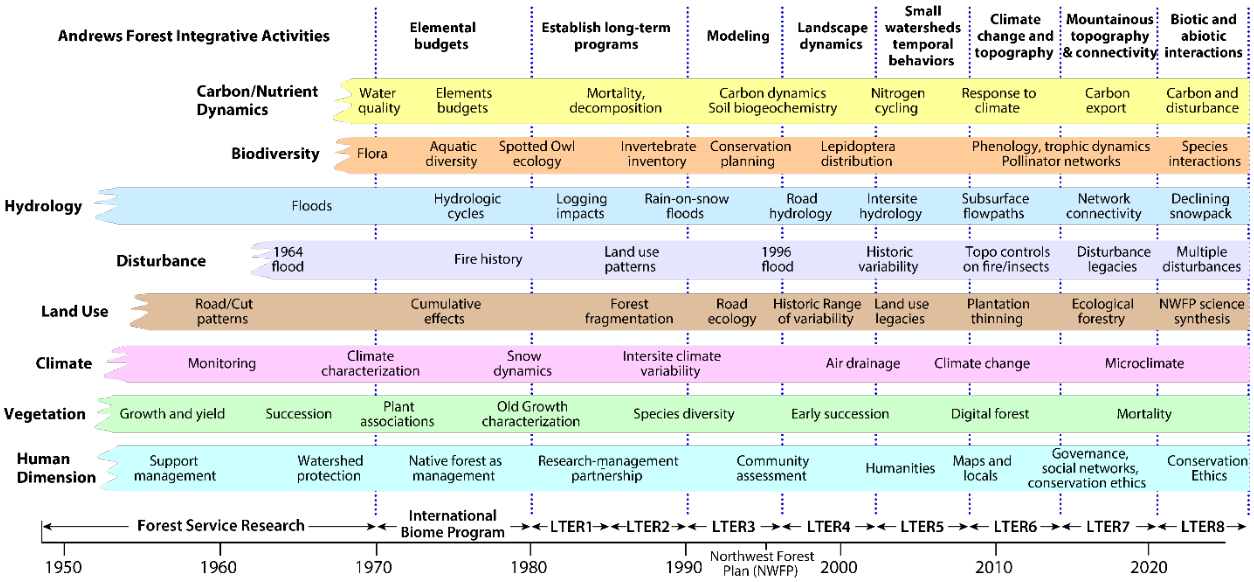
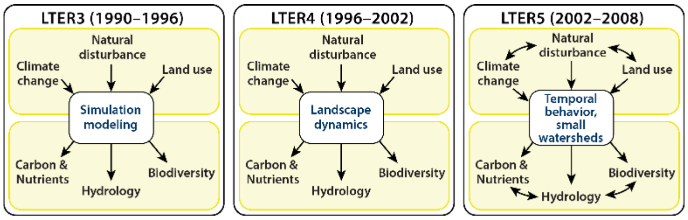


Figure 2. History of the Andrews Forest program, showing major long-term measurement and analysis programs corresponding to components of the central question (horizontal colored bars), the administrative history of the program dating from 1948 and including seven prior LTER cycles, the research foci examined in each successive LTER cycle (topics in horizontal bars), and the integrative themes in each LTER cycle.



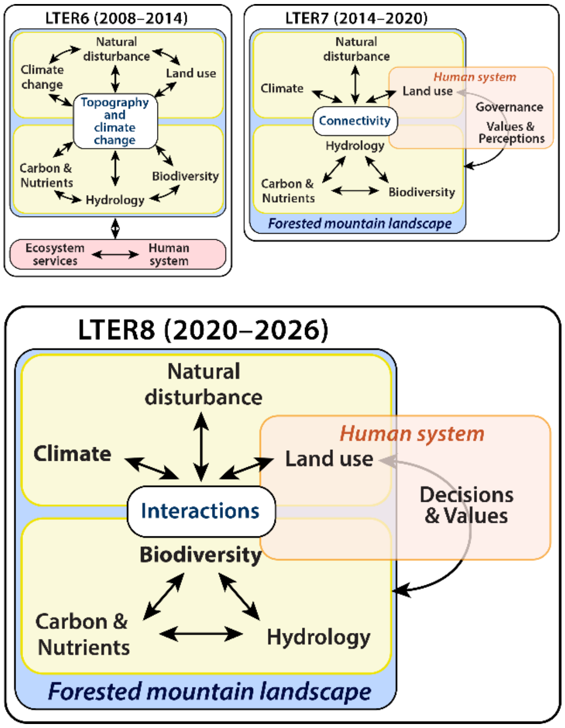


Figure 3. Evolution of the central question (*top*) and the current conceptual framework for LTER8 (*bottom right*). The central question of the Andrews Forest LTER is, "How do climate, natural disturbance, and land use as influenced by values and decisions interact with biodiversity, hydrology, and carbon and nutrient dynamics?" This broad question provides a conceptual framework for our research in forested mountain ecosystems (including biophysical processes, yellow boxes; human system, pink box), and their links (overlapping boxes). In each LTER cycle we have a theme (white box). In LTER8 we have three goals: **Goal 1**: To understand how disturbance legacies interact with environmental change to influence ecosystems; **Goal 2:** To understand how species interactions influence population and community responses to environmental change; **Goal 3**: To evaluate how interactions of science, values, and ecological conditions influence land use decisions.

STREAM ECOLOGY. In LTER7 we advanced understanding of how streamside forests influence light, primary production, in-stream wood, habitat, and food webs. Forty years after clearcutting, streams had similar productivity, light, chlorophyll a, and biomass of invertebrates, trout, and salamanders as old-growth forests (Kaylor and Warren 2018). Reductions in forest canopy cover can drive shifts from light- to nutrient-limitation in streams (**Warren et al. 2016**), shaping aquatic food webs (Kaylor and Warren 2017, Heaston et al. 2018). In cross-site studies using isotopic tracers, streams with open canopies had higher rates of N uptake, stream metabolism, and ratios of autotrophs to heterotrophs (Norman et al. 2017, Tank et al. 2018), although consumers assimilated <50% of the N available (Dodds et al. 2014). Removals of in-stream wood by disturbance and management (Ruiz-Villanueva and Stoffel 2017, Swanson et al. 2020) continue to influence stream processes (Olson et al. 2017) via effects on hyporheic flow, respiration, and reaeration (González-Pinzón et al. 2014). Connectivity of food webs was related to the role of omnivores (Zatkos 2019). Over several decades, native cutthroat trout and coastal giant salamanders in old-growth and regenerating forests exhibited unexpected decreases in body size (Fig. 4-d, Arismendi et al. in review), possibly influenced by thermal effects on inter-species competition. A 2015 summer drought temporarily reduced adult trout and salamander biomass in headwater streams (VerWey et al. 2018, Kaylor et al. 2019). In LTER8 we will examine how temperature and the effects of drought affect interactions (e.g., competition, aggression, predation, migration) between two aquatic predators.

BIODIVERSITY AND POPULATION STUDIES. LTER7 research revealed a high degree of temporal and spatial heterogeneity in moisture and temperature conditions within the Andrews Forest. Long-term patterns of birds, insects, and mammals are related to differential patterns of temperature and moisture in space and time (Fig. 4-e,f, Frey et al. 2016a, Jones et al. 2018, Weldy 2018). Responses to microclimate variability or interannual variation in environmental stress are not consistent across trophic levels or taxa (Kaylor et al. 2019, Schmidt 2019). Cold air drainage and pooling may synchronize temperature, snowmelt, and phenology across the landscape (**Ward et al. 2018b**). A high prevalence of old-growth forest in the landscape mediates the responses of forest bird populations to climate (Betts et al. 2018, **Phalan et al. 2019**) and may mediate the effects of variation in climate on other taxa (Fig. 4-e,f). In LTER8 we will explore how disturbance legacies (reflected in forest structure and composition) and microclimate interact to affect species distributions, populations, communities, and ecosystem processes. We will focus particularly on how interactions within and among species (i.e., competition, mutualism, facilitation) shift under different microclimate regimes.

HUMAN DIMENSIONS. In LTER7 we explored historical, social science, and ethical dimensions of the role of Andrews Forest science and scientists in land use, forest management, and policy in the Pacific Northwest. Historically, the Andrews Forest community of researchers and land managers influenced federal forest land management through formation of a community dedicated to science-based management; research funding from an independent source (i.e., NSF); new knowledge about old-growth forests, spotted owls, and forest-stream interactions; and a governance context that opened the window for policy change (e.g., Robbins 2018, 2020, Swanson et al. 2020). The legacies of past institutions and shifting forest governance in the Pacific Northwest (Maier and Abrams 2018, Abrams et al. 2019) may alter the consequences of forest management and how it interacts with natural disturbances and land use. For example, shifting management on federal lands from clearcutting to forest thinning reflects social-ecological resilience and adaptive capacity (Harris 2018, Gosnell et al. in press). Conservation ethics research highlighted the presence, practical implications, and plurality of values associated with forest management and conservation, and advanced the position that values and value judgments underpinning forest management and conservation should be addressed transparently and systematically (**Batavia and Nelson 2016**, 2017, 2018). In LTER8 we will investigate how interactions between science and values inform land-use decisions and thereby ecological processes.

DATA AVAILABILITY. More than 130 Andrews Forest datasets are available at the Environmental Data Initiative (EDI) data repository, which serves as a node to the Data Observation Network for Earth (DataONE). We include a list of all datasets that have been deposited into EDI as a Supplementary Document. The list of datasets is categorized by components of the central question of the Andrews Forest LTER program and the five LTER core areas. Datasets used in our 10 most significant publications are highlighted.

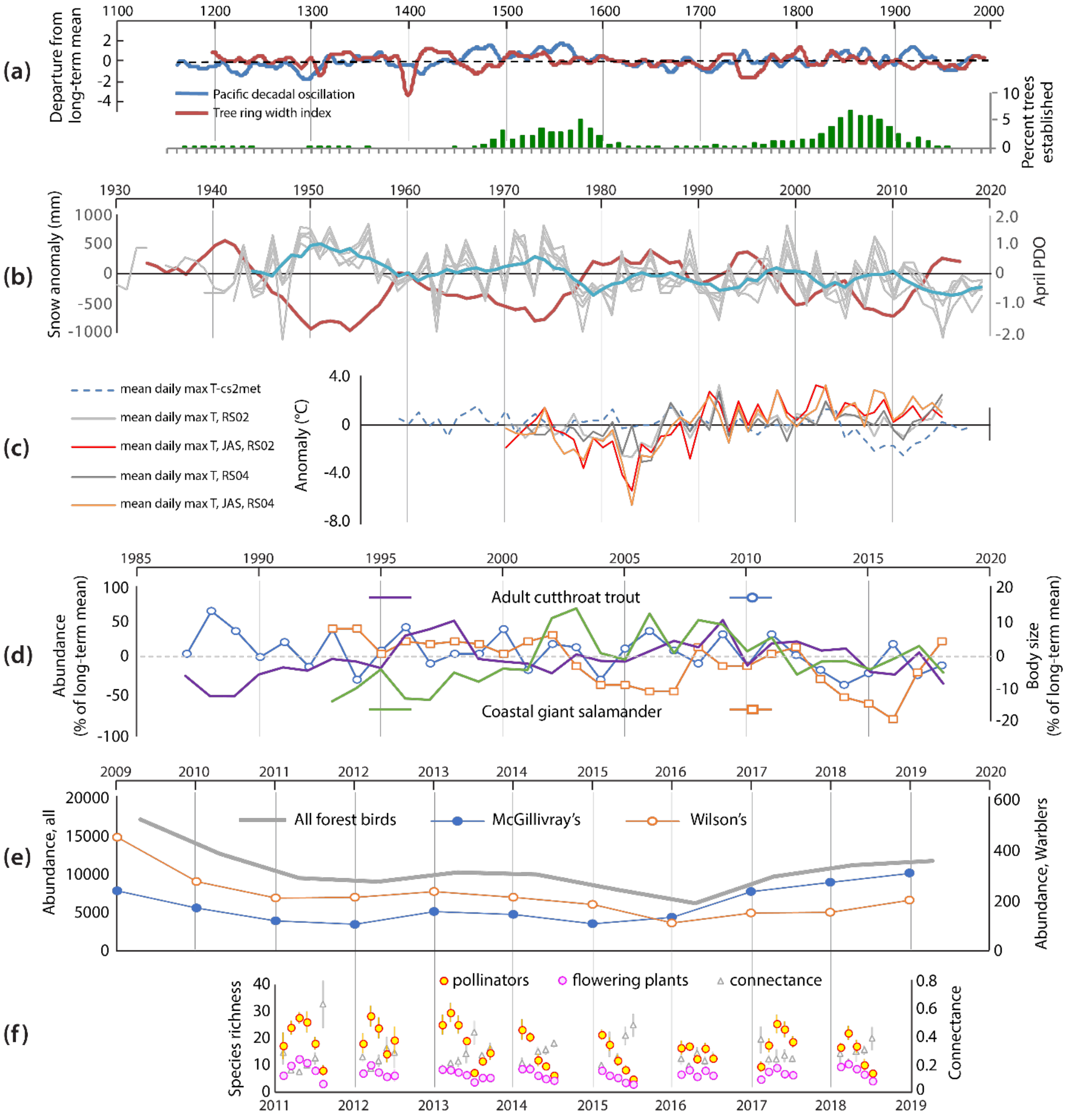


Figure 4. Long-term studies at the Andrews Forest reveal many forms of interactions (Goal 1, Goal 2). (a) The old-growth forests of the Andrews Forest regenerated after episodes of mixed-severity wildfire in the early 1500s and mid-1800s. (b) Snowpack has declined since 1950 and is inversely related to sea surface temperature. (c) Mean annual temperature has changed little since 1960, but summer daytime maximum temperature under the forest canopy has increased by 3°C since 1970. (d) Adult trout and salamander body size has declined since 1987, while populations have fluctuated, (e) Forest bird abundance has declined since 2009; site colonization by McGillivray's warbler depends on microclimate and the presence of Wilson's warbler. (f) Average pollinator and flowering plant richness and connectance in 12 meadows (150 species of plants, 700 species of pollinators) varies by temperature, moisture, season, and year.

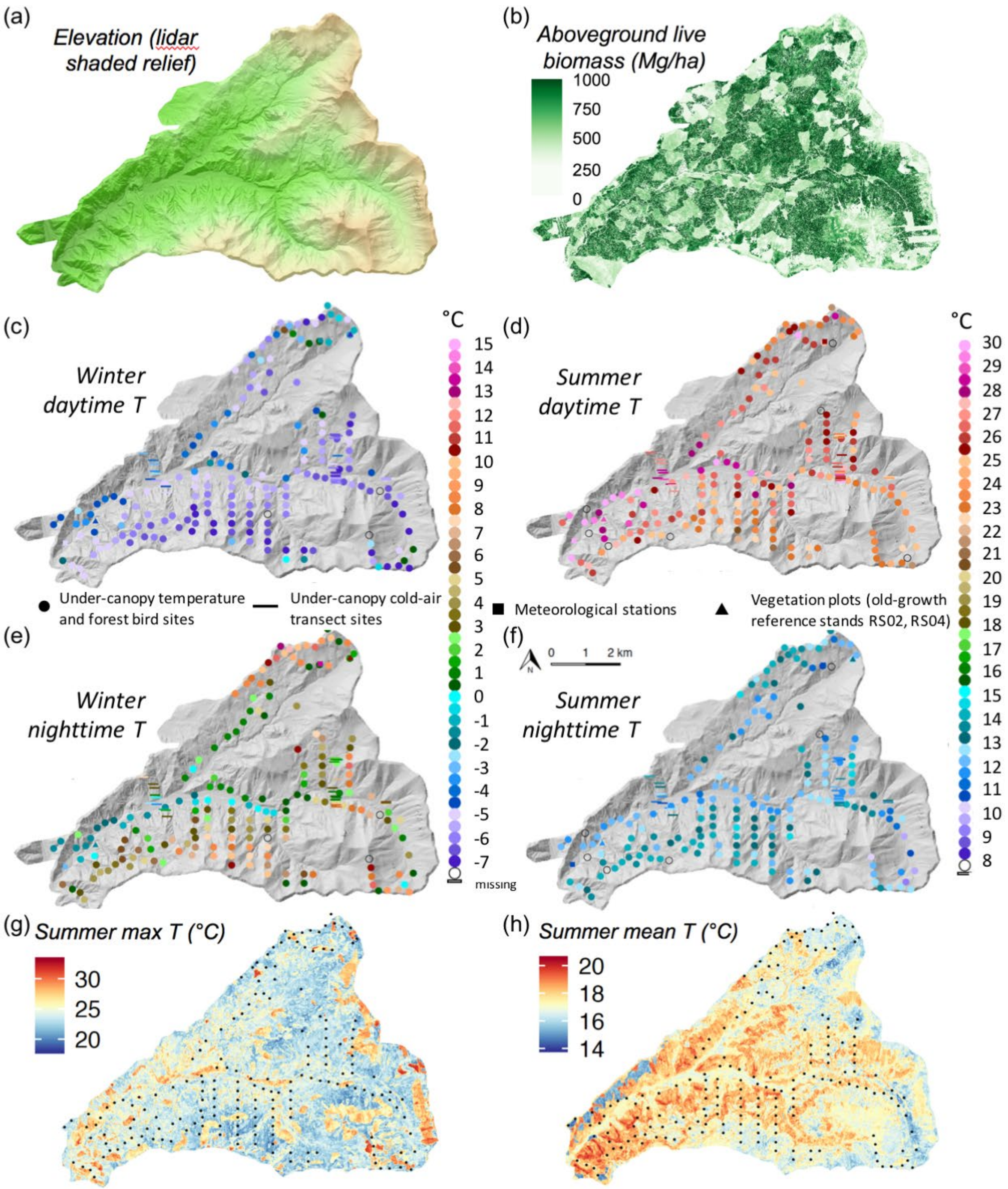


Figure 5. Microclimate of the Andrews Forest sets the stage for studies of interactions. Landforms (a) and vegetation influenced by past disturbances (b) influence spatial and temporal patterns of air temperature (c to f), which can be combined in boosted regression tree models to represent microclimate in the landscape at various time periods (g, h). Microclimate provides a context for long-term analyses (3.4) and integrated, new studies (3.5) of interactions. In winter, low elevation can be relatively warm (c), but during a typical winter daytime inversion, temperature is near-freezing in the valley and 15°C warmer on the ridges (e). Summer daytime temperature cools with elevation, consistent with the environmental lapse rate of well-mixed air (d), but this pattern is reversed by nighttime cold air pooling (f). (Maps: D. Bell, S. Frey, C. Wolf)

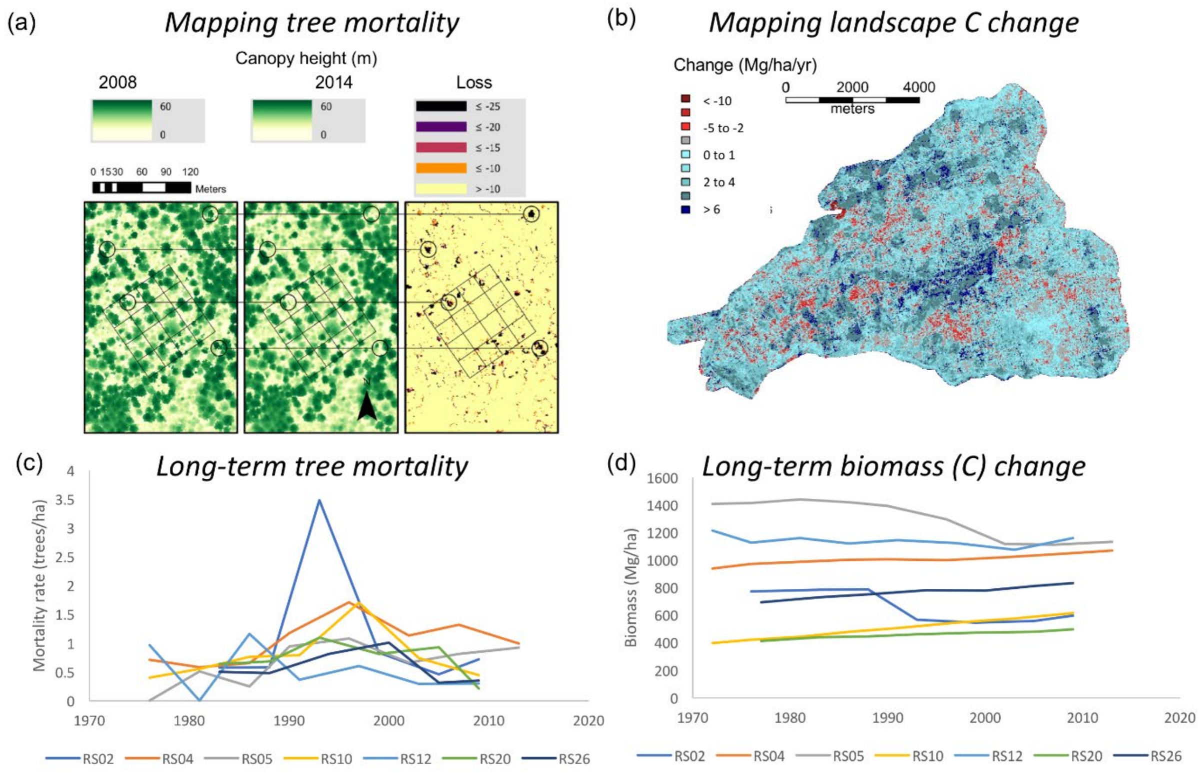


Figure 6. We will model tree mortality, productivity, biomass, and carbon stocks in the Andrews Forest over time (sections 3.4.1, 3.5.2) by examining patterns of vegetation structure before and after disturbance (e.g., snowdown) from (a) lidar-based height change inside and outside long-term vegetation plots (grids), scaled up to show (b) landscape scale changes in aboveground live carbon stocks, combined with long-term data on (c) tree mortality and (d) biomass from vegetation plots in reference stands (RS).

BROADER IMPACTS. In LTER7 we engaged in broader impacts research, outreach and education, arts and humanities programing, and academia/agency partnerships. Broader Impacts Research: More than 50% of LTER sites hosted arts and humanities programs and believe they contribute directly to LTER and site-based goals (Goralnik et al. 2015, 2017). Many factors within LTER sites and within NSF have contributed to changes in the LTER program since 1980 (Jones and Nelson 2020). Our annual outreach event (HJA Day) increased satisfaction, appreciation, knowledge, and changed perceptions (Remenick 2018). Outreach and Education work engaged >1500 people annually through classes, research, tours, and conferences at the Andrews forest. In LTER7 the Schoolyard LTER program gave more than 400 K–12 students per year opportunities for hands-on field inquiry, and engaged 100 educators in professional development related to phenology, stream ecology, climate, and trophic interactions research. These teachers collectively reach >10,000 students per year. We supported 25 graduate research assistants and 200 undergraduates as field technicians and REUs. Arts and Humanities: we hosted residencies for 6–8 creative writers, visual artists, and composers per year; displayed their work in an online archive; employed an array of media for public sharing, including an anthology (Brodie et al. 2016); and supported public performances and gallery exhibits with artist/scientist presentations. LTER7 work was featured on *National Public Radio*, in a documentary by Oregon Public Broadcasting; and in *Scientific American* and *The Atlantic*, among other publications. Partnerships between academia and agencies supported the development of stream restoration guidelines (**Penaluna et al. 2017**), analysis of new stream restoration approaches (Bianco 2018), regional science synthesis for the Northwest Forest Plan (Spies et al. 2018, 2019), and assessment of UN Sustainable Development Goals for forests and water (Creed and van Noordwijk 2018, Creed et al. 2019). The involvement of agency scientists and our long partnership with the U.S. Forest Service National Forest system is central to knowledge transfer and research-management collaborations.

CROSS-SITE SYNTHESIS. In LTER7 we co-authored 13 major cross-site syntheses in key areas of research, including disturbance theory across diverse ecosystems (Gaiser et al. 2020, Cowles et al. in review); post-disturbance plant succession (Chang et al. 2019); cross-continent stream nitrogen uptake in food webs (Norman et al. 2017, Tank et al. 2018); temperature sensitivity of litter decay in terrestrial and aquatic ecosystems (Follstad Shah et al. 2017); biogeochemical responses to disturbance (Kranabetter et al. 2016); integrating Earth system dynamics modeling and long-term, site-based research and data (Baatz et al. 2018); hydrologic responses to global change (Zhang et al. 2017); soil microbe effects on soil carbon accumulation with increasing CO_2 (Wieder et al. 2015); stream temperature effects on net ecosystem production (NEP) and CO_2 emissions from streams (Song et al. 2018); research on large wood in rivers (Swanson et al. 2020); and the effect of meadow and grassland community asynchrony on biomass (Hautier et al. 2018).

SUMMARY OF LTER7. Recent analyses and syntheses of long-term data reveal fine-scale patterns of temperature and moisture in the forest canopy and the landscape (i.e., “microclimate”) that likely have important implications for biodiversity and ecosystem processes in mountain landscapes. Old-growth forest structure and local topography buffer microclimates from temperature extremes (Ward et al. 2018b, Wolf et al. in review), while species interactions may enhance or reduce species vulnerability to changing climate (e.g., Bell et al. 2020). These interactions among multiple changing environmental drivers, and of various responders, especially biodiversity, inspire our LTER8 theme and research.

List of 10 publications chosen for impact, author diversity, long-term data use, and LTER7 research goals.

Argerich, A., et al. 2016. Comprehensive multi-year carbon budget of a temperate headwater stream. JGR: Biogeosciences 121:1-10.

Batavia, C., and M. P. Nelson. 2016. Conceptual ambiguities and practical challenges of ecological forestry: a critical review. Journal of Forestry 114:572-581.

Frey, S. J. K., et al. 2016b. Spatial models reveal the microclimatic buffering capacity of old-growth forests. Science Advances 2:e1501392.

Gaiser, E. E, et al. 2020. Long-term ecological research and evolving frameworks of disturbance ecology. BioScience 70:141-156

Harmon, M. E. and R. J. Pabst. 2015. Testing predictions of forest succession using long-term measurements: 100 yrs of observations in the Oregon Cascades. Journal of Vegetation Science 26:722-732.

Penaluna, B. E., et al. 2017. Aquatic biodiversity in forests: a weak link in ecosystem services resilience. Biodiversity and Conservation 26:3125-3155.

Perry, T. D., and J. A. Jones. 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. Ecohydrology 10:1-13.

Phalan, B., et al. 2019. Impacts of the Northwest Forest Plan on forest composition and bird populations. Proceedings of the National Academy of Sciences of the USA 116: 3322-3327.

Ward, S. E., et al. 2018b. A long-term perspective on microclimate and spring plant phenology in the Western Cascades. Ecosphere 9:e02451.

Warren, D. R., et al. 2016. Changing forests—changing streams: riparian forest stand development and ecosystem function in temperate headwaters. Ecosphere 7:e01435.

2.0 RESPONSE TO PREVIOUS REVIEWS

Two challenges were highlighted during our 2017 mid-term review. Both have been resolved.

1) The NSF review letter noted: “going forward, the lead PI will need an appointment that provides adequate time to develop and coordinate all Andrews Forest LTER activities. This is probably the most immediate threat to the site.” In response, Oregon State University (OSU) committed to a change in the lead PI’s position description, including a 60% administrative appointment for managing the Andrews Forest program. Michael Nelson will remain the lead PI in LTER8 as a result of this change.

2) The NSF review letter noted: “internet access must be improved. Failure to do so greatly compromises data archiving and makes it difficult for site personnel to communicate.” In response, the Andrews Forest program worked with the OSU Research Office to develop a connection between the Andrews Forest and OSU using 5.8Ghz unlicensed radios to transmit from the site to the campus’ network via radio towers (see *Data Management Plan* and *Facilities* sections for detailed descriptions of the wireless infrastructure). The upgraded system increased download speeds to 170mbps, or a 170-fold increase in bandwidth, allowing us to modernize data archiving procedures and meet current research needs.

Also, we appreciate the aspirational science guidance the panel and NSF officers provided. NSF suggested we “use quantitative models to integrate across [LTER’s five core] areas” and “consider placing more emphasis on model validation and predictive modeling as a way of generating new hypotheses.” In response, we engaged in a synthetic modeling exercise to examine how predicted climate change interacts with vegetation structure and function, carbon storage, and hydrology (Dong et al. 2019). Model results revealed sources of uncertainty in vegetation response to climate and consequences for microclimate, biodiversity, carbon and nutrients, and hydrology, laying the groundwork for new questions and hypotheses in LTER8.

NSF encouraged us to build on our existing strength of “unusually detailed measurement of abiotic factors and their relationship to the distribution and behavior of a wide variety of organisms.” In LTER8 we focus new analyses and experiments not only on direct responses by species to abiotic factors, but on how biotic interactions among species respond to abiotic factors—especially the spatially-heterogeneous microclimate documented in LTER7.

3.0 PROPOSED RESEARCH

In LTER8 (2020-2026) Andrews Forest research will test a number of fundamental ecological hypotheses that advance ecological theory and answer applied questions of broad societal relevance. The Andrews Forest LTER focuses on mountain ecosystems, which represent ~25% of global land area but host >85% of terrestrial biodiversity (Rahbek et al. 2019). We will address new questions motivated by uncertainty about how forested mountain landscapes are experiencing climate change, how populations and communities are responding, and how (or why) science is used in forest management.

A central question has guided our LTER research program across funding cycles since LTER3 (1990). It evolves in response to new insights in each cycle, thereby conferring continuity and flexibility. The central question for LTER8 is: ***How do climate, natural disturbance, and land use as influenced by values and decisions interact with biodiversity, hydrology, and carbon and nutrient dynamics?*** (Fig. 3).

Within each LTER cycle we re-examine our central question by framing our research questions and projects around a theme and a set of research goals that respond to contemporary ecological and social topics (Fig. 2). Prior LTER studies motivate us to focus a substantial portion of our efforts in LTER8 on how key elements of biodiversity (i.e., species distributions, populations, and communities) respond to climate—particularly at fine spatial scales.

In LTER8 our theme is *interactions* and our research goals are:

1. To understand how disturbance legacies interact with environmental change to influence ecosystems.
2. To understand how species interactions influence population and community responses to environmental change.
3. To evaluate how interactions of science, values, and ecological conditions influence land-use decisions.

Although climate change observations in the Pacific Northwest have generally been consistent with forecasts at the regional scale (Gergel et al. 2017), observed rates of change vary by season and by sub-region (Abatzoglou et al. 2014). There is also a substantial mismatch between scales experienced by organisms and the scale at which climate data are collected and modeled (Potter et al. 2013). Physical and biological processes influence temperature and moisture patterns at multiple temporal and spatial scales in forested mountain landscapes, but ecosystem processes and organisms respond at fine scales.

Therefore, in the past two cycles of the Andrews Forest LTER program, we greatly increased the spatial and temporal resolution of long-term climate measurements across the landscape and throughout the 60- to 80-m tall forest canopy. These measurements reveal fine-scale spatial and temporal variability in air temperature and associated moisture throughout the canopy and landscape. We refer to this fine-scale variability in temperature and moisture as “microclimate” (Fig. 5, Fig. 7). We have also assembled multi-decadal datasets on key taxa including vegetation, fish and salamanders, forest birds, and plants and pollinators (Fig. 4). Microclimate patterns (Rupp et al. in review, Wolf et al. in review) indicate that populations and communities in forested mountain ecosystems experience a wide range of conditions (Frey et al. 2016b), which affect phenology (Ward et al. 2018b), tree susceptibility to pathogens (Bell et al. 2020), movement of birds in the landscape (Frey et al. 2016a), and plant-pollinator networks (Jones et al. 2018). In LTER8 we will examine how natural disturbance and land use structure microclimate, and how populations, communities, and ecosystems respond to microclimate.

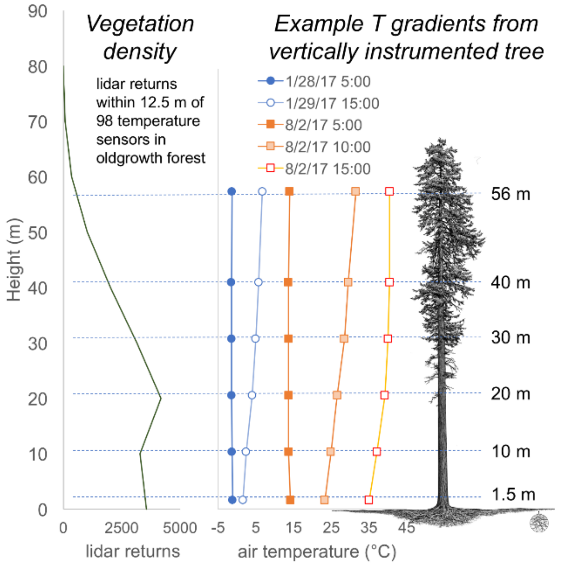
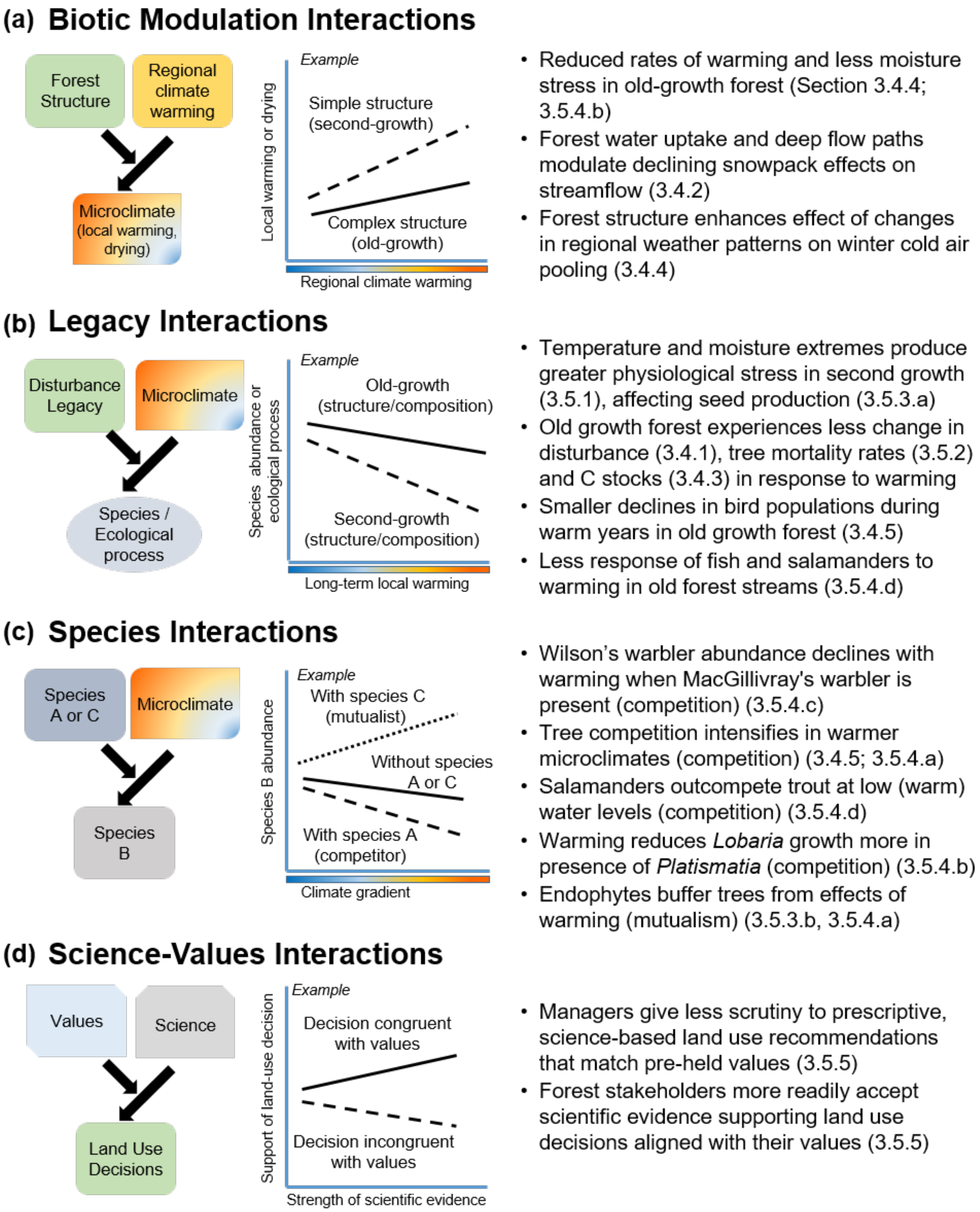


Figure 7. Microclimate within old-growth forest canopy depends on leaf area, concentrated in the lower canopy, where shade and cold air drainage maintain cooler temperature on winter days and in the morning and evening throughout the year. Data from lidar and vertically instrumented trees (since 2011). (Drawing: R. Van Pelt)

Our theme for LTER8, *interactions*, is a central concept in ecology. Most current predictions about the future of biodiversity under global change assume that species respond directly to climate, but ecological theory and empirical evidence indicate that climate responses may be indirect, and mediated by interactions with other species (via competition, predation, mutualisms, etc.) (Walther 2010, Alexander et al. 2015). Although ignoring multiple or complex interactions can make modeling and prediction more tractable, it also limits our capacity to understand future ecological change.

To guide hypotheses about how interactions influence long-term change, we propose and apply a typology of interactions (Fig. 8). Much ecological research addresses unidirectional interactions, such as climate effects on populations, or bidirectional interactions such as predator-prey interactions. However, research is needed on a broader suite of more complex interactions (e.g., Buma 2015, Urban et al. 2016). For instance, how might particular drivers of environmental or land-use change interact synergistically to affect population, community, and ecosystem responses? Or how are the effects of climate change mediated by the colonization of new competitors or mutualists? Andrews Forest LTER research will address the challenge of these more subtle, but potentially critical interactions among drivers and species. In LTER8 we explore what we term ‘*biotic modulation interactions*,’ ‘*legacy interactions*,’ ‘*species interactions*,’ and ‘*science-values interactions*’ (Fig. 8).



(a) Biotic Modulation Interactions

- Reduced rates of warming and less moisture stress in old-growth forest (Section 3.4.4; 3.5.4.b)
- Forest water uptake and deep flow paths modulate declining snowpack effects on streamflow (3.4.2)
- Forest structure enhances effect of changes in regional weather patterns on winter cold air pooling (3.4.4)

(b) Legacy Interactions

- Temperature and moisture extremes produce greater physiological stress in second growth (3.5.1), affecting seed production (3.5.3.a)
- Old growth forest experiences less change in disturbance (3.4.1), tree mortality rates (3.5.2) and C stocks (3.4.3) in response to warming
- Smaller declines in bird populations during warm years in old growth forest (3.4.5)
- Less response of fish and salamanders to warming in old forest streams (3.5.4.d)

(c) Species Interactions

- Wilson's warbler abundance declines with warming when MacGillivray's warbler is present (competition) (3.5.4.c)
- Tree competition intensifies in warmer microclimates (competition) (3.4.5; 3.5.4.a)
- Salamanders outcompete trout at low (warm) water levels (competition) (3.5.4.d)
- Warming reduces *Lobaria* growth more in presence of *Platismatia* (competition) (3.5.4.b)
- Endophytes buffer trees from effects of warming (mutualism) (3.5.3.b, 3.5.4.a)

(d) Science-Values Interactions

- Managers give less scrutiny to prescriptive, science-based land use recommendations that match pre-held values (3.5.5)
- Forest stakeholders more readily accept scientific evidence supporting land use decisions aligned with their values (3.5.5)

Figure 8. In LTER8 we develop and examine a typology of interactions, to better inform our predictions of ecological response to environmental change. We examine (A) *biotic modulation interactions*, where abiotic and/or biotic drivers interact to control local abiotic conditions, (B) *legacy interactions* where disturbance legacies amplify or dampen the effect of abiotic conditions on a species or ecological process, (C) *species interactions* where the presence of another species amplifies or dampens the effects of abiotic conditions on a focal species, and (D) *science-values interactions* where values modify the effect of science on land use decisions. The right column lists examples and associated sections of this proposal.

In a *biotic modulation interaction*, an abiotic condition may be modulated by an interaction between biotic and abiotic drivers. For example, the influence of regional climate warming could be dampened by the presence of complex forest structure (Fig. 8-a). Also, declining snow pack is likely to reduce streamflow. This effect could be modulated in areas with deep surface flow paths and by changes in patterns of water uptake by trees. In a *legacy interaction*, disturbance legacies may amplify or dampen the effect of an abiotic driver (e.g., microclimate) on a process or species (Fig. 8-b). For example, the higher-quality habitat provided by old-growth forest (e.g., greater food availability, nest sites) might dampen the effects of microclimate warming on some bird species. In a *species interaction*, biotic responses are connected; the presence of one species may amplify or dampen the effect of an abiotic driver on another species (Fig. 8-c). For example, competitive interactions between fish and salamanders may shift with reductions in freshwater habitat. Finally, in a *science-values interaction*, values affect how scientific evidence is interpreted and used to make or evaluate land-use decisions (Fig. 8-d). For example, managers may more positively assess science-based management recommendations that are congruent with their value systems.

Although interactions may play out over short time periods (e.g., Betts et al. 2010, Jankowski et al. 2010), population, community, and ecosystem responses often show lagged responses—particularly in systems such as ours with long-lived species. Analysis of long-term data is therefore essential for testing hypotheses about the importance of synergistic effects of climate and disturbance on biota, as well as how biotic interactions structure populations, communities, and ecosystems. In LTER7, as in prior LTER cycles, science questions have emerged from long-term experiments and measurements as we evaluate them in a changing context, leading us to ask new questions, which in turn lead to new science discoveries. LTER8 continues this fundamental approach, with a focus on three research goals.

3.1 LTER8 Research Goals

GOAL 1. TO UNDERSTAND HOW DISTURBANCE LEGACIES INTERACT WITH ENVIRONMENTAL CHANGE TO INFLUENCE ECOSYSTEMS.

Physical processes, such as cold air drainage and hydrologic flow paths, govern abiotic conditions at multiple scales. These processes determine how broad-scale projections of environmental change link to real landscapes (Shafer et al. 2005, Franklin et al. 2013). The resulting spatial and temporal heterogeneity in abiotic conditions affects landscape patterns of populations, communities, and ecosystems directly (by imposing stress) or indirectly (by altering disturbance risk). However, it is increasingly realized that vegetation structure (a biotic element) also feeds back to modulate abiotic microclimate conditions (De Frenne et al. 2013, Lenoir et al. 2017). Local- and landscape-scale vegetation structure is a legacy of past disturbance (e.g., fire or timber harvest), which may be influenced by past microclimate conditions. Forest microclimate therefore emerges as a function of complex and dynamic feedbacks between abiotic and biotic drivers in mountain landscapes (Pickett and White 1985, Winemiller et al. 2010, Jentsch and White 2019). Under climate change, we expect nonstationarity (Milly et al. 2008, 2015) and increasingly frequent extremes, such as heat waves and droughts (IPCC 2014, 2018, Marlier et al. 2017). Therefore, we expect this dynamic, coupled relationship between biotic and abiotic drivers of local environmental conditions to shift in potentially unexpected ways.

Long-term studies of climate, hydrology, carbon and nutrient dynamics, vegetation, and populations at multiple sites in the Andrews Forest offer exceptional opportunities to examine how interactions among biotic and abiotic components of ecosystems influence responses to environmental change. In our study of *biotic modulation interactions*, we will capitalize on our network of under-canopy and within-canopy air temperature sensors to quantify microclimate heterogeneity across the Andrews Forest and assess the consistency of those patterns across years (3.4.4). We will examine how changes in temperature, precipitation, and forest structure influence snowpack dynamics and whether earlier snow melt affects late summer streamflow (3.4.2). Multiple types of disturbances have led to *legacy interactions*, and we will examine how temperature, snow, and vegetation age interact to affect tree mortality due to snowdown events (e.g., a forest disturbance resulting from an unusually wet, heavy snowfall which led to extensive uprooting and snapping of trees) (3.4.1, 3.5.2). We will also explore the consequences of disturbance for streamflow (3.4.2) and carbon storage (3.4.3). Finally, we will explore the effect of microclimate on tree physiology, mortality, and ecosystem carbon and nutrient dynamics (3.5.1, 3.5.2).

GOAL 2. TO UNDERSTAND HOW SPECIES INTERACTIONS INFLUENCE POPULATION AND COMMUNITY RESPONSES TO ENVIRONMENTAL CHANGE.

The study of biotic interactions has a long, rich history in population ecology (Volterra 1926), community ecology (Paine 1966), and ecosystem science (Ripple et al. 2016); however, these interrelationships are not well represented in efforts to understand or predict ecological responses to climate change (Elith and Leathwick 2009, Urban et al. 2016). Most work has assumed species will respond individualistically to the physical aspects of climate and habitat change (Grether et al. 2017), despite a substantial body of theoretical and empirical work suggesting otherwise (e.g., niche theory, Hutchinson 1957, Colwell and Rangel 2009). Biotic interactions may change as physical conditions change. For example, pollination network structure varies with fragmentation (Aizen et al. 2012, Jones et al. 2018), competitive interactions among birds reverse across an elevational gradient (Jankowski et al. 2010), and trophic interactions depend upon management intensity (Tylianakis et al. 2007, Kortsch et al. 2010).

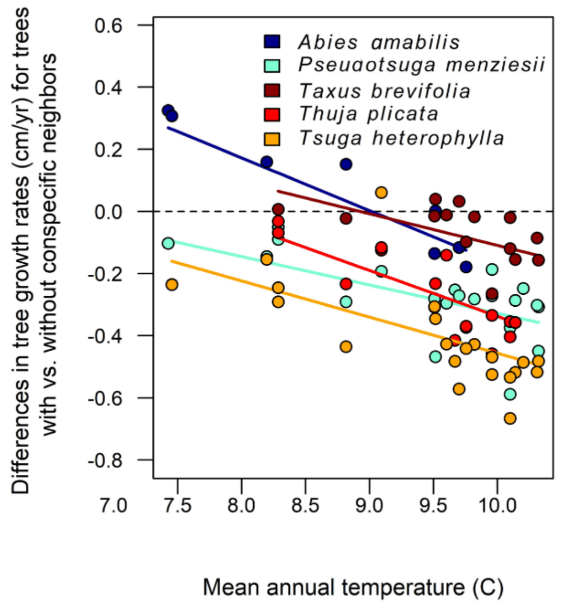


Figure 9. Greater negative effects of conspecific neighbors on individual tree growth at warm vs. cool long-term vegetation plots at the Andrews Forest for five, common, widely-distributed species, implying that climate may mediate conspecific negative density dependence in plants.

Long-term data from the Andrews Forest indicate that species interactions could strongly mediate biotic responses to climate change. For example, the negative influence of parasitic plants on tree growth and mortality is particularly severe in warm and dry years (*species interaction*, Bell et al. 2020). The processes governing tree diversity in long-term vegetation plots (density dependence) are stronger in warmer sites (*species interaction*, Fig. 9, LaManna et al. 2017). A 20-year decline in average adult body size for both trout and Pacific giant salamander might be attributed to increased interspecific competition with warming climate (*species interaction*, Fig. 4-d, Arismendi et al. in review). For some forest bird species, occupancy declines in warm locations when interspecific competitors are present, but temperature is less limiting when competitors are absent (*species interaction*, Fig. 4-e). The timing and diversity of plant-pollinator interactions depend on temperature and soil moisture (*species interaction*, Fig. 4-f, Young 2016).

In LTER8 we will build on these long-term observations highlighting the importance of species interactions in mediating climatic effects on biodiversity (3.4.5). We will evaluate species interactions as a function of microclimate heterogeneity in the landscape (3.5.4.c) and the forest canopy (3.5.3, 3.5.4.b), and conduct a drought simulation experiment in streams (3.5.4.d). We will use models and a multi-taxa reciprocal transplant experiment (3.5.4.) to test the overall hypothesis that competition and facilitation mediate the effects of climate on species distributions and abundance.

GOAL 3. TO EVALUATE HOW INTERACTIONS OF SCIENCE, VALUES, AND ECOLOGICAL CONDITIONS INFLUENCE LAND-USE DECISIONS.

Land-use decisions are influenced by and also affect ecosystem structure and function (Nightingale 2003, Turner and Robbins 2008, Ekbia and Evans 2009, Cote and Nightingale 2011, Peters et al. 2011, Gaiser et al. 2020). Therefore, it is critical to understand decision-making processes because resulting management actions are social drivers of land use, which affects ecological patterns and processes. Andrews Forest research was central to the Northwest Forest Plan, a regional conservation strategy affecting ~10 million hectares of federal forestland (Spies et al. 2019). However, conflicts in social values, often expressed through litigation, have led actual land-use practices to deviate from policy (Harris 2018, Gosnell et al. in press). To enhance our understanding of the science-management interface (e.g., Haynes et al. 2001, Littell et al. 2012, McKinley et al. 2012, Ryan et al. 2018), additional research is needed on the value basis of forest management. The Andrews Forest LTER program conceptualizes land-use decisions as practical prescriptions, which are reached by combining factual or scientific information with value judgments (Batavia 2015, Batavia and Nelson 2016, 2017, 2018, 2019). In LTER8 we build on this conceptual foundation. Using philosophical and social scientific methods, we seek to understand how and why value judgments interact with science to inform forest land-use decisions (3.5.5), which in turn affect the ecology of the landscape.

3.2 Site Description

The Andrews Forest is located in the Willamette National Forest in Oregon, on the west slope of the Cascade Mountains. The 6400-ha site is the watershed of Lookout Creek (Fig. 1), which ranges in elevation from 400 m to over 1600 m elevation. The watershed is mountainous, with steep slopes and deep, V-shaped valleys with high-gradient streams. The site lies within the temperate wet forest biome. The summer is dry and warm; precipitation is concentrated in the fall, winter, and spring—dominantly as rain at low elevations but as snow at high elevations. Historically, vegetation cover on the Andrews Forest reflected topographic patterns and fire-dominated disturbance history, with native conifer forests ranging in age from 120 to 500 years, and a network of small meadows and shrub fields on higher elevation ridges (Fig. 4, Fig. 5). Low- and mid-elevation forests in this region are dominated by Douglas-fir and western hemlock and can store more than 600 Mg of carbon per hectare (Harmon et al. 1990). Timber harvest from the 1950s through early 1980s created second-growth forests that cover 25% of the Andrews Forest. Harvest legacies along with other forest disturbances (e.g., snow and windstorms) contribute to current vegetation patterns at the site.

3.3 General Approach

Research in LTER8 explores new questions within our central question and conceptual framework—especially involving climate and biodiversity (Fig. 3). Our research plan integrates our ongoing long-term studies (3.4), and addresses the five LTER core areas (Table 1). Long-term measurements, experiments, process-based modeling, and analyses generate hypotheses to guide new studies, which synthesize multiple components and employ manipulative experiments to reveal potential mechanisms behind long-term patterns (3.5).

Our research will help refine key ecological concepts about abiotic and biotic responses to environmental variation (e.g., the niche, vegetation zones, microclimate refugia, patch dynamics). We can examine patterns and processes at increasingly fine spatial- and temporal-scales using new research tools, including: high resolution imagery of the forest canopy and landscape (lidar); fine-spatial-scale, high-temporal-resolution data from distributed sensors; technologies for marking and following individuals over time; tracers to detect the movement of particles; and DNA sequencing of biological diversity. In addition, contemporary modeling approaches including machine learning methods (boosted regression trees, collaborative filtering) and statistical approaches (hierarchical Bayesian models) will enable us to develop models that could transfer our understanding of Andrews Forest microclimates to other forest mountain landscapes. Our research will also build on current understandings of science-based management by examining how ethical value judgments interact with scientific information to affect land-use decisions. Our findings will set the stage for future analyses, beyond LTER8, to project future biodiversity in forested mountain ecosystems under anticipated future climate and land-use conditions

3.4 Long-Term Studies: Measurements, Experiments, Models, and Analyses

Andrews Forest multi-decadal studies provide the foundation for testing ecological hypotheses and answering questions that emerge from changing biophysical and social contexts. Long-term data enable discoveries that could not have been anticipated when the studies began, nor could they be revealed by short-term empirical studies, analyses, and experiments alone. Recent publications (including some by Andrews researchers) illustrate the importance of long-term studies (Hughes et al. 2017, Kominoski et al. 2018, Kuebbing et al. 2018, Nelson and Vucetich 2018, Vucetich et al. 2020). The Andrews Forest is a

Table 1. Proposed activities in LTER8 (columns) and their relationship (shown by x's) to the Andrews Forest LTER program and key elements of the NSF LTER program (rows). Columns on the left show ongoing long-term studies, and columns on the right show integrated and new studies in LTER8. The first and second sets of rows contain elements of the conceptual framework, which endures throughout multiple LTER cycles, and the theme for LTER8. The third set of rows shows how proposed activities are related to the various research methods employed in LTER. The fourth and fifth sets of rows show how proposed activities are related to the core areas of the NSF LTER program, and how proposed activities address various levels of ecological organization.

	Project Title	Disturbance and Land Use	Hydrology	Carbon and Nutrients	Climate	Biodiversity	Forest canopy physiology	Disturbance legacies & tree mortality	Species and canopy microclimate	Biodiversity & microclimate experiments	Conservation ethics
	Proposal section	3.4.1	3.4.2	3.4.3	3.4.4	3.4.5	3.5.1	3.5.2	3.5.3	3.5.4	3.5.5
Andrews Forest conceptual framework and central question	Disturbance	**x**			x	x		x		x	
	Landuse	**x**	x		x	x		x		x	x
	Hydrology		**x**	x	x	x			x	x	
	Carbon & Nutrients	x	x	**x**			x	x			
	Climate		x		**x**	x	x	x	x	x	
	Biodiversity				x	**x**	x		x	x	x
Andrews Forest LTER8 theme: interactions	a) Biotic modulation interactions		x		x					x	
	b) Legacy interactions	x		x		x	x	x	x	x	
	c) Species interactions					x				x	
	d) Science-values interactions	x									x
Research methods	Observation	x	x		x	x	x	x	x		x
	Experiment		x	x						x	x
	Modeling	x	x	x	x	x	x	x	x		
	Analysis of long-term data	x	x	x	x	x		x	x		
	Integrated/New Study (LTER8)						x	x	x	x	x
	Continuing study (many LTER cycles)	x	x	x	x	x					
LTER Five Core Areas	Primary Production	x		x		x	x	x			
	Population Studies	x				x	x	x	x	x	
	Organic Matter		x	x				x	x		
	Inorganic cycles		x	x	x				x		
	Disturbance	x			x	x		x	x	x	x
Level of organization	Population				x	x	x	x	x	x	
	Community					x	x		x	x	
	Ecosystem	x		x		x	x	x	x		
	Landscape	x	x	x	x			x	x	x	x
	Social-ecological	x		x				x			x

key source of co-located, long-term observations of major ecosystem components in our region, and our reference watersheds continue to be sentinels for the detection of environmental change in national and international comparisons (e.g., Argerich et al. 2013, Lajtha and Jones 2013, Creed et al. 2019). Many of our studies are just now sufficiently long to enable analyses that separate multi-decadal variability from long-term trends (Fig. 4). An additional six years of data will increase temporal replicates and statistical power, and our sites will likely experience additional extreme years, enabling us to test how interactions differ under varying climate conditions. Here, in section 3.4, we describe ongoing long-term studies and associated emerging questions and new analyses. In the next section, 3.5, we describe new studies that draw from and integrate across our long-term studies.

3.4.1. NATURAL DISTURBANCE AND LAND USE

Long-term research at the Andrews Forest examines the dynamics and drivers of natural disturbance, particularly legacies of past wildfire (>100 years ago; Fig. 4-a) and land use, including clearcutting of old-growth forest 30 to 70 years ago and more recent thinning of second-growth forests. Ongoing long-term studies examine many processes, including forest succession following disturbance (Lutz and Halpern 2006, Seidl et al. 2014, Tepley et al. 2014); edge effects of past timber harvesting (Chen et al. 1992, 1999, Bell et al. 2017); flooding and debris flow influences on stream channels (Swanson et al. 1998, Johnson et al. 2000); and disturbance legacy effects on carbon and nutrients (Kranabetter et al. 2016, Lee and Lajtha 2016, Lajtha and Jones 2018) as well as populations and communities (Dodds et al. 2012, Frey et al. 2016a, Warren et al. 2017). Research on disturbance considers measurable drivers, mechanisms, system properties, and human dimensions (Peters et al. 2011, Gaiser et al. 2020).

In LTER8 we will continue long-term measurements relevant to understanding how disturbance and land-use legacies interact with climate, landform, topography, and soils (*legacy interactions*, Goal 1), adding to 40 years of forest vegetation, stream flow, and stream chemistry data (Fig. 1), as well as high-resolution remote sensing data. We will examine how past disturbance (harvesting and fire) and recent disturbance (drought and snowdown) interact with landforms and climate to affect forest productivity (Fig. 6). We will quantify how biotic factors replace abiotic factors as major controls on forest dynamics throughout forest ecosystem succession (Harmon and Pabst 2015). We will use statistical models to quantify how stand age, topographic exposure, and soil characteristics influence disturbance effects on forests, which in turn affect microclimate (3.4.4), and the consequences of these changes for streamflow (3.4.2), carbon and nutrient cycling (3.4.3), and land-use decisions (Goal 3).

3.4.2. HYDROLOGY

Long-term hydrology studies at the Andrews Forest consist of 10 instrumented watersheds and three paired watershed experiments, initiated between the 1950s and the 1970s (Fig. 1), and augmented by mechanistic studies using tracers, sapflow sensors, and wells. Ongoing experiments examine many topics, including how disturbance and land use affect water yield (Rothacher 1970, Jones and Post 2004), peak flows (Jones and Grant 1996), low flows (Perry and Jones 2017), biogeochemical cycles (Argerich et al. 2013), stream temperature (Arismendi et al. 2012), and aquatic communities (Dodds et al. 2012). Andrews Forest hydrology research develops and tests concepts including ecohydrological separation (Brooks et al. 2010), transit time (Segura et al. 2019), and hyporheic exchange (Ward et al. 2019).

In LTER8 hydrology research will examine how climate stress, vegetation, and hydrologic flowpaths influence streamflow (Goal 1). We will continue to measure streamflow, stream temperature, and specific conductivity at 10 stream gages; snow lysimeters at four benchmark climate stations; and snow depth across the landscape (Fig. 1). We will investigate how declining snowpack and reduced soil water availability interact with vegetation water uptake to affect streamflow and aquatic habitats (*biotic modulation interaction*). We will fit autoregressive and machine learning models (e.g., Mosavi et al. 2018) to quantify how vegetation (since 1962), phenology (since 2009), snowpack (since 1994), precipitation and air temperature (since 1957), and transpiration (e.g., Moore et al. 2004) influence summer streamflow (since 1949), which in turn influences carbon and nutrients (3.4.3) and aquatic biodiversity (3.4.5).

3.4.3. CARBON AND NUTRIENTS

The Andrews Forest is known for old forests with massive C stocks, low nitrogen (N) inputs, and high retention of N. Long-term studies include a 200-year log decomposition study, precipitation and streamflow chemistry measurements since the 1960s, and three paired-watershed experiments (Fig. 1).

Ongoing studies examine topics including the ecological functions of dead wood (Harmon et al. 1986); C loss from clearcutting old-growth forest (Harmon et al. 1990, Cohen et al. 1996); forest management effects on global C budgets (Pacala et al. 2001, Kline et al. 2016, Spies et al. 2019); watershed C export (Argerich et al. 2016, Lajtha and Jones 2018); and N retention in forest and stream ecosystems (Sollins et al. 1980, Ashkenas et al. 2004, Sobota et al. 2012, Perakis et al. 2015, Tank et al. 2018).

In LTER8 carbon and nutrient research will contribute to understanding of how climate stress may alter C storage and N cycling in forest ecosystems (Fig.6) (Goal 1). We will conduct the 40-yr sampling of the log decomposition experiment (Harmon 1992), which we expect will reveal accelerated volume loss and changing carbon and nutrient chemistry of decomposing logs; diverging heartwood decay rates among species; and whether the heartwood of western red cedar, projected to endure for up to 3,000 years, has become colonized by decomposers. We will parameterize the Ecosystem Demography Model 2 (ED2, Xu et al. 2016, Jiang et al. 2019), to test how future increased drought and higher temperatures will interact to affect ecosystem C storage in old-growth vs. second-growth forest (*legacy interaction*). We will extend prior watershed models (Abdelnour et al. 2011, 2013) to test theoretical predictions (e.g., Vitousek and Reiners 1975, Hedin et al. 1995, Lajtha 2019) about how forest succession, N-fixation in logs, plants, and epiphytes, and dead and down wood influence observed watershed N retention and export (since 1963) (*legacy interaction*). These studies draw on disturbance (3.4.1), hydrology (3.4.2), and climate (3.4.4), and have implications for biodiversity (3.4.5).

3.4.4. CLIMATE

Andrews Forest climate research examines how the local climate is structured across multiple spatial scales by factors including forest structure, relief, elevation, regional climate, and global climate. Air and precipitation measurements were established in the 1950s in conjunction with small watershed studies, and under-story temperature measurements began in vegetation plots in 1970 (Fig. 1, Fig. 2). Distributed snow measurements began in 1978, and four benchmark meteorological stations were established in the 1990s to measure radiation, air and soil temperature, precipitation, snow, and wind. Distributed under-canopy temperature sensors were established to measure air drainage in 2001, and to capture landscape-wide variation in 2009. Collectively, these studies allow us to produce fine-resolution (10-100m grid cell) spatial models of microclimate and connect regional models of climate change to environmental variability at the scales relevant to ecological interactions (e.g., Daly et al. 2010, Sproles et al. 2013, Frey et al. 2016b, Rupp et al. 2017) (Fig. 5-g,h).

Ongoing climate studies examine topics such as climate warming, air drainage, and forest canopy effects, which motivate key questions in LTER8. For example, although many U.S. regions report the greatest long-term warming at night and during winter (U.S. Global Change Research Program 2018), our long-term records of air temperature under the forest canopy document substantial warming on summer days (0.3 to 0.6°C/decade) but little warming during summer nights or during days or nights in fall, winter, and spring since 1970 (Jones et al. in review). Landform and vegetation shading and air drainage flows episodically decouple the forest microclimate from the regional climate (Daly et al. 2010, Rupp et al. in review). Old-growth forest understories can be as much as 2.5°C cooler during the summer than 40-60-yr-old planted forests (Frey et al. 2016b). Daytime air temperature is as much as 12°C warmer, relative humidity is lower, and wind speed is higher at the top of the canopy compared to the understory (Fig. 7).

Andrews Forest climate research contributes to efforts to move beyond coarse-scale climate predictions and simplified conceptual models of mountain environments in order to accurately predict species and ecosystem response to climate change. Our research tests how biotic factors modify local abiotic conditions (Lenoir et al. 2017, Davis et al. 2019). We are expanding substantially on the classic concept of elevation zones (Rahbek et al. 2019) by integrating understanding of the abiotic-biotic interactions and feedbacks that produce microclimate patterns with implications for the concept of microclimate refugia (Zellweger et al. 2019, Jones et al. in review).

In LTER8 we will continue long-term climate measurements (Fig. 1) and modeling developed in previous cycles to examine how forest structure, landforms, and air drainage interact with the changing regional climate to drive fine-scale environmental conditions in response to climate warming (Goal 1). We examine *legacy interactions* by quantifying vertical microclimate in old-growth conifer and second-growth conifer forest canopies (3.5.3.b). To examine *biotic modulation interactions*, we link long-term climate records with machine-learning models (e.g., Wolf et al. in review) to test how forest canopy and topography modulate the influence of regional climate on microclimate (focusing on air temperature and snow). We will also link these landscape models to projections from regional climate models (e.g., Rupp et al. 2017). Ongoing climate studies will be used as a foundation to explore how tree physiology (3.5.1) and disturbance (3.5.2) respond to climate extremes, and in turn how ecophysiology affects hydrology (3.4.2). Climate data will be correlated to long-term patterns of biodiversity (Section 3.4.5).

3.4.5. BIODIVERSITY

Long-term biodiversity research at the Andrews Forest contributes to understanding of how key organisms, populations, and communities respond to environmental change.

Terrestrial Vegetation. Multiple networks of forest inventory plots (140 sites, mostly initiated 40 to 110 years ago, with 45 at the Andrews Forest; Fig. 1) provide repeated measurements of individual trees in second-growth and old-growth forests. These vegetation studies document species composition and tree growth, mortality, and recruitment, revealing forest succession at ecologically relevant scales (decades to centuries). Ongoing studies examine many topics, including old-growth forests (Franklin et al. 1981, Franklin and Spies 1991), forest succession (e.g., Lutz and Halpern 2006, Halpern and Lutz 2013, Harmon and Pabst 2015, Cook and Halpern 2018), and tree recruitment, growth, and mortality (e.g., Gray et al. 2012, Larson et al. 2015). Our long-term vegetation data were used as evidence for regional increases in tree mortality in recent decades (van Mantgem et al. 2009), but at 14 of those plots, individual old-growth tree productivity (from tree ring analysis) was not consistently related with interannual climatic variation at nearby meteorological stations (Woolley et al. 2015).

In LTER8 we will address Goal 2 using continued long-term vegetation measurements throughout the region (Fig. 1). First, we will examine how interactions between previous disturbances and microclimate (Fig. 5, Fig. 7) influence tree growth responses (*legacy interaction*). Second, we will examine how interactions between tree species as well as with their pests and pathogens may alter tree growth responses to climate (*species interaction*, Ford et al. 2017, Bell et al. 2020, Fig. 6). Finally, we will test how differences in microclimate have influenced density dependent effects on tree growth and survival over the last 40 years. These studies lay a foundation for integrated and new studies of tree mortality (3.5.2) and interactions between plant microbiomes, tree seedlings, and microclimate (3.5.3.b, 3.5.4.a).

Birds. Birds have been sampled multiple times per year during the breeding season (May–June) since 2009 at 184 sites distributed across the Andrews Forest (Fig. 1). More than 50 species of forest birds breed in the Andrews Forest. Previous work during LTER7 on bird populations revealed that species distributions and movement dynamics appear to be strongly influenced by microclimate, independent of the effects of vegetation composition (Frey et al. 2016a). Theory predicts that the niche is also strongly influenced by competitive interactions among species (Hutchinson 1957), but few species distribution models take such species interactions into account (Urban et al. 2016). Indeed, analysis of our 10-year dataset reveals recent asynchrony in the population trajectories of several bird species—even those utilizing similar habitats and strata within the forest canopy (Fig. 4-e). Our preliminary data show that the occupancy of one species is not only dependent on microclimate, but these microclimate effects strengthen or weaken depending on the presence of a potential competitor species (*species interaction*).

In LTER8 we will continue long-term breeding-season surveys of forest birds (Goal 2). We will use multi-species dynamic occupancy and N-mixture models (MacKenzie et al. 2003, Dail and Madsen 2011) to address two questions: (1) To what extent do interspecific competitors influence the spatial distribution and abundance of forest birds? (2) Is competitive dominance mediated by microclimate? (*species interaction*). We will focus on species pairs that we hypothesize should interact competitively based on their phylogeny and their foraging habits (e.g., black-headed grosbeak–western tanager, black-throated gray warbler–hermit warbler, Swainson's thrush–hermit thrush). This work draws on long-term distributed under-canopy climate data (3.4.4) and motivates new experimental manipulations of bird species distributions to test the degree to which *species interactions* are mediated by microclimate (3.5.4).

Fish and Salamanders. Populations of native cutthroat trout (*Oncorhyncus clarkii)* and coastal giant salamanders (*Dicamptodon tenebrosus*) have been surveyed annually in three old-growth and three second-growth forested reaches of Mack Creek since the 1980s (Fig. 1). We capture approximately 1,300 individuals each year (50% trout and 50% salamanders), and have measured a total of 33,000 vertebrates since 1987. Each year, beginning in 2002, approximately 500 adult trout and salamanders are individually marked using Passive Integrated Transponder (PIT) tags before release; recapture rates the following year average 15%. These long-term studies examine forest-stream interactions and individual, population, and community responses to climate, natural disturbance, and land use. Early studies documented how clearcutting of old-growth forest altered habitat, food resources, and light (Murphy and Hall 1981, Hawkins et al. 1982), producing short-term increases in fish population densities and fitness. More recent studies show that population densities and fitness levels return to pre-harvest levels as the forest regrows (Bisson et al. 1992, Kaylor and Warren 2018). However, recently Arismendi et al. (in review) have observed a long-term trend of decreasing average adult body size for cutthroat trout and salamanders in both old-growth and second-growth reaches (Fig. 4-d). In LTER8 we aim to uncover potential drivers of these trends.

In LTER8 we will continue annual sampling to quantify sizes, abundances, and associated microhabitat preferences of trout and salamanders. Using individual (PIT) and population-level data, we will examine whether annual individual relative growth rates and distribution of trout and salamanders can be predicted by previous streamflow, snowmelt timing, water temperature, and microhabitat availability (Goal 1). We will apply an individual-based trout model (inSTREAM, Penaluna et al. 2015) to explore how climate stress and temperature changes influence metabolism, growth, and energy expenditure (McCullough et al. 2009), and how changes in size distributions may alter competitive species interactions such as aggression and predation (Peters 1983) (*species interaction*, Goal 2). We will parameterize inSTREAM with existing long-term data from Mack Creek including air and stream temperature (since 1987), snow (since 1994), streamflow (since 1979), and trout and salamander demography from Mack Creek (since 1987) and multiple locations in the Andrews Forest (sampled since 2013). These analyses will build on hydrology data (3.4.2) and climate data (3.4.4) and guide new experiments directed toward testing whether species interactions are influenced by stream temperature and flow (3.5.4.d).

Pollination Networks. Plant-pollinator networks were sampled five times per summer from 2011 to 2018 at 12 montane meadows in the Andrews Forest, revealing >700 pollinator and >150 flowering plant species with high spatial and temporal turnover. Ongoing studies of these data examine topics including within-season changes in plant and pollinator diversity (Pfeiffer 2012), network structure and modularity (Helderop 2015), climate effects on timing of peak flower abundance and peak plant-pollinator interactions (Young 2016), and how meadow dissimilarity is related to soil moisture (Jones et al. 2018). Plant-pollinator networks in our system are characterized by the high turnover rates of plant-pollinator pairings over time (CaraDonna et al. 2017), which highlights considerable generalism and 'interaction rewiring' over the long term. Nevertheless, we have also observed nested structures, which are thought to promote high diversity (Bascompte et al. 2003). Over eight years, we observed changes in network connectivity and the abundances of pollinator and flowering plant species, and this connectivity varies with moisture and temperature (Fig. 4-f). Changes in temperature and moisture over time and differences among meadows may produce complementary activity periods among pollinator and flowering plant species (Bartomeus et al. 2013, Ogilvie and Forrest 2017), and specialists and native bee species may be the most sensitive to these changes (Burkle et al. 2013).

In LTER8 we will analyze our plant-pollinator data to test how shifting snowmelt and changing air temperature influence the structure of plant-pollinator networks in montane meadows that represent varying degrees of fragmentation due to conifer encroachment (*legacy interaction*, Goal 1). We will also examine how interactions among solitary bees, native bumblebees, and other groups mediate responses to climate variability (*species interaction*, Goal 2). Building on our existing machine learning models, such as latent factor models with implicit feedback (Seo and Hutchinson 2018), we will characterize mechanisms underlying plant-pollinator interactions and predict how changing climate will affect flower timing and pollinator visits. These analyses draw on long-term climate data (3.4.4).

Plant Phenology. Phenology plays a crucial role in species responses to climate variability and change (Urban et al. 2016), with implications for primary productivity and species interactions within and across trophic levels. Plant phenology has been measured since 2009 at 16 sites distributed across the Andrews Forest as part of a multi-taxa study of forest organism response to spatially-complex and temporally-dynamic microclimate (Fig. 1). We have been able to accurately model phenology of common tree and understory species based on local air temperatures and snowmelt, demonstrating that plant phenology is driven by microclimate conditions, but at different periods in the annual cycle than animals (Frey et al.

2016a, Ward et al. 2018b, Schmidt 2019). Winter snowpack and frequency of temperature inversions result in considerable spatial heterogeneity in the timing of the initiation of the growing season (Ladwig et al. 2016). This, in turn, affects resource availability for forest animals such as songbirds.

In LTER8 we ask, how does landscape variability in microclimate influence spatial heterogeneity and temporal consistency of growing season initiation and length? We will combine spatial statistical models of temperature and snow (*biotic modulation interaction*, Goal 1, Fig. 1) with models of plant phenology response to environmental forcing (Ward 2018) to develop landscape models that predict phenology of major tree and shrub species. We will also explore how year-to-year variability in landscape heterogeneity of plant phenology is related to songbird occupancy and species interactions (Goal 2). This work draws upon long-term hydrology (3.4.2) and climate (3.4.4) data.

3.5. New Integrated Studies, Analyses, and Experiments

New studies in LTER8 cut across multiple components of our ongoing long-term measurements (3.4) and the components of our conceptual framework. Our new studies explore questions emerging from long-term inquiry and include manipulative experiments to reveal mechanisms underlying long-term patterns. New studies also provide opportunities to engage new researchers and form novel collaborations.

New studies in LTER8 will contribute understanding of how climate stress effects may propagate across levels of ecological organization. We anticipate that climate stress may alter tree canopy physiology (3.5.1), with cascading consequences for disturbance susceptibility, mortality, and forest productivity (3.5.2). These changes may alter seed production cycles and affect communities of mammals and top predators (e.g., owls), but tree canopy microbiomes also may help trees adjust to change (3.5.3). Microclimate patterns provide the opportunity for mechanistic experiments to elucidate *species interactions* that may foreshadow responses to future climate stress (3.5.4), which in turn intensifies the need to understand how values and science will interact to inform land-use decisions (3.5.5).

3.5.1. CANOPY PHYSIOLOGICAL AND GROWTH RESPONSES TO HEAT AND MOISTURE STRESS

PIs: Chris Still, John Kim, Lucas Silva, Mark Schulze

Question: How will increasing heat and moisture stress influence plant productivity?

Rationale: Trees modify microclimate (Fig. 7), buffering other organisms from environmental change (Lenoir et al. 2017, Betts et al. 2018), but they bear the brunt of heat and moisture stress (Heffernan 2017, Dong et al. 2019). Atmospheric vapor pressure deficit (VPD) is projected to increase with climate change, along with its relative contribution to plant moisture stress, growth dynamics, and mortality (Novick et al. 2016, Choat et al. 2018, Yuan et al. 2019). Atmospheric constraints on productivity may play a particularly large role in Pacific Northwest forests, where tree access to deep soil moisture will influence atmospheric heat and moisture stress on the canopy (Jiang et al. 2019). Lengthening of the growing season, increased water use efficiency from CO_2 enrichment, and carbon assimilation outside of the active growing season may mitigate or compensate for increased summer water and heat stress (Emmingham and Waring 1977, Barnard et al. 2018, Sperry et al. 2019). The net effect of these mechanisms may have profound effects on forest productivity and structure, with both direct and indirect effects on ecosystem processes and forest microclimates. Differences in heat and moisture extremes with forest structure and individual canopy position, in water use efficiency and soil water access by tree age and species, and in microclimate regime by topographic position may result in variability of response within and among forest stands (Moore et al. 2004, Winner et al. 2004, Daly et al. 2010, Heffernan 2017).

Prediction: Increasing summer heat and VPD stress will constrain primary productivity despite lengthening of the growing season, with greater impact in second-growth forest and on mid-story individuals of shade-tolerant species in old growth (*legacy interaction,* Goal 1).

Methods: This project builds upon analyses using long-term climate and phenology records to quantify relationships between regional climate, microclimate variability, growing season length, and environmental extremes experienced within the forest canopy (Fig. 5, Fig. 7). We will explore the implications of these patterns for productivity and stress with 1) new measurements at paired second-growth and old-growth sites spanning a range of topographic contexts and with co-located long-term records (vertically instrumented trees and long-term vegetation, microclimate, and phenology plots), and

2) an ecosystem modeling framework. We will add measurements of canopy and understory VPD and soil moisture to complement long-term air and soil temperature records. We will examine responses of predominant tree species at each site across size classes and a range of temperature, VPD, and soil moisture conditions, using established methods (Johnson et al. 2009, Scherrer et al. 2011, Kim et al. 2018, Still et al. 2019) to take targeted measurements of sap flow, stomatal conductance, water potential, and canopy thermal IR patterns. These relationships will inform analysis of how temperature and moisture stress affect long-term records of within- and among-year growth patterns from dendrometer bands (3.4.4), tree ring analyses (Silva and Horwath 2013, Castruita-Esparza et al. 2019), and vegetation plots (3.4.5). We will model forest response to increasing stress across the Andrews Forest, as predicted by climate models, using local parameterization of the Ecosystem Demography 2 (ED2) model, including a hydraulics sub-model, which has been parameterized for a similar old-growth forest at the Wind River Experimental Forest and NEON core site (Jiang et al. 2019). This study will provide a model comparison to Dong et al. (2019) to test how below-ground moisture limitation and canopy stress interact with disturbance legacies to constrain the response of primary productivity and forest dynamics to increasingly dry summers. This project will contribute to the study of disturbance and tree mortality patterns (3.5.2).

3.5.2. DISTURBANCE LEGACIES, CLIMATE, AND TREE MORTALITY

PIs: David Bell, Meg Krawchuk, David Shaw

Question: How do past disturbances and land-use legacies interact with abiotic conditions to influence spatial patterns of tree mortality?

Rationale: Multidecadal studies at the Andrews Forest and elsewhere highlight increases in tree mortality rates in western North America (van Mantgem et al. 2009, Harmon and Pabst 2015). Many agents contribute to tree mortality throughout forest succession (Franklin et al. 1987, 2002, Tepley et al. 2013, Reilly and Spies 2015), and each agent may respond differently to climate change. Examples include enhanced tree mortality due to the interaction between hot and dry conditions and dwarf mistletoe infection (Bell et al. 2020), or drought reducing the capacity of some vegetation or topographic conditions to support fire refugia (Meddens et al. 2018). In addition, the combined effects of past disturbance legacies and subsequent disturbances can produce unexpected ecological consequences (Nakamura et al. 2000, Buma 2015), especially if changes in disturbance regimes drive synergistic effects on ecosystems (Turner 2010). Andrews Forest research indicates that disturbance legacies influence ecosystem patterns and processes for decades to centuries, including carbon stocks and forest structure (Seidl et al. 2014, Zald et al. 2016, Bell et al. 2017), dissolved organic matter (DOM) export (Lee and Lajtha 2016, Lajtha and Jones 2018), stream productivity and function (Warren et al. 2016, 2017), and forest birds (Frey et al. 2016a). To identify forest vulnerability to tree mortality from anticipated climate change (Allen et al. 2015a), we need to determine how disturbance and land-use legacies alter the influence of abiotic factors (climate, topography) on tree mortality associated with various agents, including snowdown, drought, fire, insects, and disease (Goal 1).

Predictions: Because past disturbances influence forest structure and composition, we expect disturbance legacies and abiotic (climate and topography) conditions will synergistically influence tree mortality rates by altering the sensitivity to and prevalence of differing mortality agents (*legacy interaction*, Goal 1).

Methods: We will leverage existing and continued (1) repeat lidar acquisitions (four at the Andrews Forest in 2008, 2014, 2016, and 2020), (2) multispectral remote sensing from the Landsat program (1984-present for all lands), and (3) long-term tree measurements for the Andrews Forest and surrounding regions (0.5-5.6 ha plots; n=140) to determine how disturbance legacies, topographic position, and climate influence spatiotemporal variation in tree mortality and disturbance at multiple scales (Fig. 6). Within the Andrews Forest, we will exhaustively map tree mortality prior to and following recent disturbances (2015 drought, 2019 and 2020 snowdown) based on lidar remote sensing and long-term tree data (Duncanson and Dubayah 2018). Across the western Cascade Mountains region, we will use an existing Landsat-based disturbance and vegetation mapping framework (Kennedy et al. 2018) to map disturbance (snowdown, recent fires, management regimes, and insect and disease attack) occurrence and forest biomass losses for all forestlands since 1985. Using both lidar- and satellite-based maps, we will develop statistical models to test whether tree mortality and disturbance are associated with pre-disturbance forest structure, topographic exposure, and land use (Zald et al. 2016, Bell et al. 2017). We will explore how the effects of disturbance agents on tree mortality magnitude and spatial patterns differ between second-growth and old-growth forests (*legacy interaction*). Using our long-term tree measurements, we will develop hierarchical Bayesian statistical models to predict mortality rates (trees/ha and biomass/ha) of differing mortality agents and tree species as a function of forest structure, species composition, climatic conditions, and topography or landform (e.g., Bell et al. 2015) to examine how past forest disturbances influence tree sensitivity to spatial and temporal variation in climate over 40 years (*legacy interaction*). This study will draw on new studies of physiology (3.5.1) and contribute to studies of species interactions in forest canopies (3.5.3).

3.5.3. SPECIES INTERACTIONS IN FOREST CANOPIES

Building on analyses of tree physiology and disturbance, we explore how canopy structure influences vertical microclimate in tall conifer forests (Goal 1); how climate stress may influence seed production and the organisms that depend on conifer seeds; and how the conifer needle microbiome may enable trees to withstand climate stress (Goal 2).

3.5.3.a. Climate, seed production, and northern spotted owls

PIs: Julia Jones, David Bell, Mark Schulze, Clint Epps, Damon Lesmeister, Matt Betts

Question: How do prior climate and cone production cycles influence predators in forested mountains?

Rationale: The food web of the northern spotted owl (*Strix occidentalis*), a threatened, old-growth-dependent species in the Pacific Northwest, includes small mammals and conifer seeds (Gashwiler 1959, 1967, Forsman et al. 2004, Smoluk 2011, Weldy 2018). Preliminary analyses of long-term records indicate that seed production of upper-elevation conifers experiences two- to three-year spatially synchronized cycles throughout the region. Spotted owl nesting success (Dugger 2018) is positively correlated with prior year seed production.

Prediction: Synchronous seed production may be driven by exogenous factors such as climate (Koenig et al. 2015). In turn, such synchronous cycles may cause bottom-up trophic cascades where populations of seed predators track synchronously with mast years (Liebhold et al. 2004).

Methods: We will fit stochastic antecedent models (Ogle et al. 2015) to test how prior climate influences cone production cycles and both factors influence predators (*species interaction*, Goal 2). We will conduct cross-wavelet analyses (e.g., Jennings and Jones 2015) of regional climate variables and cone counts (since 1962) (Fig. 1). We will examine cross-correlations among small mammals, invasive barred owls, and northern spotted owl nesting success (*species interaction*, Goal 2, Dugger et al. 2016, Dugger 2018). This study will draw on studies of canopy physiology (3.5.1) and disturbance and tree mortality (3.5.2).

3.5.3.b. Forest canopy and landform effects on the canopy microbiome

PIs: Julia Jones, Chris Still, Mark Schulze, Posy Busby

Questions: (1) How do temperature, light, and moisture vary across vertical space within old-growth forest? (2) How does canopy microclimate influence distributions and composition of the needle microbiome community (i.e., bacteria, fungi, and other microorganisms that live on and in plant tissues)?

Rationale: Forest canopies and landforms both influence the forest microclimate of old-growth forest (Jones et al. in review). The lower canopy of old-growth trees is frequently decoupled from the overlying air and experiences less variable temperature and moisture compared to the upper canopy (Fig. 7, McLaughlin et al. 2017, Davis et al. 2019). However, trees at high elevation may experience more within-tree variability (Daly et al. 2010). Early work at the Andrews Forest (Carroll and Carroll 1978) set the stage for studying the needle microbiome, its spatial distribution, and response to abiotic factors.

Prediction: Patterns of cold air drainage will favor drought and heat-tolerant microbiome communities in the upper canopy and at upper elevation, relative to the lower canopy and in the valley.

Methods: Using unique datasets of temperature and light measurements at 5- to 10-m intervals up to 50 m throughout eleven trees in the landscape (since 2011), data on air and soil temperature, light, wind, relative humidity, leaf wetness at 10-m intervals up to 56 m in the old-growth Discovery Tree since 2016 (Fig. 7), and DNA-sequence-based measurements of needle endophyte communities (e.g., Brown et al. 2018), we will examine the effects of tree species, age, height, and landform position on vertical canopy microclimate (*biotic modulation interaction*, Goal 1). We will use PERMANOVA (e.g., Anderson 2014) to predict needle endophyte species and community structure (e.g., richness) as a function of canopy air temperature and moisture, which vary with disturbance history (*legacy interaction*, Goal 2). This study will draw on studies of canopy physiology (3.5.1) and contribute to new experiments (3.5.4).

3.5.4. BIODIVERSITY AND MICROCLIMATE TRANSPLANT EXPERIMENTS

Our long-term tree, fish and salamander, and bird data (Fig. 4) suggest an important role of biotic interactions as drivers of species' populations. However, strong inference requires an experimental approach. We will therefore conduct a set of experiments involving reciprocal transplants and other manipulations (Fig. 10) to identify mechanisms that explain long-term relationships between climate and the biodiversity components of our conceptual framework. The experiments will test how the strength of species interactions are mediated by microclimate, but also how species' responses to microclimate may amplify or dampen as a function of interspecific interactions (Goal 2, Fig. 10). Importantly, the coordinated experiments (3.4.5.a, b, c, d) constitute a cross-taxa, synthetic effort to test hypotheses about differences between the fundamental niche (i.e., species are primarily driven by abiotic conditions) versus the realized niche (i.e., responses to abiotic conditions are strongly mediated by biotic interactions, particularly competition) (Hutchinson 1957). Terrestrial transplant experiments (trees, endophytes, birds, lichens) will be co-located across a stratified gradient in microclimate, where we are also quantifying under-canopy temperatures.

3.5.4.a. Plant microbiome interactions with host trees and microclimate

PIs: Posy Busby, Joseph LaManna

Question: How do interactions between trees and their microbiomes influence plant responses to microclimate?

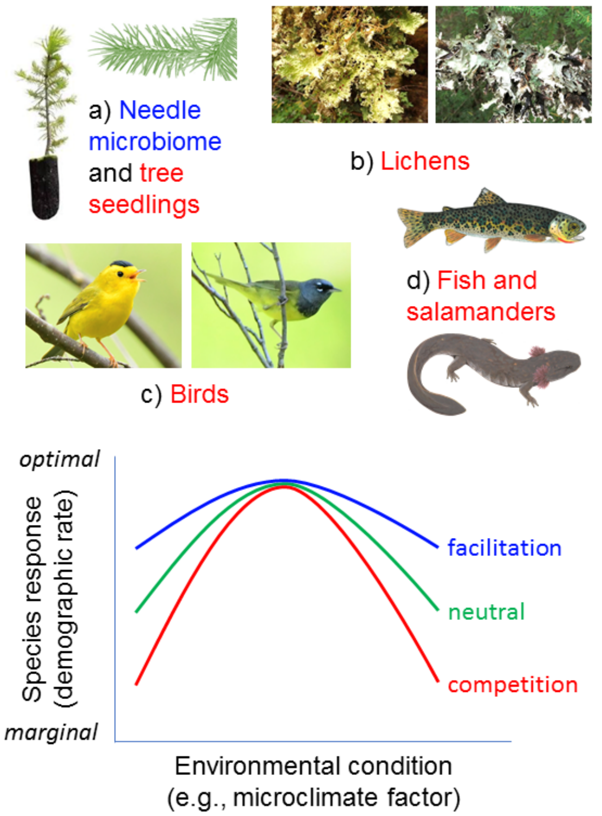


Figure 10. Biodiversity experiments will test how different types of species interactions increase or decrease demographic rates near optima versus margins of environmental conditions in (a) needle microbiome and tree seedlings, (b) lichens, (c) birds, and (d) fish and salamanders. (Drawing: A. Roshani)

Rationale: Microclimate may affect not only individual plant performance but also interactions among plants and interactions between plants and their associated microbes. Long-term Andrews Forest research has shown how light and moisture affect tree species regeneration (Gray and Spies 1997, Gray et al. 2012) and implied a declining role of density-dependent tree mortality as forests age (Larson et al. 2015). The plant microbiome—the diverse communities of bacteria, fungi, and other microorganisms that live on and in plant tissues—can be essential for a plant's ability to tolerate abiotic stress (Burgess and Dawson 2004, Busby et al. 2016) and interactions with other species (Mangan et al. 2010, Liu et al. 2015). Microbiome-host plant interactions may depend on microclimate (Karhu et al. 2014); hence, locations with particular temporal patterns of temperature and moisture may select for certain microbial communities and plant traits. Microclimate may cause endophytic (i.e., non-disease-causing) fungi to become pathogenic (i.e., disease-causing). Thus, plant microbiome, conspecific negative density dependence (CNDD), and interspecific competition interspecific competition may stabilize population and community responses to climate change. In particular, CNDD has been proposed as one of the key mechanisms that perpetuates species diversity in forest systems (Janzen 1970, Comita et al. 2014, LaManna et al. 2017). Long-term studies of tree demography and understory and canopy climate data at the Andrews Forest reveal that plant communities are strongly driven by microclimate (e.g., Zobel et al. 1976). However, the effect of CNDD is much stronger in warm than in cool microclimates (Fig. 9). Because the species interactions that drive CNDD can be unclear (e.g., plant-plant vs. pathogen-host), improved understanding of interactions between the plant microbiome and plant hosts, as well as competition among plants themselves, is crucial for predicting plant responses to climate change, and understanding the mechanisms that enable plant diversity to persist in forests (LaManna et al. 2017).

Hypotheses: (1) If microbes sourced from hot/dry microclimates are most protective or beneficial, tree seedlings with endophytes from hot/dry conditions will exhibit greater growth, photosynthesis, and survival, regardless of host. (2) Alternatively, locally sourced host-microbiome combinations will be most protective or beneficial. (3) Microbe sourcing effects will vary with proximity to conspecific adults, heterospecific seedlings, and microclimate.

Methods: We will conduct a reciprocal transplant experiment to test how plant-microbe interactions influence plant performance in a variety of microclimate settings (Fig. 10). Tree seedlings sourced from contrasting microclimate conditions will be inoculated with microbiome communities from contrasting microclimate conditions using established methods (Busby et al. 2016), and planted across the range of microclimate conditions in the Andrews Forest. Seedlings of three dominant tree species, Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) will be grown from seed and planted in various microclimate and light conditions determined from long-term temperature sensors, under different adult tree species, and with and without seedlings of different species. Seedlings will be inoculated with a local or foreign community, sourced from endophyte communities recently surveyed across the Andrews Forest landscape. We will track how seedling survival, growth, and photosynthetic activity respond to endophyte inoculation treatments, the foliar fungi (from ITS metabarcoding) on seedlings after several years, the presence of conspecific adults, and the presence of heterospecific seedlings. This experiment will determine whether the interaction between the needle microbiome and its host influences tree seedling performance (1) in varied microclimates and (2) with varied densities of neighbors of the same species and, if so, which host-microbiome combinations are most beneficial under stressful environments (*species interaction*, Goal 2). This work draws upon long-term climate data (3.4.4) and vegetation data (3.4.5)

3.5.4.b. Competitive interactions between lichen species in the forest canopy microclimate

PIs: Bruce McCune, Matt Betts

Questions: (1) To what extent does interspecific competition influence the growth and distribution of lichen species in old-growth forest canopies? (2) Does microclimate mediate competition?

Rationale: Epiphytic lichens are a dominant feature of the old-growth forest canopy, and they influence moisture, temperature, and habitat (McCune et al. 2003). N-fixation by the cyanolichen *Lobaria oregana* is crucial for nutrient cycles in conifer forests of the Pacific Northwest given the very low levels of atmospheric N deposition in the region (1.6 kg $ha^{-1}yr^{-1}$). Although *Lobaria oregana* dominates lichen biomass in old-growth forests in warmer areas and at lower levels of the canopy, it is nearly absent in cooler areas or in the upper canopy (McCune et al. 2003, Berryman and McCune 2006), while other genera, such as *Platismatia*, are more abundant in these locations. *Lobaria oregana* is a tripartite lichen with fungus, alga, and cyanobacteria; physiological functioning of the cyanobacteria requires liquid water (Lange et al. 1993). *Platismatia glauca* is a bipartite green algal lichen that does not require liquid water for net photosynthesis. At the Wind River Canopy Crane (NEON site paired with Andrews Forest), *Lobaria* transplants thrived in the upper canopy of old forests, despite very low natural occurrence at that canopy height, while *Platismatia* species were dominant in the upper canopy. Andrews Forest studies document strong variation in vertical air temperature and moisture with height in old forest canopies (Fig. 7). We will test whether lichen species response to canopy microclimate is primarily driven by abiotic conditions or biotic interactions (*species interaction*, Goal 2).

Hypotheses: (1) If distributions of *Lobaria* and *Platismatia* are constrained solely by microclimate, the growth and mortality of the two species will be similar when grown together versus separately. Alternatively, if competition is important, growth of one species will be reduced and mortality increased when they are grown together. (2) The superior competitor will vary depending on microclimate.

Methods: We will conduct a lichen transplant study (Fig. 10) following established methods (e.g., McCune et al. 1996, Sillett et al. 2000). We will transplant single species and mixtures of *Lobaria* and *Platismatia* in a full factorial design, using silicone sealer to attach lichens to a single point on gridded cotton fabric stretched on 15 cm diameter frames, a method that has been used successfully for a two-year period using *Parmelia sulcata*, another foliose species. The frames will be suspended in shaded portions of the canopy of old trees in various locations with differing microclimate conditions as indicated by long-term records of vertical air temperature (e.g., Fig. 5, Fig. 7). Survival rates and changes in lichen cover (of each species) will be evaluated photographically over several years. This study draws on long-term climate data (3.4.5), vegetation data (3.4.5), and carbon and nutrient data (3.4.3)

3.5.4.c. Forest bird species interactions in the forest sub-canopy microclimate

PI: Matt Betts

Questions: (1) To what extent do interspecific competitors influence the spatial distribution and abundance of forest birds? (2) Does microclimate mediate competition?

Rationale: Long-term studies of forest birds at the Andrews Forest reveal a high degree of dynamism in distributions both within the breeding season, and across the 11-year time series (Frey et al. 2016a). Preliminary correlative results indicate that the presence (occupancy) of a bird species at a site depends on the presence or absence of other species, and these competitive dynamics appear to be mediated by microclimate (Fig. 4-e). Improved understanding of how bird species interact with one another and with microclimate is essential for predicting forest bird responses to changing climate.

Hypotheses: (1) If competition influences bird distributions, and species B is the dominant competitor, experimental attraction of species B to a site should cause species A to vacate the site. (2) If microclimate mediates competitive interactions, the supplanting effect of experimentally attracting species B will vary across a range of microclimate conditions.

Methods: We will conduct an experimental playback study following established methods (Betts et al. 2008, Anich and Ward 2017) to attract hypothesized competitors of two species pairs (Fig. 10). The species pairs (Macgillivray's warbler [A] versus Wilson’s warbler [B], Swainson’s thrush [A] versus hermit thrush [B]) have similar ecological traits but differ in their spatial distributions. For each pair, bird songs will be broadcast (“playbacks”) to attract species B to sites which it currently does not occupy, but which species A occupies (and vice versa—attracting species A to sites previously occupied only by species B). These methods have been used to attract warblers to locations outside of their existing geographic range (Anich and Ward 2017), so we expect to be able to move individuals across short geographic distances. Sites with varying microclimate conditions and bird occupancy will be selected from the 184 monitored sites with 11-year histories of bird and air temperature observations (Fig. 1). The response of species A to the experimental attraction of species B will be recorded and related to the microclimate of the site. This experiment will determine whether the interaction between two competing bird species influences their site occupancy in varied microclimates (*species interaction,* Goal 2), and if so, which bird species are most successful across a range of microclimatic conditions. This work draws upon long-term bird studies (3.4.5), climate data (3.4.4), and disturbance data (3.4.1).

3.5.4.d. Aquatic species interactions with drought and warming streams

PIs: Dana Warren, Brooke Penaluna, Ivan Arismendi, Catalina Segura, Sherri Johnson

Questions: How do low flows influence trout and salamander demographics and interactions? To what extent do interactions between these stream predators change with temperature exposure?

Rationale: Decreasing snowpack in mountain landscapes (Mote et al. 2018) is expected to reduce summer streamflows and increase the frequency and intensity of droughts. Reduced water availability alters the amount of space within which stream biota can exist, while temperature affects bioenergetics and growth, which influence behavioral interactions and survival (Chapman 1962). Both drivers can ultimately influence inter- and intraspecific interactions between native cutthroat trout (*Oncorhyncus clarki*) and coastal giant salamanders (*Dicamptodon tenebrosus*), the two apex predators in western headwater streams which compete for limited space and food resources (Power et al. 2008). Our long-term studies of trout and salamanders, conducted annually since 1987, show decreasing body size for both species (Fig. 4-d). Interactions between fish and salamanders can be structured by size (Nakano

1995), and these interactions, especially during drought and warmer stream temperatures, may strongly affect aquatic species responses to changing climate. In LTER8 we will undertake experiments to determine whether the interaction between two competing aquatic species is influenced by reduced habitat during drought and differing temperatures, and if so, how groundwater contributions of cool water mediate these interactions (*species interactions*, Goal 2). These studies draw upon long-term studies in hydrology (3.4.2) and on fish and salamanders (3.4.5).

1. Reach-Scale Drought Experiment

Predictions: Under low-flow conditions, trout and salamanders will aggregate in pools or cooler water, intensify competition for macroinvertebrate prey, and show reduced growth and survival. We predict that groundwater inputs will reduce the severity of drought effects on stream flow and temperature.

Methods: We will conduct drying and warming experiments in streams of the Andrews Forest. We will create separate sections of stream with (a) low flow (using methods of Walters and Post 2008) and (b) elevated temperatures (using passive solar panels to heat water in diversion pipes before returning the water to the stream). Experiments will be conducted in summer (when streamflow is minimal) and will mimic a severe summer drought in 2015 (Kaylor et al. 2019). Groundwater contributions will be measured using longitudinally distributed temperature sensors and synoptic measurements of δO^{18} per Segura et al. (2019). Prey availability, fish and salamander individual growth (using PIT tags), abundance, survival, and use of deep pools will be measured in each treated reach and an upstream control reach.

2. Experimental examination of inter- and intra-specific dominance as a function of temperature

Predictions: At warmer temperatures, aggression within and between species will increase. Because salamanders have higher thermal tolerances than trout, salamanders will show more dominance.

Methods: During summer we will install flow-through mesocosms following established methods (Connolly and Pearson 2007) in streams of differing temperature regimes, identified from long-term stream temperature data. These cooler and warmer sites will be representative of headwaters and downstream portions of the stream network. Mesocosm treatments will include both interspecific (salamander + trout) and intraspecific (salamander + salamander; trout + trout) interactions of similar densities. Preliminary findings from prior mesocosm experiments have shown a higher frequency of density-dependent aggression between salamanders than between trout. We will record interactions among paired animals over time (e.g., guarding, retreating, biting, fighting, or chasing) using video cameras and direct observations. We will track the condition and performance of individuals within each enclosure using PIT tags. Survival, growth, and condition of animals will be assessed at the end of the experiment.

3.5.5. CONSERVATION ETHICS: INTERACTIONS OF SCIENCE AND ETHICS AFFECTING LAND-USE DECISIONS

PIs: Michael Paul Nelson, Chelsea Batavia, Jeremy Bruskotter

Question: How do value judgments of forest stakeholders and decision-makers interact with Andrews Forest science to inform forest management in the Pacific Northwest?

Rationale: In a forest management context, the word “value” often refers to the ways in which a forest or a species is deemed to be good, with the understanding that these notions of value underpin more specific beliefs about and attitudes toward forest management (Fig. 11, Brown and Reed 2000). Social scientific methods can be used to empirically understand the values people hold with regard to forests (e.g., Bengston 1994, Xu and Bengston 1997, Brown and Reed 2000, Brown 2013, Connell et al. 2015). However, values also fall within the purview of ethics, a philosophical discipline that questions (among other things) the nature of value, how it should be assigned, and its significance for how we ought to act in the world (Schroeder 2016). Rooted in this intellectual tradition, conservation ethics contributes to the Andrews Forest program the unique insight that forest values can be both described and evaluated using systematic, critical methods of inquiry. The core methodology of conservation ethics, called argument analysis, shows that prescriptive recommendations, which take the form “we should do X,” are logically predicated on both scientific (fact) and ethical (value) premises. In LTER7 we primarily worked to demonstrate that science and values interact to inform management (Batavia 2015, Batavia and Nelson 2016, 2017, 2018). In LTER8 we build on this foundation, seeking to understand how Andrews Forest science interacts with values to inform prescriptive recommendations and/or regional management decisions (*science-values interactions*). This work addresses Goal 3, and contributes to an extant body of literature on the science-management interface (e.g., Littell et al. 2012, McKinley et al. 2012, Ryan et al. 2018) by specifically and critically investigating how value judgments interact with scientific information to mediate this interface. This work draws upon long-term disturbance and land-use data (3.4.1).

Research Question 1: How do forest managers' pre-held beliefs affect how they evaluate inferences from scientific facts to prescriptive conclusions?

Prediction: Forest managers will assess inferences to be weaker and generate a greater number of counter-arguments when a conclusion is incongruent with their pre-held beliefs.

Method: We will adapt a procedure used by Edwards and Smith (1996) in their study testing for a disconfirmation bias in the evaluation of prescriptive policy judgments. In a pre-test, managers will receive a questionnaire eliciting their forest values (Brown and Reed 2000) and beliefs around controversial issues in forest management. One to two months later the same managers will be asked to evaluate a set of inferences, each composed of one scientific premise and a conclusion. Inferences will be prescriptive and pertain to a set of forest management issues informed by Andrews Forest research. For each issue managers will receive one 'pro' inference (e.g., we should actively manage federal forests to represent a range of seral stages across the landscape) and one 'con' inference (e.g., we should not actively manage federal forests to represent a range of seral stages across the landscape). Managers will assess the strength of each inference (i.e., the extent to which the conclusion follows from the premise), and then, within a set time limit, list any thoughts, ideas, or arguments that occur in response to one of the inferences (pro or con) for each issue. Paired t-tests and mixed-model ANOVAs will be used to test how congruence between pre-held beliefs and the direction of inference affects assessments of inference strength, as well as the number and type of thoughts generated in response.

Research Question 2: How do key forest governance actors on federal lands in the Pacific Northwest integrate facts and values to arrive at management prescriptions?

Method: With partners in Willamette National Forest and OSU Extension, we will organize a series of workshops focused on scientific findings reported in the recent regional science synthesis, which integrates 25 years of research conducted since the implementation of the Northwest Forest Plan (Spies et al. 2018), much of it drawing on long-term data from the Andrews Forest. In the workshops, we will use argument analysis as a procedural template to investigate how participants select and apply scientific information; how they handle scientific uncertainty; how they identify and evaluate value judgments; and how they handle controversial claims (ethical or scientific). Data will include pre- and post-workshop interviews, which will be transcribed and analyzed qualitatively (Weiss 1995); material generated throughout the workshop (e.g., notes and worksheets), which will be analyzed using document analysis (Bowen 2009); and recordings of small group discussions, which will also be transcribed and analyzed qualitatively (Saldaña 2013). Results will be reported in a peer-reviewed paper, along with a report summarizing key findings and lessons learned, geared specifically toward a management audience.

Figure 11. Interactions (e.g., competition for prey) between species, such as Northern Spotted Owls and Barred Owls, are partially driven by land management decisions in Pacific Northwest forests. Under Goal 3, conservation ethics in LTER8 will examine how facts and values interact in decision-making processes underlying land use and conservation. (Paintings: D. Hyde, visiting artist at the Andrews Forest.)

3.6. Synthesis

The objective of the Andrews Forest LTER8 research program is to apply the knowledge and concepts gained from LTER1 to LTER7 to understand and predict the effects of environmental change in forested mountain ecosystems. In LTER8 research will continue to be guided by a central question, “How do climate, natural disturbance, and land use as influenced by values and decisions interact with biodiversity, hydrology, and carbon and nutrient dynamics?” (Table 1).

Recent analyses and syntheses of Andrews Forest long-term studies identified knowledge gaps that require further research and data collection. In response, LTER8 activities are tied together by two main concepts, ‘microclimate’ and ‘interactions,’ which integrate components of our conceptual framework and LTER core areas. Our long-term studies have revealed that fine-scale variation in temperature and moisture—microclimate—is strongly affected by regional climate, but also natural and anthropogenic disturbance legacies. Microclimate quantified at this scale appears to have strong, long-term implications for hydrology, carbon and nutrients, and biodiversity. Analyses of long-term data from the Andrews Forest indicate that incorporating information about climate at fine scales under the forest canopy could be critical for informing ecological projections. Interactions involving *biotic modulation* integrate long-term studies of climate, hydrology, and vegetation. LTER8 studies will address the key question of how physical processes such as regional climate change can be meditated by biotic elements such as old-growth structure and composition. *Disturbance legacy interactions* connect long-term studies of disturbance, vegetation dynamics, hydrology, carbon and nutrient cycling, and animal populations. LTER8 studies will address how the legacies of past disturbances mediate climate effects on vegetation dynamics, carbon and nutrient cycles, streamflow and other processes. *Species interactions* cut across populations and communities, including plants, microbes (needle endophytes), and animals (birds, pollinators, fish, salamanders). LTER8 long-term studies and short-term experiments will provide cross-taxa tests of the degree to which such interactions (competition, mutualism) modify microclimate effects on populations and species distributions. *Science-values interactions* connect ecological conditions with human land use and decision-making. In LTER8 we will test how the values held by resource managers or stakeholders affect their application of science in land-use decisions, with important implications for regional policy.

Andrews Forest LTER8 research will advance understanding of how populations, communities, and ecosystems interact and respond to climate change across a range of ecologically relevant spatial and temporal scales. Our studies of long-term, under-canopy microclimate address uncertainty about how global climate change will scale down to forested mountain ecosystems. LTER8 will advance understanding of abiotic and biotic drivers of microclimate, providing a basis for improving climate model downscaling, project future microclimates, and explain spatial variation in long-term ecological processes such as phenology, tree growth, seed production, and bird populations. Improved understanding of microclimate requires detailed, long-term data on climate and associated ecological processes, which the Andrews Forest has been collecting over multiple LTER cycles. Continued research and data collection in LTER8 will enable refinement of the concept of microclimate in order to improve future predictions of ecological responses to environmental change in forested mountain landscapes in the region and globally.

LTER8 studies of interactions address uncertainties in predicting long-term ecosystem response to environmental change, and specifically how multiple factors may interact to produce unexpected outcomes. Our long-term data and new experiments will enable us to quantify the magnitude of biotic effects on population, community, and ecosystem responses to climate change, and explore their consequences in models, including models of trout response to drought, higher temperatures, and salamander competitors; tree physiology and associated ecosystem C storage responses to climate stress; and future distributions of forest bird species. These efforts will permit us to compare model performance with and without species interactions and microclimate effects. Results will inform whether current coarse-scale approaches to projecting the future of populations, communities, and ecosystems under climate change are sufficient, or whether more detailed estimates—which include microclimate and interactions—are necessary. Thus, results from LTER8 will reveal the timing, magnitude, and direction of key ecological interactions, and how to incorporate interactions in order to improve model predictions and anticipate surprises in an era of unprecedented anthropogenic global change.

4.0 RELATED RESEARCH PROJECTS

Strong institutional support from our partnership with OSU, the USDA Forest Service Pacific Northwest Research Station (PNW), and the Willamette National Forest provides the foundation upon which Andrews Forest LTER activities are built. In addition to fostering a strong foundational partnership, we actively seek ways to leverage LTER efforts. The Andrews Forest LTER program leverages support from related research projects at a rate of about 1:4. Although many related research projects contribute to the success of our LTER program, and researchers from both OSU and PNW provide essential contributions to Andrews Forest research by successfully obtaining competitive grants, here we describe only those efforts that are essential to address the questions posed in this renewal.

PNW has funded and staffed the small watershed hydrology program at the Andrews Forest since the 1950s, studying streamflow, sediment, air and water temperature, and specific conductivity. PNW also co-supports, with LTER, the analyses of aquatic chemistry and forest vegetation measurements. The continuous records of streamflow, chemistry, sediment, and vegetation dynamics are crucial data used by researchers at the Andrews Forest and throughout the world. These data will be analyzed in LTER8 to address questions related to studies of stream and forest ecosystems, and for extending the scope of inference to multi-decadal time scales from short-term, high spatial- and temporal- resolution observations of hydrology and vegetation productivity. PNW co-supports, with LTER, the Andrews Forest information management program by staffing an information manager. PNW is also responsible for maintaining the Andrews Forest Headquarters facilities and for staffing the Site Manager position. PNW’s contribution goes well beyond research infrastructure; PNW researchers are full intellectual partners in our LTER program. PNW is committed to continuing its essential collaborative role in LTER8.

5.0 BROADER IMPACTS, EDUCATION, AND OUTREACH

Our work in LTER8 will benefit society by continuing our strong tradition of fostering public engagement with science through our active research-management partnerships. We will also lead cross-site efforts within and beyond the LTER Network to interpret, synthesize, and disseminate the findings of long-term ecological research. These efforts help policymakers and members of the public understand how the ecosystems humans depend upon are functioning at broad temporal and spatial scales. We continue to seek new ways to share our work.

Schoolyard LTER (sLTER). In LTER8 we will build capacity for Oregon K–12 teachers to engage their students in authentic, field-based inquiry and provide opportunities for middle and high school students to engage with the Andrews Forest research through field trips and long-term datasets. Our sLTER program will partner with the STEM Research Center at OSU. Notably, the STEM Research Center brings strong connections to Oregon-wide STEM education programs, environmental education and citizen science research, and programs and research focused on improving scientist engagement with teachers and publics. Funding will be used to: 1) engage middle and high school teachers with Andrews Forest research through the Oregon Season Tracker project (see below); 2) coordinate extended experiences for teachers who desire further training in field-based research through the Research Experience for Teachers (RET) program; 3) facilitate student participation in the Andrews Forest Discovery Trail (DT), an interactive, interpretive learning trail that draws upon scientific and humanistic inquiry, to enhance students’ understanding of and connection with forest ecosystems and development of sense of place; 4) conduct formative evaluation to iteratively improve projects, understand impacts on participants, and, through leveraged funds, continue to engage in STEM learning research (e.g., Giamellaro et al. 2020); and 5) share results of our work at conferences and in peer-reviewed journals. sLTER activities support students in attaining proficiency in the practice of science, in keeping with the Next Generation Science Standards (NGSS Lead States 2013). In our recruiting of teacher participants, we will prioritize those working with underserved audiences including Title I Schools, those with high populations of English Language Learners, and from a mix of rural and urban districts. Based on these plans and our LTER7 experience, we estimate that approximately 400 students per year will engage in hands on inquiry at the Andrews Forest, and we will work with at least 100 teachers over the course of LTER8. On average, each teacher involved with sLTER professional development reaches 100 students per year.

Research Experience for Undergraduates (REU). Research experiences have shown to be beneficial to undergraduates, in particular in improving persistence in STEM for historically underrepresented groups (National Academies of Sciences, Engineering, and Medicine 2017). In addition, REU students provide meaningful contributions to research projects. In LTER8 we will engage two REU students per year to conduct supervised research and work closely with faculty and graduate student mentors to design and implement individual projects. We actively seek academically qualified candidates from diverse and traditionally underrepresented backgrounds for these positions.

Graduate Students. We are committed to graduate student involvement, mentorship, training, and scholarship, with an eye toward helping students cultivate their future science leadership skills. Our graduate students are involved with planning and hosting symposia and field tours, present their science at our monthly meetings, and share posters at the Andrews Forest symposium and the LTER All-Scientists Meeting. They are introduced to data curation through workshops with our Data Managers. We prioritize funding for graduate students to attend the LTER All-Scientists Meeting.

Public Outreach. We are committed to engaging the public and increasing understanding of the value of long-term ecological research through tours and site programs, media interactions, and links with arts and humanities. We publish a widely-distributed, semi-annual newsletter highlighting our findings and activities. We use our website, Facebook page, and Twitter feed to communicate broadly. Andrews Forest books like *The Hidden Forest* (2006) continue to connect readers to our place and work. We anticipate that a forthcoming book on the history of the Andrews Forest (Robbins 2020) will add to this public outreach. Our LTER children's book, *Ellie's Log* (Li 2013) is popular with schools and teachers in the region.

Tours and Site Programs. The Andrews Forest attracts ~1,500 visitors annually from around the region and world. Site personnel give tours and field classes for U.S. and international university courses (~20 per year), resource managers (100–200), and the general public (100–200). An annual public field day draws between 120–140 people, with field presentations focused on themes of our research and afternoon field trips with interactive activities. In Schoolyard LTER, the Discovery Trail is used regularly for public outreach and the innovative Canopy Connections middle school education program, conducted in collaboration with the Environmental Leadership Program at University of Oregon.

Media Interactions. We actively engage with the media by serving as sources for regional, national, and international media. Our research on microclimate and biodiversity in forests has been covered by National Public Radio and was profiled in a 10-minute Oregon Public Broadcasting TV documentary (Burns 2019). We also provide *Science Findings* reports of the PNW Research Station, work with OSU's News and Research Communications, host field tours with media groups, and inform articles in the OSU research magazine and blog, *Terra* (Vorster 2019).

Arts and Humanities. The Andrew Forest program is a leader in actively integrating the arts and humanities into our research efforts. Our arts and humanities program (LTEReflections) aims to enhance public science literacy, by interpreting and conveying the value of long-term ecological research, and inspiring awe, wonder, and action with a wider audience. The Long-Term Ecological Reflections program is a partnership between the Andrews Forest program and OSU's Spring Creek Project for Ideas, Nature, and the Written Word. This program creates ongoing occasions for reflection and creative expression on topics central to ecology and conservation, and we host residencies for writers, musicians, and humanities scholars. We also collaborate with other LTER sites that host similar programs and have engaged recently in research on this component of our program (e.g., Goralnik et al. 2015, 2017). Our Lead PI is a philosopher and environmental ethicist, whose work has for decades sat at the nexus of ecology, ethics, and social science. Our program began integrating conservation ethics more formally in the LTER7 proposal.

Citizen Science and Extension. Oregon Season Tracker, a citizen science and education partnership between OSU Extension and the Andrews Forest, launched in 2014, engaging landowners and K–12 students from around the state in weather and phenology research to facilitate communication about climate change and its impacts on natural and human systems. By developing collaborative climate change-related research and educational activities within existing Extension and education networks (e.g., Master Woodland Managers, 4-H, Schoolyard LTER), and leveraging two existing national citizen science programs (National Phenology Network (NPN)'s Nature's Notebook; and Community Collaborative Rain Hail & Snow Network), Oregon Season Tracker has been able to grow relatively rapidly into a community of practice with 350 observer stations, including 13 teachers and >650 students.

Applications to Management and Policy. Our relationship with policy and management will continue to build on the decades-old foundation of the partnership between the Andrews Forest research community and the Willamette National Forest, organized formally under the Central Cascade Adaptive Management Partnership (CCAMP). Through CCAMP, researchers and managers collaborate to conduct applied research involving management of forest ecosystems. Ongoing collaborative experiments during LTER8 will provide insight into the potential to reduce drought stress in managed forests, tradeoffs between managing mature forests for timber and early seral habitat versus forest microclimate buffering and carbon storage, and the long-term implications of new stream restoration methods (Powers et al. 2019). These projects include demonstrations that serve as focal points for field discussions concerning the future of forested mountain ecosystems and management. CCAMP also organizes workshops and seminars engaging researchers and managers on current topics (e.g., Northwest Forest Plan revision, the science of riparian management, early seral forest, landscape analysis, and how social science and ethics can inform public discussions of resource issues). Andrews Forest researchers play a critical role in these workshops, and in generating and synthesizing the relevant science (Spies et al. 2018, Phalan et al. 2019). Moreover, we seek to understand how our science may contribute to society by engaging the public, resource managers, and policymakers in explicit studies of changing social networks and conservation ethics analyses of arguments used in forest management. In LTER8 Andrews Forest researchers will more formally explore the relationship between our ecological science and the role of science in land-use decision-making by managers.

Diversity and Inclusion. In LTER8 the Andrews Forest LTER will continue to promote diversity, equitable access, and inclusion at all levels of our program by working within existing strategic efforts and committees at OSU and PNW, and leveraging relationships with local, regional and national partners. For example, our Schoolyard LTER program will continue to provide opportunities for teachers working with high percentages of economically disadvantaged students to build their capacity in active-learning, inquiry-driven, and student-centered pedagogies that promote inclusive learning experiences for all students. Our REU programs will focus on recruiting students from diverse backgrounds, including first-generation college students, by partnering with the ESA SEEDS SPUR Fellowship program. Our public outreach efforts, including the researcher-manager partnership and the arts and humanities program, will continue to reach diverse audiences, engaging the public in ways that are more variegated and creative than traditional science communication. The visiting writer program will continue to host people representing a diversity of disciplines (e.g., theology), gender and sexual orientations, and racial backgrounds. These residents create and share Andrews Forest science-inspired stories with broad audiences through nature-inspired writing and various types of performances. In LTER8 we will continue to engage an increasingly diverse team of researchers, graduate students, undergraduate students, and REUs, with respect to disciplinary background, age, gender, culture, and ethnicity (*also see Efforts to Increase Diversity Among Site Participants section in the Project Management Plan*.)

FACILITIES, EQUIPMENT, AND OTHER RESOURCES

ORGANIZATIONAL PARTNERSHIP

The HJ Andrews Experimental Forest is managed cooperatively by Oregon State University (OSU), the Pacific Northwest Research Station (PNW) of the U.S. Forest Service (USFS), and the Willamette National Forest (WNF), on which the Andrews Forest is located.

OSU: The OSU Forest Director coordinates research at the site, leads tours and other educational activities, and supervises long-term environmental measurements and maintenance staff. The Forest Director oversees operation of the forest and the facilities in collaboration with the PNW lead scientist for the Andrews Forest. An OSU climate technician oversees operations and maintenance of climate stations, including data collection, sensor calibration and repair, and assessment of data for the long-term climate program. An OSU wireless, computer network and information manager is based on site. An LTER data manager and IM team leader is based in Corvallis.

PNW: The PNW Lead Scientist is responsible for general oversight of the Andrews Forest and directing PNW funded research. A Site Manager oversees day-to-day operations of the Andrews Forest headquarters, including facilities reservations and serves as the site safety officer. PNW USFS has primary authority for managing and maintaining the Experimental Forest and headquarters facilities, with use by OSU and others through Special Use Permits. PNW has primary responsibility for the watershed facilities and a PNW hydrology technician manages the stream gauging and water chemistry program at the experimental watersheds.

WNF: The WNF has primary responsibility for the management of forest roads, trails, fire, invasive species, emergency dispatch and field communications, and NEPA (National Environmental Policy Act) processes for research-related activities.

Facilities at the Andrews Forest

Headquarters: The facilities at the headquarters of the Andrews Forest comprise ~40,000 sq. ft. of offices, residences, conference hall, teaching lab, dining hall, storage facilities, shop, and other space.

- Five laboratories (watershed, vegetation, vertebrate, water chemistry, soils) are available for use by scientists and students . Each lab is equipped with basic equipment appropriate for the primary use, such as pH and conductivity meters, and fume hood in the watershed lab; microscopes, herbarium cabinet, and a freezer in the vegetation lab; a vacuum pump, bottles, graduated cylinders and fume hood in the chemistry lab; and a muffle furnace, a drying oven, and a fume hood in the soils lab.
- The computer lab has four workstations, printers, and direct LAN connections to OSU servers and networks.
- A large laboratory-style classroom is equipped with work benches, dissecting microscopes, and audiovisual equipment.
- Housing is available in 17 furnished apartments that range in size from 1-5 bedrooms and can accommodate short-term to sabbatical stays. Total maximum overnight capacity at the headquarters site is 80 people.
- The cafeteria and conference hall have capacity for 100-plus users.
- PNW and OSU both provide field vehicles and machinery which include a backhoe, pick-up trucks, snow cats, and a wood and metal shop that serves as the center for equipment design and building maintenance.

Computing and communications equipment: The computing facilities at the Andrews Forest headquarters consist of a local area network (LAN) with servers and workstations and wireless network. Wi-Fi is available in all headquarters buildings using managed radio access points and SSIDs for bandwidth shaping to prioritize research and education objectives. The LAN includes a domain controller, application server, file server, and web server. Servers are mirrored to an OSU COF server on campus, with backups made daily. Computer software includes R, ArcGIS, Matlab, StatGraphics, and Microsoft Office. Full scanning, printing and plotting capabilities are available to lab users. A high-precision GPS unit and rugged field laptop are used to geo-reference research plots and sensor locations. Virtual servers for the website and associated databases (as well as shared disk space for Andrews Forest staff) are provided by the Computing Resources Group, OSU COF on the Corvallis campus.

We have developed an extensive wireless communications network to transmit data from remote field research and education installations and for highspeed internet connectivity between headquarters and the OSU main campus (Fig 1-Facilities). A 5.8 Ghz radio connection (170 Mbs) links the Andrews LAN with the internet and campus computer network through the OSU College of Forestry (COF) through a series of ridgetop towers. OSU staff have developed and manage this radio internet connection and have a long-term lease on the one tower that is not located on Andrews or USFS property; this arrangement provides both security and flexibility. Data from remote climate and hydrology installations are sent hourly via 900 Mhz and 2.4 Ghz radios to access points on the Andrews Forest wireless network and back to headquarters using the 5.8 Ghz radio bridge for processing at a workstation equipped with Loggernet software, and then transferred to the OSU campus via the same radio internet bridge. Other research installations, such as instrumented hyporheic wellfield in watershed 1, can access this wireless infrastructure for data streaming and remote monitoring of equipment. This infrastructure also facilitates education installations on site, such as the Discovery Trail, a forest classroom and digital interpretive trail within walking distance of Headquarters.

Field Instrumentation: Climatic and hydrologic sensors are deployed at numerous locations throughout the forest for unattended measurements. *Note: parentheses ( ) with italicized codes indicate the database code, detailed in the Datasets Table of the proposal)*.

Hydrology: At 10 gaged watersheds, stream stage height is measured in trapezoidal flumes and weirs and streamflow calculated. Each gage has a Stevens Type A chart recorder with a float in a stilling well as the backup for the Stevens Instruments Model 2 Position Analog Transmitter (PAT) recorders controlled by Campbell Scientific CR-3000 and CR1000 data loggers (*HF004*). Stream and air temperatures (Campbell Scientific 107 thermistors) and specific conductivity (CS547A) are also measured at each gage at 5-minute intervals year-round (*HT004, CF012*). Stream chemistry samples are collected proportionally to stream flow using a battery powered Sigma Model 900 standard portable sampler and a Campbell Scientific CR-1000 data logger (*CF002*).

Climate: Four primary climate stations continuously measure and record air temperature (CS107), relative humidity (CS HMP45C), soil temperature (CS107), soil moisture (CS615 water content reflectometer), snow water equivalence (Park Mechanical pressure pillow with CS or Druck pressure transducer), snow depth, solar radiation (Kipp and Zonnen CM-6B pyranometer), wind speed and direction (RM Young Model 05103 Wind Monitor and Gill WindObserver II sonic anemometer), and precipitation (*MS001*). Climate data are collected year-round using Campbell Scientific dataloggers (CR1000, CR3000) and supported sensors at a frequency of collection of 5 minutes for most parameters. A subset of benchmark stations have instruments to measure atmospheric pressure (CS100), net radiation (Hukseflux NR01), photosynthetically active radiation (CS LI190SB) and snow melt (custom installation) Five secondary climate stations measure a smaller suite of parameters, including precipitation and air temperature. Ten additional sites under the forest canopy have understory air temperature measurements at 1.5-3m height (dependent on depth of maximum snowpack) and soil temperature measurements (*MS005*). At an additional 200 sites throughout the Andrews Forest, air temperature is measured at 20-minute intervals in the understory and across the vertical gradient into the canopy (*MS036, MS045, MV008*). Precipitation for analysis of chemistry is collected with a bulk collector at the primary met station at headquarters and a secondary station at 998m elevation (*CP002*). The Andrews Forest also hosts and maintains a precipitation sampler as part of the National Atmospheric Deposition Program (NADP-OR10).

Discovery Trail: This education area is equipped with an interpretive trail network, informational kiosk, wifi radios linked to Andrews Forest servers and the internet, webcams, and trees instrumented with Campbell Scientific dataloggers and dendrometer bands (Ecomatik DC3), leaf wetness (METER LWS), temperature (CS107) and relative humidity (EE181 and H2CS3) sensors, sonic anemometers (*MV005*). The trail infrastructure and dedicated Discovery Trail web and database server, along with a suite of tools and lesson plans available for checkout (ruggedized iPads, handheld microclimate and forest measurement tools), facilitates K-University class engagement with the forest from multiple perspectives, and is critical to Andrews education and outreach programs.

Remote cameras: Associated with the wireless communications sites, remote web (Stardot and Axis) and thermal IR (FLIR) cameras provide information on weather, road conditions, phenology, and canopy temperature, critical to field safety as well as research.

FACILITIES ON CAMPUS AT OREGON STATE UNIVERSITY

Oregon State University (OSU) is one of only two institutions in the US designated as a land, sea, space, and sun grant institution. OSU provides laboratories and facilities with available equipment relevant to the scope of the proposed project. Andrews Forest LTER researchers are affiliated with multiple departments and colleges across campus, which provide office and laboratory facilities for their faculty, researchers, students, and technicians. Research laboratories are equipped with equipment appropriate for their primary use, such as fume hoods, muffle furnaces, drying ovens, desiccators, microscopes, refrigerators and freezers vacuum filtration systems, and computers. The OSU library provides immense resources, including periodicals, journals, and other literature. In addition, the OSU library provides online search capabilities as well as interlibrary loans.

The Cooperative Chemical Analytical Laboratory (CCAL) is a water chemistry laboratory at OSU specializing in high-quality, trace-level analyses. CCAL is jointly operated by OSU COF and the USFS. CCAL chemists provide analysis of aqueous constituents including ammonia, nitrate, orthophosphorus, silicon (Lachat Quikchem 8500), total nitrogen and total phosphorus (Technicon AutoAnalyzer II), organic carbon, inorganic carbon (Shimadzu TOC-VCSH Combustion Analyzer), sodium, potassium, calcium, magnesium, iron, manganese, (Shimadzu AA 7000), sulfate, chloride, bromide (Dionex 1500 Ion Chromatograph), alkalinity, pH (ManTech PC-Titrate Auto Titrator System), specific conductance, dissolved solids, suspended sediment, and more. CCAL participates in Quality Assurance Programs in collaboration with USGS Standard Reference Water Survey Program, EPA surface water chemistry criteria, and the National Water Research Institute’s (NWRI) Environment and Climate Change Canada Proficiency Testing (PT) Program.

Computing and Communications*:* The OSU COF Forestry Computing Services (FCS) group provides services including a well-staffed helpdesk, local network administration, and maintenance of a substantial library of professional software licenses. The OSU COF Computing Facilities consist of an extensive Windows and UNIX-based workstation network which services approximately 1200 devices (computers, printers, servers, etc.). It is managed by 8 full-time Information Technology professionals with the support of 4-6 student technicians. COF buildings have 802.11ac wireless network coverage providing access to both the forestry and public campus networks. This primary network is connected to OSU and PNW networks and provides access to 4 satellite networks, one of which is the Andrews Forest. Servers and disk space include: Windows and Unix file servers with over 130TB of disk space for public, workgroup, and user files; a Microsoft SQL server cluster providing over 600GB of space for college and workgroup databases; Enterprise backup system providing roughly 390TB of backup storage; six Web and Internet servers hosting Web Applications, ArcGIS Enterprise Server, FTP, and Remote Access. This infrastructure provides the necessary technology to house the FSDB and its corresponding applications for access. Servers and software are maintained at current patch levels and backup services are provided daily with changes maintained for 6 months.

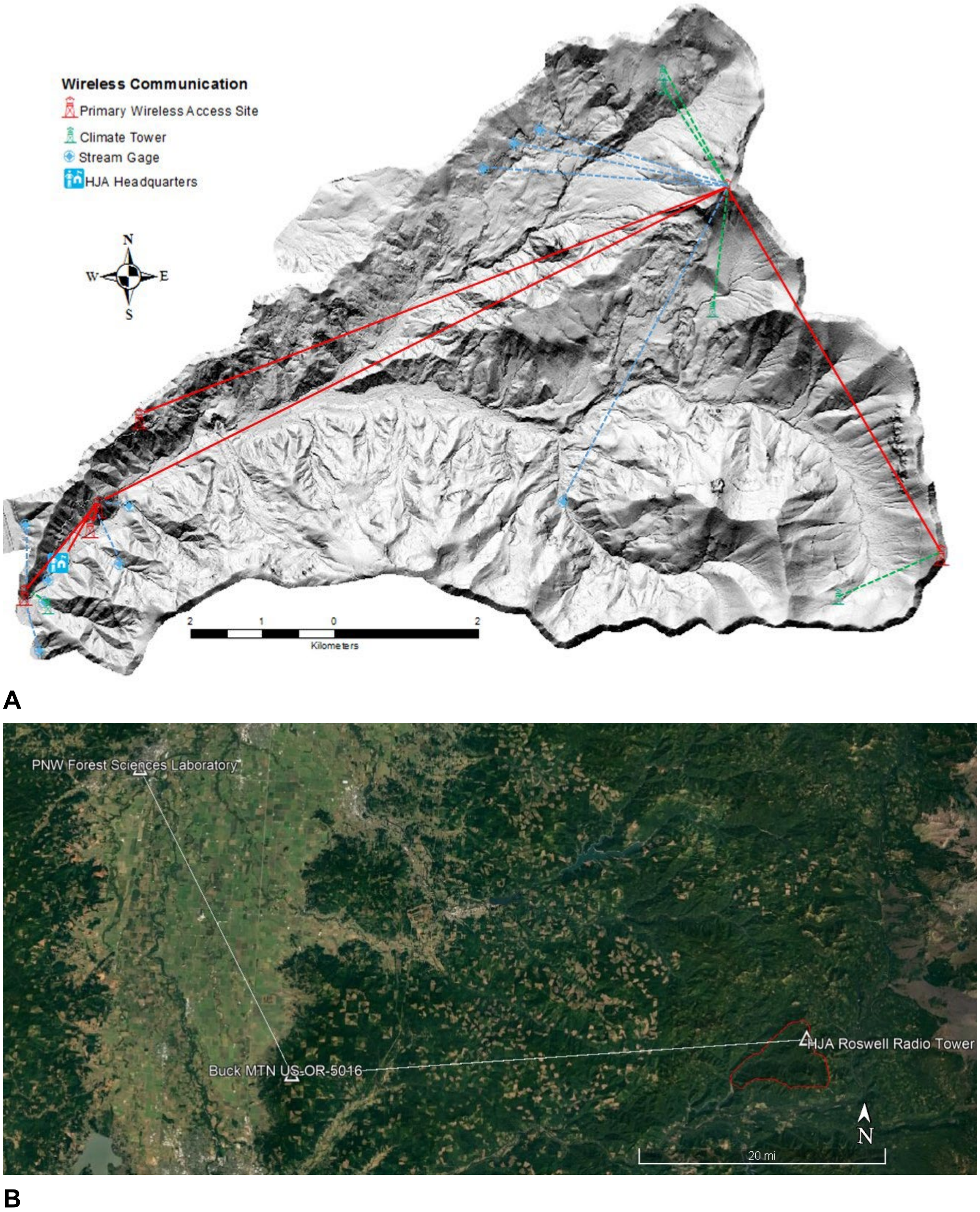


Figure 1-Facilities. Wireless comminication infrastructure (A) within the H.J. Andrews Experimental Forest – HJA and (B) linking HJA to the OSU campus and USFS PNW Research Station in Corvallis, Oregon.

DATA MANAGEMENT PLAN

Introduction

The mission of Andrews Forest LTER Information Management (IM) is to ensure that environmental research and education data collected as part of the Andrews Forest LTER are archived and openly available. The primary IM goals are to 1) preserve high-quality and well-documented data collections, 2) serve the Andrews Forest and broader community through the development and management of informational products and tools, 3) provide education and training on the collection, archiving, and publishing of research data, and 4) provide leadership and participation in relevant committees and activities at both the site and LTER Network level.

In this document, we describe the components of our information management system, publication and online access to our products, data access policy, information management resources, LTER Network participation, and milestones and deliverables. The Data Observation Network for Earth (DataONE) data life cycle framework (i.e., *Plan, Collect, Assure, Describe, Preserve, Discover, Integrate, Analyze*) is used to illustrate the components of our system.

Data Life Cycle

The Andrews Forest LTER Information Management System (AIMS) supports the complete data life cycle of a rich and diverse collection of Andrews Forest LTER and other environmental data. The IM team uses AIMS to standardize data curation from design, data collection, processing, validation, documentation, publication, access, and analysis of research data. Ultimately, datasets are uploaded to the Environmental Data Initiative (EDI) data repository, which serves as a node to DataONE where well-described Earth observational data are easily discovered.

PLAN. Information management continues to be an important and unifying theme at the Andrews Forest LTER, and the availability of long-term data provides incentive for researchers to conduct further research at the site. A representative from the IM Team serves as a regular member of the Andrews Forest LTER Executive Committee and participates in new proposal planning. The IM Team works with site leadership to establish awareness and priority for all LTER-collected data. Data contributions from Andrews Forest researchers and graduate students require specific planning with the IM Team. Individual consultations begin with design of study database and continue through data collection, quality control, and archival of data. When planning new research efforts, researchers understand the value and importance of early interaction with the IM Team so as to assure smooth and efficient archiving of data and curation in long-term data repositories (Stafford 1993). To this end, IM training workshops for graduate students and researchers are conducted annually as a means of assuring data contributions and providing IM education.

Andrews Forest LTER data include long-term datasets such as meteorological station and distributed meteorological collections, stream gauging station measurements, stream chemistry, and permanent vegetation plot data. These specific long-term datasets are collectively managed by LTER PIs, staff, and the IM Team. Additionally, many PI-managed data collections, including phenology measurements of vegetation and birds, associated air temperature and other distributed understory air temperature collections, canopy processes, aquatic ecology, and vertebrate populations are archived. Planned new collections include studies on biotic-abiotic effects on ecosystem properties, species response to abiotic drivers, and interpretation of science, values, and decisions.

The IM Team has designed specific applications within AIMS for adding new and updating ongoing study data. A comprehensive SQL relational metadata database serves as the driver for these applications that broadly apply to all data to perform quality control (QC) checks, data versioning and Ecological Metadata Language (EML) generation. Detailed workflows have been developed that serve as documentation of key processing routines for long-term climate, stream discharge and chemistry, and vegetation data. These workflows provide a clear path for data processing from field collection into archival formats, provide necessary provenance for data construction, and buffer the site against disruption from changes in personnel.

COLLECT. Data collection efforts are continual and widespread throughout the forest. Many studies collect data manually and web-based applications, data loggers, field recorders, and radio telemetry are becoming more common. A wireless communication backbone installed across the forest collects and transmits high-temporal resolution data from data loggers located at meteorological and gauging stations back to a base station at Andrews Headquarters (Henshaw et al. 2008). Radio telemetry at 5.8 Ghz provides near real-time data and is particularly useful given the remoteness and limited accessibility of most sites during the winter. A dynamic system using GCE Data Toolbox in Matlab is employed to provide initial QC, web access and near real-time graphics of streaming hydro-meteorological data. This system pre-screens data and flags potential errors in this provisional data. Problem data are quickly identified, and the IM team is alerted as problems occur, enabling technicians to provide rapid attention to the issue. This pre-screening improves efficiency in delivering final data products for public access and building user confidence in the data streams. Field technicians enter notes and comments to further document other problem issues that are discovered through a locally developed web application. The notes are used to assign method and event codes in the data. Standard naming conventions are applied on more than 60 data loggers across all hydro-meteorological datasets to ensure efficient data management. This system, and the wireless capabilities, has the capacity to accommodate more data streams in the future. The Andrews Forest has adopted best practices for managing streaming sensor data documented by the EnviroSensing cluster (Gries et al. 2014) within the Earth Science Information Partners (ESIP).

ASSURE. A metadata-driven QC system, consisting of a set of procedures that provide generic data validation for any dataset, provides another example of an efficient software tool that relies directly on the metadata. In this case, a desktop control program uses relevant metadata to validate that the attributes for each table in a dataset are properly described in the metadata. Problems are recorded in an error report and validation includes checks against illegal null values or duplicate records (entity integrity), checks against listed numeric ranges for extreme values and against enumerated domains for undefined codes (domain integrity), and special database checks that are pre-determined in discussion with the PI for individual datasets. This QC system provides valuable metadata checks for researchers that serve to identify data inconsistencies not discovered in earlier stages of QC. The resulting cleaned dataset is thus prepared for near-seamless delivery into the EDI data repository, which requires each dataset to pass a series of additional congruency checks to verify that data tables are compliant with and ingestible from the EML metadata.

DESCRIBE. The IM team has focused on improving efficiency in order to manage documentation for increasing volumes of data collected by the LTER. The SQL relational metadata database is tailored to accommodate all necessary elements within the LTER metadata standard, EML. Metadata content for all study datasets including detailed entity (data table) and attribute (variable) descriptions is established within the metadata database, and metadata templates and software tools are used to facilitate adding information. EML files are easily generated from a locally developed application that maps elements from the metadata database into EML using style sheet transformation scripts and new metadata content is instantly incorporated into new EML files. A similar EML generation program has been used to map ESRI ArcGIS metadata from the federal FGDC spatial standard into EML descriptions of spatial entities. Our EML documentation adheres to LTER EML "best practice" recommendations and assures a standardized approach for consistency with other LTER sites. These applications are easily modified to add new EML elements or adhere to new EML versions, such as the recently released EML version 2.2. A data versioning system assures that all versions of both the EML metadata and associated datasets are archived, and that new versions are immediately generated for public access.

The IM Team facilitates the collection of study metadata by providing webpage descriptions of the data submission process. A web-based administrative interface allows any researcher associated with a study to enter and revise descriptive metadata for that data, relieving the information manager of this effort. "Metadata writing parties," where PIs and students come together and collectively use the software tools under Information Manager guidance, have proven to be effective in collecting and improving titles, abstracts, methods, and other study metadata.

PRESERVE. The central component of AIMS is the Forest Science Data Bank (FSDB), a long-term data repository initiated in 1983 (Stafford et al. 1984, 1988, Henshaw and Spycher 1999, Henshaw et al. 2002), supported by the Andrews Forest in partnership with the U.S. Forest Service Pacific Northwest

Research Station (PNW) and the OSU College of Forestry (COF). The FSDB stores complete collections of datasets and current and historic publications from the LTER as well as from pre-LTER research at the H.J. Andrews Experimental Forest (data collection started in 1948). The highly structured metadata database includes a data catalog with all associated metadata and publication citation information for these collections. All Andrews Forest LTER datasets including key long-term and ongoing data collections, are curated in FSDB, published online on the Andrews Forest LTER webpage, and uploaded to EDI, where a Digital Object Identifier (DOI) is assigned. Short-term data products are published to EDI within two years, and ongoing data products are uploaded on regular intervals (typically annually or biennially). A table that lists all datasets from the site that have been deposited into EDI is provided as a Supplementary Document with this proposal.

In addition to the EDI repository, the Andrews Forest LTER website provides access to datasets. Beyond local preference and familiarity, one key advantage of continuing to provide data locally is the value-added capabilities available for accessing and subsetting large datasets. Local features include filters to download desired subsets or to request subsets of data at specific time intervals, thereby speeding download time and not having to download extremely large datasets. We provide the dataset DOI, assigned by EDI, in our local online data citation through a regularly run script that harvests the current version DOI from EDI and inserts it into our metadata database.

DISCOVER. All Andrews Forest LTER data webpages are dynamic. Webpages use web integration software to display metadata and provide access to the data. A website search engine permits simple search strings to find data and publications and allows additional searches using person, place or theme keywords. Our locally developed theme keyword list has been mapped to, and includes elements from, the LTER Controlled Vocabulary in the EML document. The primary Andrews Forest LTER website is in a Drupal content management system that pulls personnel, publication, and database information from our metadata schema in an XML file to allow a comprehensive text searching mechanism from the main search box. Both EDI and DataONE employ search capabilities to locate desired data based on the EML metadata document. Basic infrastructure spatial data have been moved into ArcGIS Open Data Hub for standardization, easy access, and direct import into an ArcGIS system.

The Andrews Forest LTER data access policy is compliant with the LTER network data policy. Both policies were revised in 2017, and include three sections: data release, data access, and data use agreement. Contributions of data are required when any LTER funding is involved and are expected for all approved site research projects. Andrews Forest LTER researchers make every effort to release data in a timely fashion and with attention to accurate and complete metadata. Datasets are released to the public domain under the Creative Commons Attribution 4.0 International Public License. Data and information derived from publicly funded research in the Andrews will be made available online within two years of collection. Some data may be restricted due to documented institutional or legal requirements of the owner, but these occurrences are rare and exceptional. Primary observations collected for core research activities directly or partially supported by LTER funding receive the highest priority for data release. Other types of data including affiliated studies or legacy data are released as resources permit.

INTEGRATE. The DataOne life cycle term “integration” refers to creating homogeneous datasets that can be readily analyzed by combining data from disparate sources. Given the specific needs of the Andrews Forest, the IM team has focused on approaches that integrate and improve processing efficiency for datasets of similar data types. For example, there is a common data structure for climate data. Similarly, data from several large, long-term vegetation growth and mortality studies are being reorganized into standard formats. This is cost-effective in that it encourages creation of standard field collection forms, which simplify data processing, and enables calculations of summary data. Additionally, automation of field data collection is being used to reduce the time for manual data entry and correction. Efficiencies in management of climate and vegetation data are essential given their time-consuming nature and inherent complications in properly documenting and processing. Analogously, increasing volumes of streaming sensor data require standardized approaches in data management (Campbell et al. 2013).

Data integration not only streamlines processing and management of these data collections but allows the use of web-based applications to more easily access and analyze the datasets. For example, several of our long-term datasets contain multiple sites and parameters. While these datasets could be structured into tens of individual databases, our use of standard formats and local web features allows users to efficiently select, filter or subset data from these large datasets:

- Meteorological station data for all 7 primary and secondary benchmark stations, beginning in 1957 to present, includes daily and high-resolution measurements in 32 data tables with multiple parameters. Over 30 million meteorological observations are added each year (MS001).
- Stream discharge data from 10 watershed gauging stations, beginning in 1949 to present, with over 10 million stream discharge observations added each year (HF004).
- Permanent vegetation plot tree data, some data collected as early as 1910, includes regular tree measurements for 380 plots on 8 watersheds plus over 180 reference stands and represents over 130,000 tagged trees that have been repeatedly measured over time (TV010).

ANALYZE. The IM team provides tools for analysis of data such as calculating or aggregating data for many datasets. The previously described web-based applications that provide value-added features for accessing the large datasets enable analysis of data. Examples of these applications include:

- GLITCH, which allows users to filter high temporal resolution climate entities for a selected station, sensor, date range, and requested output interval.
- FLOW, which recalculates stream discharge for user specifications, similar to GLITCH.
- Generic AIMS tools that take advantage of entity metadata to allow any dataset table to be subset using its primary key (i.e., site code and date) as an aid to users downloading data for analysis.

Information Management Resources

Information management is an essential component of the Andrews Forest program and benefits from institutional partnerships with the COF and the PNW. The LTER grant funds 2.25 FTE IM positions, including a data manager, an on-site systems administrator, and a part-time programmer. Historically, the Andrews Forest IM team has benefited through long-term and continued support provided by the PNW for additional positions.

The Andrews Forest IM Team includes the following individuals; their role, funding source, and time in position are indicated:

- Suzanne Remillard (*IM Team Leader/Database*, LTER, OSU, 2000-Present)
- Adam Kennedy (*Site System Admin/Wireless Communications*, LTER, OSU, 2011-Present)
- Hans Luh (*System Admin/Programmer*, LTER, OSU, 0.25 FTE 2011-Present)
- Jonathan Burnett (*GIS Specialist*, PNW, part-time, 2018-Present)
- Recently retired, Don Henshaw (*IM Programming Lead/Climate/Hydrology,* PNW*,* 1978-2020)

Remillard transitioned to team leader during the middle of the previous LTER7 grant and works on LTER database and system development at OSU campus. Kennedy is responsible for Andrews Forest on-site system administration and communication networks including the Local Area Network (LAN), local web server, wireless LAN, radio telemetry for wireless sensors, and GCE toolbox. Over his 40-year career in IM at Andrews Forest and the LTER Network, Henshaw was instrumental in the development of the AIMS and associated applications; additionally, he shepherded the flow of sensor data from provisional to final archival and guiding the development of processes to improve the efficiency needed to manage increasing volumes of data being collected. PNW will be hiring a replacement for Henshaw. Two field technicians (one from PNW, one from LTER) assist by supporting data loggers and field computers used in routine data collection, describing methods for metadata, identifying and replacing malfunctioning sensors, and providing data.

The Andrews Forest LTER has agreements with COF for computer system administration, backup of production servers, and other information technology services including system administration support for LTER-related campus computer servers, production and development web servers, production and development database servers, shared file server directories, two tape backup servers, and cloud storage. With the improved internet capabilities at the field station, large data volumes (e.g., imagery) are now backed up directly to OSU servers and cloud storage, removing a previous vulnerability in the data archiving process.

LTER Network-Level Participation

Andrews Forest IM Team members have served key roles in IM leadership across the LTER Network for several decades and continue to be involved as new initiatives arrive. Remillard currently serves as co-Chair of the IM Committee. Henshaw provided leadership in the development of the EnviroSensing cluster within ESIP. The IM Team has participated in network-wide administrative databases (PersonnelDB, All-site Bibliography, SiteDB) and led developers in the ClimDB/HydroDB synthetic research database (Henshaw et al. 1998, 2006). The IM Team is currently involved in the next generation ClimDB/HydroDB database project, which is investigating the use of the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) for archiving high temporal resolution meteorological and hydrological data. The IM Team is involved with emerging network-wide administrative or research processes; for example, we recently helped test the LTER Network Office's new process for updating the LTER all-site personnel database.

As LTER Network policies and best practices have evolved, AIMS has been modified to comply with accepted standards. Metadata best practices for EML, the unit dictionary, webpage recommendations, and the network-developed Guidelines for LTER Information Management Systems (v2.1) have all shaped the evolution of the AIMS. The Andrews Forest IM Team have played strong leadership roles in the development of these standard policies and practices (Michener et al. 1997, 1998, Baker et al. 2000, Brunt et al. 2005).

Milestones and deliverable products for LTER 8

ANNUALLY

- Conduct internal site review of data management activities and prioritize development of LTER datasets for posting; update and archive all ongoing LTER signature data and metadata; update individual LTER researcher data collections; post all LTER data on the site webpage and to EDI.
- Update personnel and publication databases within the local system; synchronize with network.
- Conduct IM training on data submission procedures and policies for the LTER community.
- Participate in the annual IM Committee meeting, related teleconferences and committee activities.

YEARS 1-4

- Post all LTER data from previous LTER grant on site webpage and upload to EDI.
- Make necessary modification of local metadata system and modify EML generation program to produce EML 2.2 compliant metadata.
- Continue modifying local applications for efficient quality control and posting of streaming climate and hydrology data.
- Complete reorganization of data structures and processing code for vegetation growth and mortality data to allow timely posting on the site webpage and uploading to EDI. Continue testing QC system for streaming sensor data to allow for 1) near real-time posting and access of telemetered data on the site webpage and 2) annual deposition into EDI.
- Contribute data to Next Generation ClimDB/HydroDB and CUAHSI for selected stations.
- Complete migration of study locations to ArcGIS OpenDataHub for ease of maintenance and access.
- Identify and design metadata and data structures for new LTER8 data collections, post LTER8 data on the site webpage and upload to EDI.
- Review priorities for information product delivery and make necessary updates and enhancements to the site webpage.

YEARS 5-6

- Assure update, archival, web posting and uploading to EDI for every LTER-funded dataset collected within the grant cycle; prepare for renewal.

PROJECT MANAGEMENT PLAN

INSTITUTIONAL PARTNERSHIP. The overall Andrews Forest Program is administered cooperatively by Oregon State University (OSU), the US Forest Service (USFS) Pacific Northwest Research Station (PNW), and the Willamette National Forest (WNF). The Andrews Forest Program includes research and education activities funded by the Andrews Forest LTER, the USFS PNW, and other grants that occur at the HJ Andrews Experimental Forest. The three administrative institutions maintain a highly collaborative relationship. Individuals from each institution play critical roles in the program and each institution contributes importantly to research, education, and maintenance of the Andrews Forest Program. This partnership results in more students, technical staff, and information managers than would be possible with LTER funding alone.

RESEARCH COMMUNITY. The Andrews Forest LTER program brings together interdisciplinary groups of researchers from many institutions and agencies. Our immediate community (see Senior Personnel biosketches) includes researchers from OSU, USFS PNW, USFS Region 6, US Geological Survey, University of Oregon, Indiana University, Marquette University, Western Michigan University, and University of Washington.

MANAGEMENT PHILOSOPHY. While the Andrews Forest LTER program is the highly visible focal point for a wealth of research and educational activities, the Andrews Forest is also a USFS Experimental Forest that attracts national and international research. In keeping with our dual LTER- and experimental-forest designations, we consider and manage the Andrews Forest as a regional, national, and international research and educational resource. The sharing of data from ongoing and long-term studies—funded by LTER and USFS PNW—provides a platform that is widely known and extensively used, encourages new and innovative research, and significantly leverages research investments in innovative ways.

PROGRAM ADMINISTRATION. The Lead PI (Michael Paul Nelson) is responsible for project administration, site representation on the LTER Science Council, and coordination of the Andrews Forest LTER Executive Committee (EC) (Fig 1-PMP). The EC is composed of researchers from multiple disciplines, and from the partner institutions of OSU and USFS PNW. The committee is chaired by the Lead PI (Nelson) and includes four co-PIs (Johnson, Jones, Bell, and Betts), the Andrews Forest Director (Schulze), and the lead of the Information Management Team (Remillard). One or two researcher(s) from the list of Senior Personnel also serve(s) on the EC as a voting, rotating member(s), allowing newer scientists leadership training and providing new perspectives and expertise to the EC. The EC governs the Andrews Forest LTER program with input from the broader Andrews Forest science community.

Staffing for the Andrews Forest LTER program is described in the "Organizational Partnership" section in *Facilities, Equipment, and Other Resources*. Both OSU and PNW partners have committed to providing critical staffing resources.

DECISIONS RELATED TO FUNDING, RESEARCH, AND PERSONNEL

Input into decisions about funding, research directions, and personnel are made at multiple levels. While the Lead PI is responsible for final decisions, the EC, and specifically the Signatory PIs, provide critical input into those decisions. Senior Personnel also provide input through discussions, meetings, and proposals of ideas. Proposals for any new on-site research are submitted through an on-line system, are reviewed by the Forest Director, PNW Lead Scientist, and others in the Andrews Forest science community for compatibility with existing and prospective research and Andrews Forest research guidelines, with final approval by the Station Director of PNW. An annual meeting of all Andrews Forest LTER PIs and senior personnel is convened to review progress on LTER research, to report on past and future spending, and to discuss research opportunities. This management approach, based on transparency and distributed leadership, has served the Andrews Forest LTER well over its 40-year history, and we expect it to be productive in the future.

During LTER7, we invested ~25% of the LTER budget on long-term studies, ~25% on information management, and ~25% on integrative science activities specific to the current grant cycle. The remaining investments went toward graduate student support, program support, and covered indirect expenses. We anticipate a similar investment allocation in LTER8. In addition to funding long-term studies, the Andrews Forest program has a long tradition of investing strategically in activities, infrastructure, faculty, students, and products to meet LTER program goals and to foster new and diverse research participants. The EC discusses budget planning and strategic investments throughout the grant cycle.

COMMUNICATIONS. Communication is facilitated through general Andrews Forest Program monthly meetings, regular EC meetings, meetings of disciplinary groups, tours and field trips for various visitors and groups, and annual large group events. Monthly meetings are open to all and cover business (*e.g.*, site administration, data management, events planning, graduate student activities, and proposed research projects) and a science hour with invited presentations and discussion, emphasizing inclusion of prospective new and diverse research participants. We host annual events that provide colleagues a variety of accessible introductions to the Andrews Forest community. Our symposium features presentations and a poster session that highlight Andrews Forest LTER research. Graduate students are especially encouraged to share their study plans or findings. Our annual public field day, HJA Day, connects researchers, students, partners, and visitors to the site, to one another, and to the current program of work. HJA Day draws between 100-120 people and features presentations at the headquarters focused on large themes of our work and afternoon field trips where researchers create interactive activities that provide a sense of their field work and findings. We use our website (*andrewsforest.oregonstate.edu*), Facebook page (*facebook.com/AndrewsForest/*), and twitter feed (*twitter.com/HJA_Live*) to communicate within our research community and beyond. Our semi-annual *Andrews Forest Newsletter* reaches >1,300 subscribers.

INTEGRATING NON-LTER SCIENTISTS INTO RESEARCH ACTIVITIES. The Andrews Forest program actively integrates many non-LTER researchers through an extensive network including federal agencies and national and international research institutions. The strong OSU-PNW partnership and the presence of the USFS PNW, EPA, and USGS on the OSU campus create many opportunities for collaboration. We foster collaborative efforts that allow non-LTER participants to leverage the Andrews Forest and/or LTER resources. We integrate non-LTER scientists into site activities and planning through group meetings and events and through joint grant proposals for research that leverage LTER data and infrastructure.

RECRUITMENT OF NEW SCIENTISTS TO THE PROJECT. Recognizing that the success of our program requires a large, diverse, and collaborative group of participants, we actively encourage researchers at various career stages at OSU and other institutions and agencies to participate in the Andrews Forest LTER program, to initiate research that involves the Andrews Forest site, and to utilize Andrews Forest data. As we seek out and meet individually with new researchers and scholars, we highlight the long-term nature of studies that are useful in providing background or foundational information for new investigations and discuss the open availability of LTER data. Andrews Forest researchers are in multiple colleges across OSU and other universities, and often play a role through department and college committees in recruiting and mentoring new faculty with interests in interdisciplinary collaborative research. Our events, classes, and new faculty field tours, provide an introduction to research at the Andrews Forest and are successful outreach tools to local, regional, and distant researchers.

EFFORTS TO INCREASE DIVERSITY AMONG SITE PARTICIPANTS. We actively promote diversity, equity, and inclusion at our LTER through active recruitment and support of researchers, educators, faculty, and students from underrepresented populations (*also, see Diversity and Inclusion in Section 5.0 of Proposed Work*). We advertise graduate and REU positions broadly and target institutions that provide connections to minority and underrepresented groups. We have partnered with the ESA SEEDS program, hosting a national field trip and REUs, and will partner with the SPUR Fellowship program in LTER8. Our RET, Canopy Connections, and LTER Schoolyard programs work closely with teachers from schools with diverse demographics. The training of diverse students as future researchers and professors is an important function of the Andrews Forest Program, providing a multicultural perspective to the LTER science community. Female researchers have long filled key leadership positions at the Andrews Forest (e.g., in LTER8, 2 of the 5 co-PIs are female), and women and underrepresented groups represent 42% of LTER8 Senior personnel. Andrews Forest researchers, staff and students participate in Diversity, Equity and Inclusion working groups and committees through OSU, the USFS PNW Research Station, and the LTER Network. We will continue to attract and retain diversity among site participants by strategic recruitment of new members, through attentive informal mentoring, and through research investments of LTER funds.

CONTINUITY OF LEADERSHIP AND SUCCESSION PLANNING. The Andrews Forest LTER program plans for changes while maintaining continuity. Our Lead PIs have generally served for six to nine years, often continuing on as a co-PI. Lead PIs include Michael Paul Nelson (mid-LTER6 through LTER7); Barbara Bond (mid-LTER5 to mid-LTER6); Mark Harmon (mid-LTER4 to mid-LTER5); and Fred Swanson (mid LTER2 to mid-LTER4). Because OSU has modified his position description to adequately allow for program administration, Michael Nelson will continue as Andrews LTER Lead PI in LTER8. Nelson has expertise in environmental philosophy and ethics and interdisciplinary studies of ecology, ethics, and social science; and he leads work on science, values, and decisions, and coordinates long-term ecological collaborations within and outside of the LTER Network. Sherri Johnson and Julia Jones have been co-PIs since LTER5, and were involved with LTER before then. Johnson and Jones will rotate off as co-PIs prior to the LTER8 mid-term review; we will identify replacements for Johnson and Jones after LTER8 begins. Johnson has expertise in stream ecology and biogeochemistry. She is the USFS Lead Scientist for the HJ Andrews Experimental Forest and facilitates long-term climate, hydrology, chemistry, and aquatic studies. Jones has expertise in hydrology, climate, landscape ecology, and spatiotemporal statistics. She is one of our PIs who facilitate analyses of Andrews Forest long-term datasets. Matt Betts has been engaged since LTER6 and was a co-PI in LTER7. He has expertise in population and community ecology, wildlife landscape ecology, and movement ecology; and he manages long-term forest bird and microclimate studies. David Bell became an LTER co-PI in year 5 of LTER7. He has expertise in forest, disturbance, and landscape ecology, remote sensing and statistical modeling; he also manages long-term vegetation studies. We have several promising future leaders in the program who have served as Executive Committee rotators during LTER7. We will use our Executive Committee in the first years of LTER8 to identify and integrate future PIs. As we move forward, we expect to have continued seamless transitions in leadership.

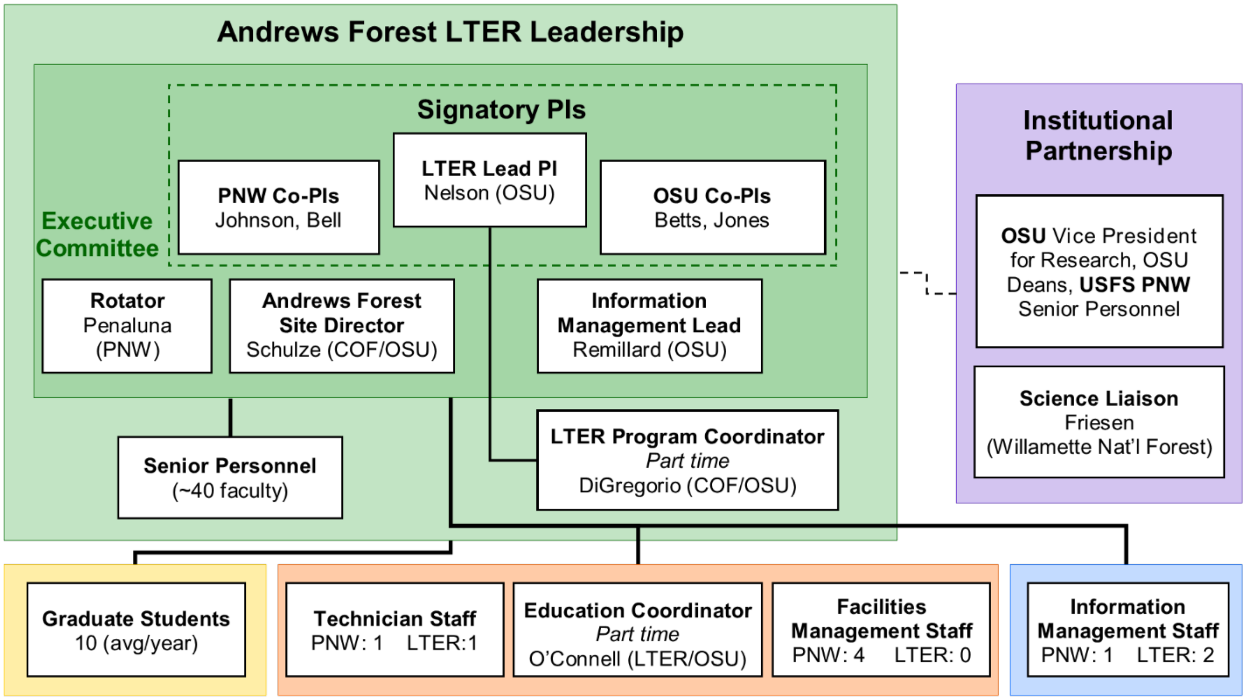


Figure 1-PMP. Organizational structure of the administration, leadership, and staffing of the Andrews Forest Program, showing LTER leadership and co-funding of staff. The College of Forestry (COF) at Oregon State University (OSU) and the Pacific Northwest Research Station (PNW) support personnel that fill collaborative roles throughout our program. Connecting lines denote oversight, advice, and other forms of cooperative effort, rather than supervision. Graduate student numbers are shown as the average number per year supported by LTER and LTER-related funding.

POSTDOCTORAL MENTORING PLAN

Andrews Forest LTER Senior Personnel at Oregon State University have many years of experience in postdoctoral mentoring and advising a diverse set of individuals from several countries. The goal of the mentoring plan, detailed below, is to provide the skills, knowledge, and experiences necessary for the postdoc to excel in their position and feel prepared for future career paths. Typically, Andrews Forest LTER postdocs are based at Oregon State University (OSU). At times, postdocs are located elsewhere or spend time at the Andrews Forest working with staff, graduate and undergraduate students, and other faculty researchers on site.

Specific elements of the mentoring plan at OSU include the following:

- A required *Individual Development Plan* will be drafted initially by the postdoc and finalized with feedback and discussion with the sponsoring Andrews Forest LTER Senior Personnel member.
- *Orientation topics* will include setting expectations of the postdoc's responsibilities and the PI's responsibilities, interaction with coworkers and collaborators, productivity, including the importance of publications as well as outreach and citizen science materials, commitments to work-life balance, work habits/lab safety, and documentation of research methodologies and data management plans.
- *Career Counseling* will be provided by the designated senior personnel and other project team members who represent a diversity of backgrounds and different career paths. OSU has an Office of Postdoctoral Programs dedicated to supporting these trainees. The Office provides support including initiatives for career advancement, as well as opportunities such as grant-writing workshops, workshops for networking with professionals, support for travel to conferences, teaching seminars, and teaching experience.
- *Exposure to the proposal process and management of grants* will be gained by direct involvement with senior personnel and other relevant project team members. The postdoc will be exposed to effective strategies for developing key research questions, defining clear and tractable objectives, describing the approach and rationale, and constructing a work plan, timeline, and budget.
- *Publications and Presentations* are expected to result from the work supported by the grant. The postdoc will be lead author on papers stemming from this project and attend project-related conferences to present their work. Funding for these activities has been allocated in the budget.

  Specific publications and authorship roles will be outlined during the orientation and an open dialogue will be maintained as roles change throughout the lifetime of the research project. Publications will be prepared under the direction of the PIs, with flexibility in meeting the degree of oversight the postdoc prefers and/or needs. The postdoc will also receive guidance and training for conference presentations (practice talks or reviewing poster drafts with project team members). Conference travel has been budgeted for the postdoc.
- *Teaching and Mentoring Skills* will be developed with the senior personnel and relevant university staff. The postdoc will have the opportunity to develop teaching and mentoring skills by collaborating with experienced teaching staff and asked to mentor undergraduate and graduate students in the senior personnel's research group.
- *Instruction in Professional Practices* will include fundamentals of the scientific method, laboratory and field safety, and other standards.

Success of the mentoring plans will be assessed by tracking the progress of the postdoc through their Individual Development Plan, which outlines specific, measurable, attainable, relevant, and time-specific goals that are assessed quantitatively. Finally, the sponsoring senior personnel will help the postdoc to hone their skills in writing, speaking, teaching, negotiating, conflict resolution, and communicating with the media, policy makers and citizen groups.

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List of Datasets

All Andrews Forest LTER datasets available through the Environmental Data Initiative (EDI) data repository are listed in this table. Datasets are organized by categories from the Andrews Forest LTER conceptual framework and central question. Datasets that have contributed to Andrews Forest LTER '10 Most Significant Publications' (see Results of Prior Support) are highlighted. The columns in the table show a) EDI Data Package Identifier with the local Andrews FSDB database code; b) dataset citation including dataset title, creators, date of publication to EDI, and DOI; c) associated LTER Core Research Areas (PP=primary production, PS=population dynamics and trophic structure, IN=inorganic inputs and movements of nutrients through the ecosystem, OM=organic matter accumulation or utilization, and DP=patterns and frequency of disturbances); and d) databases that were evaluated in publications during LTER7 marked with X.

CLIMATE

knb-lter-and.3222.36 (MS001)	Meteorological data from benchmark stations at the Andrews Experimental Forest, 1957 to present. Daly, Christopher; McKee, W. Arthur. 2019. doi:10.6073/pasta/c021a2ebf1f91adf0ba3b5e53189c84f	DP; PP; OM; IN; PS	X
knb-lter-and.5482.3 (MS004)	Precipitation measurements from historic and current standard, storage and recording rain gauges at the Andrews Experimental Forest, 1951 to present. Rothacher, Jack S. 2017. doi:10.6073/pasta/6022898a200f7fac09aa36e79e0e66d7	DP; PP, IN; PS	X
knb-lter-and.3980.15 (MS005)	Air and soil temperature data from the Reference Stand network at the Andrews Experimental Forest, 1971 to present. Daly, Christopher; McKee, W. Arthur. 2019. doi:10.6073/pasta/d0abe716146004268bb5f876ee42c992	PP; PS; DS; IN; OM	X
knb-lter-and.4019.14 (MS007)	Snow depth and snow water equivalent measurements along a road course and historic snow course in the Andrews Experimental Forest, 1978 to present. Levno, Alfred B. 2017. doi:10.6073/pasta/ff5465b74f592e3114138a79d5cfe290	PP; DS; PS; IN	X
knb-lter-and.3993.5 (MS027)	Average monthly and annual precipitation spatial grids. (1971-2000 and 1980-1989), Andrews Experimental Forest. Daly, Christopher. 2015. doi:10.6073/pasta/772a54d148ad9d1e291e4a951fd43cc2	DP; PP; OM; IN; PS	X
knb-lter-and.3995.5 (MS029)	Mean monthly maximum and minimum air temperature spatial grids (1971-2000), Andrews Experimental Forest. Smith, Jonathan W. 2015. doi:10.6073/pasta/283ca6ee268dbc286cbbb438a9de8686	DP; PP; OM; IN; PS	
knb-lter-and.3999.5 (MS033)	Radiation spatial grids, Andrews Experimental Forest, 1995-2000. Smith, Jonathan W. 2015. doi:10.6073/pasta/147f76771288fe204c7733d1309bf712	DP; PP; OM; PS	
knb-lter-and.4543.5 (MS036)	Cold air drainage transect studies at the Andrews Experimental Forest, 2002 to Present. Daly, Christopher. 2019. doi:10.6073/pasta/460003ebdbaf016d3f0b3292b56b956b	DP; PP; PS	X

knb-lter-and.5370.4 (MS045)	Air temperature at core phenology sites and additional bird monitoring sites in the Andrews Experimental Forest, 2009-2018. Frey, Sarah J. K. 2019. doi:10.6073/pasta/f64dc0ba1f0e2015a6b4da92939efe37	DP; PP; PS	X
knb-lter-and.5178.3 (MV003)	Throughfall and Isotopic Ratios on WS1 at the Andrews Experimental Forest, 2010-2011. Allen, Scott Thomas. 2016. doi:10.6073/pasta/4a0a5c35bc2c70a29e5011280daa6a64	IN; PP	X
knb-lter-and.5476.2 (MV005)	Meteorological data from the Discovery Tree at the Andrews Experimental Forest, 2015 to present. Still, Christopher J. 2019. doi:10.6073/pasta/3f2717e614e96d67bbe59918a75ee646	DP; PP; PS	X
CLIMATE (cont.)			
knb-lter-and.5513.2 (MV007)	Advanced Resolution Canopy FLOw (ARCFLO) experiment employing the SUbcanopy Sonic Anemometer Network (SUSAN) in WS01 of the HJ Andrews Experimental Forest, July-September 2012. Thomas, Christoph K. 2017. doi:10.6073/pasta/e1dcac713961e62c3aaad2816bbf7780	DP; PP	X
knb-lter-and.5524.2 (MV008)	Vertical tree air temperature measurements within the canopy of the HJ Andrews Experimental Forest, 2011-2019. Frey, Sarah J. K.; Jones, Julia A . 2020. doi:10.6073/pasta/50c497d3d87de2d623d9d88c8c486cf1	DP; PP; PS	X
knb-lter-and.4528.10 (TW006)	Ecohydrology and Ecophysiology intensively measured plots in Watershed 1, Andrews Experimental Forest, 2005-2011. Bond, Barbara J. 2016. doi:10.6073/pasta/9556699360b9fc4a554d332e0ac97c76	PP; DP	X
HYDROLOGY			
knb-lter-and.5453.7 (HF003)	Stream discharge and bedload accumulation in gauged watersheds at the South Umpqua Experimental Forest, Coyote Creek, 1963 to 1981 and 2001 to present. Jones, Julia A.; Rothacher, Jack S. 2019. doi:10.6073/pasta/ba6f0a9e4850c4fe4fd75323f2364a3d	DP; PP	X
knb-lter-and.4341.31 (HF004)	Stream discharge in gaged watersheds at the Andrews Experimental Forest, 1949 to present. Rothacher, Jack S. 2019. doi:10.6073/pasta/c85f62e9070a4ebe5e455190b4879c0c	DP; PP	X
knb-lter-and.4030.7 (HF010)	Stream stage and water table elevation in hyporheic and ground water from McRae Ck well network, Andrews Experimental Forest, 1989-1993. Wondzell, Steven M. 2016. doi:10.6073/pasta/a1473259756bf2818f18602efb7d745c	IN; PP	X
knb-lter-and.3194.7 (HF011)	Stream tracer experiments to assess channel and hyporheic residence times of streams in the Andrews Experimental Forest in 2001 & 2002. Wondzell, Steven M. 2016. doi:10.6073/pasta/2f52b9b221dc17e6b57dfa3b8bb1be15	IN	X

knb-lter-and.3238.6 (HF013)	Stream network from 1997 survey and 2008 LiDAR flight, Andrews Experimental Forest. Lienkaemper, George W. 2016. doi:10.6073/pasta/66d98881d4eb6bb5dedcbdb60dbebafa	DP; PS	X
knb-lter-and.3239.4 (HF014)	Experimental watershed boundaries and gaging station locations, Andrews Experimental Forest, 2011. Lienkaemper, George W. 2005. doi:10.6073/pasta/2d9fc802d082abf245dd474b86a4d391	DP; PP; OM; IN; PS	X
knb-lter-and.3240.4 (HF015)	Hydrologic response units (base units for PRMS streamflow model), Andrews Experimental Forest, 1993. Grant, Gordon E.; Sikka, Alok K. 2005. doi:10.6073/pasta/4a89bbf6b846db175c2f5bca6069b5ee	DP; PP; OM; IN; PS	
knb-lter-and.3241.4 (HF016)	Flow accumulation grid generated from 10 meter DEM, Andrews Experimental Forest, 1998. Valentine, Theresa J. 2005. doi:10.6073/pasta/3b60fb9ffe711df437f7c661fe6880c8	DP; OM; IN; PS	X
knb-lter-and.4541.3 (HF020)	A Study of Hyporheic Characteristics Along a Longitudinal Profile of Lookout Creek, Oregon, 2003. Ninnemann, Jeffery J. 2013. doi:10.6073/pasta/2c149c55bcc729b9cbc7f17fe286ad50	DP	
HYDROLOGY (cont.)			
knb-lter-and.3162.11 (HS004)	Annual bedload accumulation from sediment basin surveys in small gauged watersheds in the Andrews Experimental Forest, 1957 to present. Johnson, Sherri L.; Rothacher, Jack S. 2019. doi:10.6073/pasta/73b09502b3e6b0b2622f53810afa093b	DP; OM	X
knb-lter-and.4062.7 (HS005)	Nutrient and microbial characteristics of mountain stream fine benthic organic matter in the H.J. Andrews Experimental Forest, 1995 to 1996. Bonin, Heather L. 2013. doi:10.6073/pasta/1c7d15aa7533dec1cf3616a57ffadf20	OM; IN	
knb-lter-and.3164.4 (HT001)	Periodic stream temperature data (1957-1983) in the Andrews Experimental Forest. Rothacher, Jack S. 2019. doi:10.6073/pasta/57f74959c511efd0b3a043e8881d6995	DP	
knb-lter-and.4349.3 (HT002)	Stream and air temperature data from stream network in the Andrews Experimental Forest, 1997-2001. Johnson, Sherri L. 2019. doi:10.6073/pasta/9616d9947b733674a3d91a28cb050ca3	DP; PP	
knb-lter-and.4020.23 (HT004)	Stream and air temperature data from stream gages and stream confluences in the Andrews Experimental Forest, 1950 to present. Gregory, Stanley V.; Johnson, Sherri L. 2019. doi:10.6073/pasta/9437d1603044f5b92189110dd8343763	DS; PS; PP; IN	X
knb-lter-and.4792.3 (HT006)	Stream temperature at core phenology stream sites in the Andrews Experimental Forest, 2009 - 2014. Johnson, Sherri L. 2017. doi:10.6073/pasta/7dc5e1f888281081de71818082bd0c78	DP	
CARBON AND NUTRIENTS			

knb-lter-and.5346.3 (AN006)	Lotic Intersite Nitrogen eXperiment II (LINX II): a cross-site study of the effects of anthropogenic land use change on nitrate uptake and retention in 72 streams across 8 different biomes (2003-2006).. Mulholland, Patrick J. 2015. doi:10.6073/pasta/eac34b6c1cfb0268dd76ef68a7a90bfc	IN; OM; DP	X
knb-lter-and.4021.23 (CF002)	Stream chemistry concentrations and fluxes using proportional sampling in the Andrews Experimental Forest, 1968 to present. Fredriksen, Richard L. 2019. doi:10.6073/pasta/bb935444378d112d9189556fd22a441d	IN; OM	X
knb-lter-and.4028.6 (CF004)	Stream, hyporheic, and ground water chemistry of McRae Creek in the Andrews Experimental Forest, 1989 to 1992. Wondzell, Steven M. 2016. doi:10.6073/pasta/1a283b16ba38c5008c7f141e05d4ff2a	IN; PP	
knb-lter-and.4548.7 (CF006)	Storm nutrient dynamics at Andrews Experimental Forest stream gages, 2001 to 2003. Johnson, Sherri L. 2013. doi:10.6073/pasta/809735b6ef217b7c4ab4426f7285401f	IN; DP; PP	
knb-lter-and.4789.6 (CF008)	Stream nutrient sampling during winter baseflow conditions in the Andrews Forest and Willamette River Basin, February 2009. Frentress, Jason J.B. 2014. doi:10.6073/pasta/473900eb2f3204e522270467fef2274c	IN	
knb-lter-and.5275.3 (CF010)	Stream and hyporheic carbon dioxide (CO2) measurements in a headwater catchment, Watershed 1, and throughout Lookout Creek watershed at the HJ Andrews Experimental Forest, July 2013 to July 2014. Dosch, Nicholas T. 2017. doi:10.6073/pasta/0fcd8f3db5ee4afa9a9484046bbef9ea	OM	X
CARBON AND NUTRIENTS (cont.)			
knb-lter-and.5276.4 (CF011)	Carbon Dynamics in the Hyporheic Zone of a Headwater Mountain Stream in the Cascade Mountains, Oregon - Watershed 1 at HJA - June 2013 to March 2014. Corson-Rikert, Hayley. 2016. doi:10.6073/pasta/7a070aab134c1add4f239fab6318b4d7	OM	X
knb-lter-and.5357.4 (CF012)	Stream specific conductance and temperature from small watersheds in the Andrews Forest. Johnson, Sherri L. 2019. doi:10.6073/pasta/604f888863096799db3f24b165b741f2	IN	X
knb-lter-and.4022.20 (CP002)	Precipitation and dry deposition chemistry concentrations and fluxes, Andrews Experimental Forest, 1969 to present. Fredriksen, Richard L. 2019. doi:10.6073/pasta/2cee34b1d3c0836888444f9033c1c1c8	IN	X
knb-lter-and.5489.3 (HF028)	Water stable isotopes for streams and precipitation samples in the HJ Andrews Experimental Forest and Mary's River Watershed, 2014-2016. Segura, Catalina. 2019. doi:10.6073/pasta/3b3063e67b7445f5405a2603c75f667e	DP	X
knb-lter-and.3190.7 (SP002)	Soil Moisture and vegetation cover patterns after logging and burning an old-growth Douglas-fir forest in the Andrews Experimental Forest, 1960-1983. Rothacher, Jack S. 2013. doi:10.6073/pasta/a56385be60eeb67ba0a8edbefa5f9e93	DP; PP	

knb-lter-and.3167.6 (SP004)	Seasonal relationships between soil respiration and water-extractable carbon as influenced by soil temperature and moisture in forest soils of the Andrews Experimental Forest, 1992-1993. Griffiths, Robert P. 2013. doi:10.6073/pasta/01eaba04da76031bf04c3a8940d15221	IN; OM	
knb-lter-and.3168.8 (SP005)	Synoptic soil respiration of permanent forest sites in the Andrews Experimental Forest (1993 REU Study). Griffiths, Robert P. 2013. doi:10.6073/pasta/e069aad91673f3c8e873c4ce14659671	IN; OM	
knb-lter-and.3169.7 (SP006)	Chemical and microbiological properties of soils in the Andrews Experimental Forest (1994 REU Study). Griffiths, Robert P. 2013. doi:10.6073/pasta/7b9d3319314c4561440474bfc1001e1a	IN; OM	X
knb-lter-and.3184.7 (SP007)	Disturbance effects on soil processes in the Andrews Experimental Forest (1995 Stand Age Study). Griffiths, Robert P. 2013. doi:10.6073/pasta/0cf569d70a0141e552c34b2424ba46d6	DP; OM	
knb-lter-and.3142.7 (SP008)	Effect of thinning pole stands on soil processes in southern Oregon, central Coast Range, and central western Cascades of Oregon (1994-1995 BLM Study). Griffiths, Robert P. 2013. doi:10.6073/pasta/b03a6ec9e701c0de8763b6ca5b6e10d8	DP; IN; OM	
knb-lter-and.3185.7 (SP009)	Role of vegetation and coarse wood debris on soil processes and mycorrhizal mat distribution patterns at the Hi-15, Andrews Experimental Forest, 1994-1995. Griffiths, Robert P. 2014. doi:10.6073/pasta/7f341b0080bdc428ff871d2e19c6b93a	IN; OM; PP	X
knb-lter-and.3137.9 (SP010)	Respiration in soils collected from the REU synoptic sample grid in the Andrews Experimental Forest, 1994-1995. Griffiths, Robert P. 2019. doi:10.6073/pasta/7eb9d9c55e18a726a0b29db5d0f58915	IN; OM	
knb-lter-and.3113.7 (SP012)	The relationship between early succession rates and soil properties in the Andrews Experimental Forest, 1999-2000. Griffiths, Robert P. 2016. doi:10.6073/pasta/fb4a5c51c96924f77cd2acae6f32a3ea	PP	
CARBON AND NUTRIENTS (cont.)			
knb-lter-and.3118.8 (SP020)	Effects of topography on soil characteristics in the Andrews Experimental Forest, 1998. Griffiths, Robert P. 2019. doi:10.6073/pasta/891259b761f1e4ccbbbaddd528d19adb	IN; OM	
knb-lter-and.3985.4 (SP026)	Soil survey (1964, revised in 1994), Andrews Experimental Forest. Lienkaemper, George W.; Norgren, Joel. 2005. doi:10.6073/pasta/7929a43cec090cc21e2e164ef624ddf3	DP; PP; OM; IN; PS	
knb-lter-and.4003.3 (SP027)	Willamette National Forest soil resource inventory (SRI 1992) clipped to the Andrews Experimental Forest. Costello, Rosana A. 2005. doi:10.6073/pasta/d1539849c2306edada10b15ff6ab2b82	DP; PP; OM; IN; PS	X

knb-lter-and.4791.3 (SP033)	Soil respiration associated with ectomycorrhizal mats in an old-growth stand along lower Lookout Creek, HJ Andrews Experimental Forest (2008-2009). Phillips, Claire. 2013. doi:10.6073/pasta/7bbf7126f8fbf624ad2e5c6935e74304	PS; OM	
knb-lter-and.4032.10 (TD012)	Dimensions, cover, volumes, mass and nutrient stores of Coarse Woody Debris (bark and wood from logs, snags, and stumps) from forests plots in the western United States and Mexico, 1977 to 2005. Harmon, Mark E. 2016. doi:10.6073/pasta/e683b01f0ab3b1e4b4566471072bcedf	DP; OM; PP	1
knb-lter-and.4053.10 (TD014)	Long-term log decay experiments at the Andrews Experimental Forest, 1985 to 2185. Franklin, Jerry F. 2018. doi:10.6073/pasta/7c67241d2ff15de1f82e33164e8655b4	IN; OM; PP; DP	1
knb-lter-and.4057.10 (TD017)	Comparison of terrestrial versus aquatic decomposition rates of logs at the Andrews Experimental Forest, 1985 to 2015. Harmon, Mark E. 2018. doi:10.6073/pasta/5ecf901df15a5ea1c74d4b41611b3e65	OM; IN	1
knb-lter-and.3140.9 (TD018)	Nitrogen fixation and respiration potential of conifer logs at Andrews Experimental Forest, 1987 to 2006. Harmon, Mark E. 2016. doi:10.6073/pasta/f9ab1f1e736b7e504953e7d9faa63710	IN; OM	1
knb-lter-and.3112.7 (TD020)	Respiration patterns of logs in the Pacific Northwest, 1986-1996. Harmon, Mark E. 2015. doi:10.6073/pasta/a58e2ea9314cd64d87cede824569f38a	OM	1
knb-lter-and.4055.13 (TD021)	Fine wood decay studies at the H.J. Andrews and other Forests across the world, 1989 to 2006. Harmon, Mark E. 2018. doi:10.6073/pasta/d6f1a8f8fa284f126baa50df4011e758	IN; OM; PP	
knb-lter-and.4041.11 (TD023)	LTER Intersite Fine Litter Decomposition Experiment (LIDET), 1990 to 2002. Harmon, Mark E. 2016. doi:10.6073/pasta/f35f56bea52d78b6a1ecf1952b4889c5	OM; IN; PP	X
knb-lter-and.4052.7 (TD024)	Fine woody detritus volume and mass from line transect inventory in WS06, WS07, WS08, and WS09 at Andrews Experimental Forest, 2002 to 2003. Harmon, Mark E. 2013. doi:10.6073/pasta/3ac1a2da901b86f2daec18680cf65208	OM; PP	X
knb-lter-and.4046.7 (TD028)	Mass of forest floor litter from cores in reference stands and inventory plots in the Pacific Northwest, 1992 to 2003. Harmon, Mark E. 2015. doi:10.6073/pasta/5299816444be546821f7d6c6d8f77c19	OM; PP	X
knb-lter-and.3125.7 (TD030)	Fine woody debris inventory data from reference stands and inventory plots in the Pacific Northwest, 1992 to 2000. Harmon, Mark E. 2016. doi:10.6073/pasta/a171e3ec7f589eab4a9cbe25762cc19f	OM	X
knb-lter-and.4064.6 (TD031)	Decomposition of Fine Woody Roots: a Time Series Approach, 1995 to 2006. Harmon, Mark E. 2016. doi:10.6073/pasta/5769ed5597ebee8f04a72d6f30bc18a3	OM; IN; PP	

CARBON AND NUTRIENTS (cont.)			
knb-lter-and.3124.9 (TD035)	Coarse woody debris volume and mass from line transect inventory from reference stands and inventory plots of the Pacific Northwest, 1997 to 2005. Harmon, Mark E. 2015. doi:10.6073/pasta/7ca711bd80730b8fb8f520b1548be875	OM	X
knb-lter-and.4550.4 (TN025)	Nutrient Concentrations of Vegetation in Small Watersheds at H. J. Andrews Experimental Forest, 2005 to 2006. Harmon, Mark E. 2016. doi:10.6073/pasta/fbbfc439ed14e178c178713f99b7f46c	OM; IN; PP	X
BIODIVERSITY			
knb-lter-and.4027.13 (AS006)	Aquatic Vertebrate Population Study in Mack Creek, Andrews Experimental Forest, 1987 to present. Gregory, Stanley V. 2018. doi:10.6073/pasta/e0cdc59665eea0e7becd4d163f33ac83	DP; PS	X
knb-lter-and.5330.3 (AS010)	Riparian controls on light availability, primary producers, invertebrates, fish and salamanders in streams in and near the Andrews Experimental Forest, 2014-2018. Kaylor, Matthew J. 2019. doi:10.6073/pasta/4159cb86beb23c683b59b329601f1861	DP; PS; PP	X
knb-lter-and.5484.2 (AS011)	Aquatic vertebrate populations in streams across the upper Andrews Experimental Forest, 2013 to present. Johnson, Sherri L.; Penaluna, Brooke E. 2019. doi:10.6073/pasta/a1271ef4e52f51a35e57b15baa4e2e84	DP; PS	X
knb-lter-and.5169.2 (FS123)	Uneven Aged Management Project (UAMP), Andrews Experimental Forest. Emmingham, William H.; Tucker, Gabriel F. 2018. doi:10.6073/pasta/13eb1d0efd32b228f916067e98aa7f46	PS; DP	
knb-lter-and.2719.6 (SA001)	Invertebrates of the Andrews Experimental Forest: An annotated list of insects and other arthropods, 1971 to 2002. Lattin, John D.; Parsons, Gary L. 2014. doi:10.6073/pasta/397e0bba0f8aeac013d01fc982a74ea8	PS	
knb-lter-and.2720.8 (SA002)	Vascular plant list on the Andrews Experimental Forest and nearby Research Natural Areas, 1958 to 1979. McKee, W. Arthur. 2014. doi:10.6073/pasta/ded9fb37c339581807365334708d0353	PS	
knb-lter-and.2721.6 (SA003)	Bird species list for the Andrews Experimental Forest and Upper McKenzie River Basin, 1975 to 1995. McKee, W. Arthur. 2014. doi:10.6073/pasta/877a3e148da1dc35d6c72b57e710a46e	PS	
knb-lter-and.2722.6 (SA004)	Amphibian and reptile list of the Andrews Experimental Forest, 1975 to 1995. Beatty, Joseph J. 2014. doi:10.6073/pasta/09702481ce4d9c76dd3cc25a6bb700b8	PS	

knb-lter-and.2726.6 (SA005)	Mammal species list of the Andrews Experimental Forest, 1971 to 1976. Anthony, Robert G. 2014. doi:10.6073/pasta/10e4204c0f25c6d1c8193a519e63ebf4	PS	
knb-lter-and.2725.6 (SA008)	Moss species list of the Andrews Experimental Forest, 1991. Peck, JeriLynn Eloise. 2013. doi:10.6073/pasta/8d7078a108c00a5e15c5a680feb4e629	PS	
knb-lter-and.2727.7 (SA009)	Riparian bryophyte list of the Andrews Experimental Forest, 1994/1995. Jonsson, Bengt Gunnar. 2014. doi:10.6073/pasta/fad1929d40aa8bcaff4ae5ca59a8da04	PS	
BIODIVERSITY (cont.)			
knb-lter-and.2728.7 (SA010)	Epiphyte species list of Watershed 10, Andrews Experimental Forest, 1970 to 1972. Carroll, George C. 2014. doi:10.6073/pasta/87d3d2cbf980e0b10e8c8c00ac1e17a1	PS	
knb-lter-and.2733.6 (SA011)	Lichen abundance and biodiversity along a chronosequence from young managed stands to ancient forest, 1993 (Neitlich thesis). Neitlich, Peter N. 2011. doi:10.6073/pasta/c313f622f54ae86f0ea23abd246ff403	PS	
knb-lter-and.2730.7 (SA012)	Macroinvertebrate species list of the Andrews Experimental Forest, 1992. Gregory, Stanley V. 2014. doi:10.6073/pasta/a01c60813d15b254422b917eb853dfd1	PS	
knb-lter-and.2732.7 (SA014)	Mycorrhizal belowground fungi species list of the Andrews Experimental Forest, 1992 to 1994. Smith, Jane E. 2014. doi:10.6073/pasta/ee0612be7ddadd5d5945118c70550d2e	PS	
knb-lter-and.2739.7 (SA015)	Spatial and temporal distribution and abundance of moths in the Andrews Experimental Forest, 1994 to 2008. Miller, Jeffrey C. 2013. doi:10.6073/pasta/0cebe58bcc514e2bbf890ee7b2ea21c1	PS	X
knb-lter-and.3136.5 (SA016)	Spatial and temporal distribution and abundance of butterflies in the Andrews Experimental Forest, 1994-1996. Ross, Dana N. R. 2014. doi:10.6073/pasta/b75017cddc991a02d3ed3302578b5b45	PS	
knb-lter-and.4346.6 (SA017)	Aquatic insect sampling in Lookout Creek at the H.J. Andrews Experimental Forest, 2001. Farrand, Alex M. 2014. doi:10.6073/pasta/babf56fed5882756432f28982312a551	PS	X
knb-lter-and.4547.5 (SA021)	Epiphytic macrolichens in relation to forest management and topography in a western Oregon watershed, 1997-1999 (Berryman thesis). Berryman, Shanti D. 2014. doi:10.6073/pasta/5983313a0889f90f824b8e4c14c98ba8	PP; DP	
knb-lter-and.4345.8 (SA022)	Headwater Stream Macroinvertebrates of the H.J. Andrews Experimental Forest, Oregon, 2003-2004. Frady, Charles H. 2019. doi:10.6073/pasta/0fd89ea87c5b13959209a6e2f64a501b	PS; PP	X

knb-lter-and.4781.3 (SA024)	Forest-wide bird survey at 183 sample sites the Andrews Experimental Forest from 2009-2019. Frey, Sarah J. K.; Kim, Hankyu; Betts, Matthew G. 2019. doi:10.6073/pasta/a4a5c9debf1c21e82b191e7d7d7f7197	PS; PP	X
knb-lter-and.4782.5 (SA025)	Aquatic and terrestrial insect activity phenology with trap collections at the Andrews Experimental Forest, 2009-2014. Johnson, Sherri L.; Li, Judith L. 2019. doi:10.6073/pasta/89707e1fc94c1d4fa96f48fc5f273c59	PS; DP	X
knb-lter-and.5216.4 (SA026)	Plant Pollinator data at HJ Andrews Experimental Forest, 2011 to present. Pfeiffer, Vera Wilder. 2017. doi:10.6073/pasta/fdb23c02e2e9b5ed98e03f62da603045	PS; PP	X
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knb-lter-and.3213.11 (TP041)	Post-logging community structure and biomass accumulation in Watershed 10, Andrews Experimental Forest , 1974 to present. Gholz, Henry L. 2019. doi:10.6073/pasta/065e8bdaf36478d8e85ab0837d76bbe5	DP; OM; PP	X
BIODIVERSITY (cont.)			
knb-lter-and.3217.15 (TP073)	Plant succession and biomass dynamics following logging and burning in Watersheds 1 and 3, Andrews Experimental Forest, 1962 to Present. Dyrness, C. Ted. 2019. doi:10.6073/pasta/f1e9b226cb0fb6254f10692477ff6d6d	DP; OM; PP	X
knb-lter-and.3145.17 (TP103)	Species interactions during succession in the western Cascade Range of Oregon, 1990 to present. Halpern, Charles B. 2019. doi:10.6073/pasta/4f23d0d998bc19db6ee68b767c8772bf	DP; PP	X
knb-lter-and.4525.9 (TP108)	Demonstration of Ecosystem Management Options (DEMO) Study, western Oregon and Washington (post-treatment data, 1998-2016). Halpern, Charles B. 2018. doi:10.6073/pasta/331e366226a29672d8dc9bb373d37249	DP; PP	
knb-lter-and.4054.7 (TP114)	Plant biomass dynamics following logging, burning, and thinning in Watersheds 6 and 7, Andrews Experimental Forest, 1979 to present. O'Connell, Kari B. 2015. doi:10.6073/pasta/f45b3280ab4fab12ff879813495cb869	PP; DP; OM	X
knb-lter-and.94048.3 (TP119)	Vegetation history classification for Watersheds 1, 2, and 3, Andrews Experimental Forest, 1959-1990. Bredensteiner, Kim. 2005. doi:10.6073/pasta/b9fc50f6cb577f1efa9d72f0d973fae1	PP; DP	X
knb-lter-and.4544.4 (TP120)	Annual tree productivity in permanent plots within the H.J. Andrews Experimental Forest. Woolley, Travis J. 2013. doi:10.6073/pasta/d39e81049702599b291d99079a3b7ed9	PP; DP	X

knb-lter-and.3143.9 (TV009)	Dendrometer studies for stand volume and height measurements of trees of the western US, 1976 to 1993. Franklin, Jerry F. 2015. doi:10.6073/pasta/7285268c91826498ef60bb6bd2f823c1	OM; PP	X
knb-lter-and.2742.13 (TV010)	Long-term growth, mortality and regeneration of trees in permanent vegetation plots in the Pacific Northwest, 1910 to present. Franklin, Jerry F. 2019. doi:10.6073/pasta/10ebe50351d20960e4ef0fdb28cc4334	PP	X
knb-lter-and.3254.15 (TV019)	Cone production of upper slope conifers in the Cascade Range of Oregon and Washington, 1959 to present. Schulze, Mark D; Franklin, Jerry F. 2019. doi:10.6073/pasta/2143c0c75491d2923e3302032ddca1f8	PS; PP	
knb-lter-and.3182.8 (TV036)	Streamside mosses at the Andrews Experimental Forest, 1994. Jonsson, Bengt Gunnar. 2019. doi:10.6073/pasta/6264baad5fa8d54044803e89b3bb7bc6	PS	
knb-lter-and.3976.1 (TV056)	Comparisons among five canopy-cover estimating methods in five Douglas-fir/western hemlock structure types in the western Oregon Cascades. Fiala McIntosh, Anne C.S. 2004. doi:10.6073/pasta/325f2cd2e4dd5569e700556b00e44604	PP; PS; DS	
knb-lter-and.3989.7 (TV061)	Vegetation classification, Andrews Experimental Forest and vicinity (1988,1993,1996,1997,2002, 2008). Lienkaemper, George W. 2015. doi:10.6073/pasta/68296d816c9f4d8fe6e8bc3ed1668a5b	PP; PS; DS	
knb-lter-and.4009.5 (TV062)	Plant community typing (2009 update), Andrews Experimental Forest. Hawk, Glenn M. 2014. doi:10.6073/pasta/1b9d9a1bf44d3df7431c9703c9be602f	PP; DS; PS	
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knb-lter-and.4780.4 (TV075)	Vegetative Phenology observations at the Andrews Experimental Forest, 2009 - Present. Schulze, Mark D. 2020. doi:10.6073/pasta/c7f7251bd46ae8622b2c520eaeeaa9fe	PP; DP	X
knb-lter-and.5277.6 (TV080)	Aboveground Live Biomass (2008), Andrews Experimental Forest. Spies, Thomas A. 2015. doi:10.6073/pasta/3f91854669d9cccd12b29235f4d7f892	OM; PP; DP	X
knb-lter-and.5316.4 (TV081)	Forest metrics derived from the 2008 Lidar point clouds, includes canopy closure, percentile height, and stem mapping for the Andrews Experimental Forest. Spies, Thomas A. 2014. doi:10.6073/pasta/875e10383e8c8aee3c9a49e0155eef1d	PP; DP	X
knb-lter-and.3147.7 (WE027)	Vertebrate-habitat relationships: Logistic regression models predict probability of occurrence of bird and small mammal species in western Oregon. Garman, Steven L. 2013. doi:10.6073/pasta/14b840b2623903b54a44cec19198bbca	PS	

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knb-lter-and.3178.10 (DF007)	Dendrochronology study of fire history, Andrews Experimental Forest and central western Cascades, Oregon, 1482-1952. Teensma, Peter D. Adrian. 2016. doi:10.6073/pasta/ad9a79f8fcb4ce8475949601caae4aeb	DP; PP	
knb-lter-and.3982.7 (DF018)	Spot fire locations (1991), Andrews Experimental Forest. McKee, W. Arthur. 2013. doi:10.6073/pasta/e0c0a481f8619366278617499d6781d4	DP	
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DISTURBANCE (cont.)			
knb-lter-and.4000.6 (GE010)	Mass movement assessment: cascade hazards ratings, Andrews Experimental Forest, 1992. Swanson, Frederick J. 2005. doi:10.6073/pasta/51209123216e105a58cd6a7a9df84243	DP	
knb-lter-and.4002.5 (GE012)	Landslide inventory (1953-1996), Andrews Experimental Forest and Blue River Basin.. Swanson, Frederick J. 2014. doi:10.6073/pasta/0f28e7e81b0fde808e86d28e4f1782aa	DP	X

knb-lter-and.3189.10 (GS002)	Stream cross-section profiles in the Andrews Experimental Forest and Hagan Block RNA 1978-present. Swanson, Frederick J. 2014. doi:10.6073/pasta/37f143145be39f2d78cf4b02ecab6a26	DP	X
knb-lter-and.4031.8 (GS006)	Dynamics of large wood in streams: Tagged log inventory, Mack Creek, Andrews Experimental Forest, 1985 to 2008. Gregory, Stanley V.; Lienkaemper, George W. 2013. doi:10.6073/pasta/9e6e1ea340fdde0e8309d5e8d5664ddb	DP; OM; PP	X
knb-lter-and.5328.2 (SS002)	Landcover change analysis of the McKenzie Basin for the Maps and Locals (MALS) project.. McCune, Myrica. 2014. doi:10.6073/pasta/8e6e5cf7ffd7335bcc07d766ea61dfcd	DP	
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LAND USE			
knb-lter-and.3228.4 (DH001)	Road construction history (1952 - 1990), Andrews Experimental Forest. Lienkaemper, George W. 2005. doi:10.6073/pasta/b05b3ac90d8fe8d10575a5f92c7cf114	DP	X
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knb-lter-and.3230.4 (GI002)	30 meter digital elevation model (DEM) clipped to the Andrews Experimental Forest, 1996. Lienkaemper, George W. 2005. doi:10.6073/pasta/283ce7118c4c11b4f222896d46be81bd		X
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knb-lter-and.3234.6 (GI006)	Adminstrative boundary, Andrews Experimental Forest, 1997 survey, 2009 update. DeSilva, Tere. 2014. doi:10.6073/pasta/5257cf486a501a50f83890bff2f1d9bb		X
knb-lter-and.4043.4 (GI007)	Transportation network system including trails, road construction history, and gates for the Andrews Experimental Forest, 1952-2011. Lienkaemper, George W. 2014. doi:10.6073/pasta/c093067b268705ba0ec2a0d9c85c7fb9	DP	
knb-lter-and.4044.5 (GI008)	Land use designations, Andrews Experimental Forest, 1998-2011. McKee, W. Arthur 2014. doi:10.6073/pasta/2425e56ddf0a03499ed78915eca46783	DP	X
knb-lter-and.5030.6 (GI010)	LiDAR data (August 2008) for the Andrews Experimental Forest and Willamette National Forest study areas. Spies, Thomas A. 2013. doi:10.6073/pasta/c47128d6c63dff39ee48604ecc6fabfc	DP; PP	X

LAND USE (cont.)			
knb-lter-and.5345.2 (GI011)	LiDAR data (October 2011) for the Blue River Watershed, Willamette National Forest. Spies, Thomas A. 2014. doi:10.6073/pasta/8e4f57bafaaad5677977dee51bb3077c	DP; PP	X
HUMAN DIMENSION			
knb-lter-and.5329.1 (SS001)	Record of Public Communications at the HJ Andrews Experimental Forest (1980-2002). Swanson, Frederick J. 2014. doi:10.6073/pasta/cdd0de8b2ffc06a77d26930f179011c7		
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knb-lter-and.5420.2 (SS006)	H.J. Andrews Forest Discovery Trail: An interpretation of place based on curriculum of interpretive learning trail and field trip support, 2016.Goralnik, L. and K.B. O'Connell. 2020. doi:10.6073/pasta/67de94357b7fba74a03c736a7f5b86b4		X
knb-lter-and.5444.3 (SS007)	Influences on charitable giving for conservation: Online survey data of 1,331 respondents across the US, August 2017. Batavia, Chelsea. 2019. doi:10.6073/pasta/926e6270e324a1322a900da14d38b96c		
knb-lter-and.11856.2 (SS009)	Oral history transcripts from the H.J. Andrews Experimental Forest Program, 1996 to 2018. Swanson, Frederick J.; Schmieding, Samuel. 2020. doi:10.6073/pasta/a4bd042b2d75ade0aad3406779de4fe4	DP	X

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