LTER: The Interacting Effects of Hydroclimate Variability and Human Landscape Modification in the Southern Appalachian Mountains

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Project Summary

Southern Appalachian forests are highly productive ecosystems that are globally rich in biodiversity, yet vulnerable to the effects of global warming and human activities. The challenges are to understand key processes at a range of scales, and to identify interventions to advance management objectives while mitigating and adapting to the forces of change. This requires long-term data across multiple scales that transcend traditional disciplinary boundaries. The objective of the CWT VII renewal is to understand: **How hydroclimate variability and the human-modified landscape separately and interactively alter southern Appalachian Mountain ecosystem processes and biotic communities that, in turn, affect the vulnerabilities of regional socio-ecological systems.**

Intellectual Merit: Research will continue and build on long-term studies and monitoring activities across numerous permanent plots within and beyond the Coweeta Basin that include over 20 years of tree demographic data representing more than 350,000 tree-years. Activities will consist of a large-scale throughfall displacement experiment across an elevation-moisture gradient; an examination of performance and abundance of a suite of herb, invertebrate, salamander and bird species across a range of existing and new sampling plots; a large-scale rhododendron removal experiment to examine processes at the interface between terrestrial and stream ecosystems in relation to management; and, modeling of past and present hydroclimate variability and the generation of future scenarios to establish ecosystem function and risks across square-meter to regional geographies.

The throughfall displacement experiment will consist of treatment and control plots paired in first-order catchments at each of three landscape positions in which approximately 2/3rd of throughfall will be removed to understand how ecosystems respond to hydroclimate extremes. Focal taxa observations and measurements will be taken across more than 60 1-ha plots within the Coweeta Basin, the Upper Little Tennessee River and the French Broad River basins. A series of intensive plot-scale experiments and extensive reach-scale treatments will be used to assess the post-rhododendron removal rates of recovery for vegetation dynamics, soil microbial communities, soil extracellular enzyme activity, and nutrient pools and fluxes. Hydroclimate variability and land use will be quantified from 1880 to 2080 to improve the RHESSys model then analyze future scenarios from Coweeta sub-basins through the Little Tennessee River and the French Broad River basins.

Broader Impacts: Understanding the relationships between ecosystems, organisms, and their responses to the forces of hydroclimate variability and human activities on the land are essential if ecological science is to anticipate, respond to, and mitigate these changes and the associated vulnerabilities. The Coweeta Listening Project and the Coweeta Scholyard Program translate and communicate community-relevant results from CWT LTER research to engage society with science in the southern Appalachian Mountains. Educational activities will include field-based environmental education and in-classroom support for middle school teachers and students; internships and mentoring in research and science communication for undergraduate and graduate students; support for outreach programs to land owners on the importance of riparian corridor integrity; and, publishing a bi-weekly newspaper column under the byline of Science, Policy and Management.

Section 1: Results of Previous Support

1.1. Introduction: The Coweeta (CWT) LTER program was established in 1980 and we are now completing CWT-VI (2008-14), which involves 28 Project Investigators and 12 Affiliated Investigators from 9 institutions. During this funding cycle we published 268 peer-reviewed publications, one edited book, 10 book chapters, and 26 theses and dissertations. This brings our cumulative total since 1980 to 1,227 publications, and 249 theses and dissertations. We effectively leveraged the CWT-VI award for additional funds from NSF, NASA, PUF, USDA, USGS, and elsewhere to achieve project objectives.

The CWT LTER program was established to quantify ecosystem response to 'natural' and human disturbance regimes in the southern Appalachian Mountains (e.g., Swank and Crossley 1988, Swank and Webster 2014). In CWT-VI we focused on how key ecosystem processes along with water quantity, water quality, and biodiversity were impacted by the a) transition in land uses from wildland to urban and peri-urban; b) changes in mean climate; and c) interaction between changes in land use and climate. We summarize our results by the five thematic areas into which the 2008-2014 research was organized: 1) parcel- to regional-level decision making; 2) longitudinal variation in hillslope, riparian, and stream ecology; 3) impacts of climate and land use change on biodiversity; 4) baseline data and temporal reconstruction; and, 5) synthesis and scaled integration. Our 10 signature publications are: Bain et al. (2012), Band et al. (2012), Chamblee et al. (2011), Clark et al. (2013a), Ford et al. (2011) Kuhman et al. (2013), Long and Jackson (2013), Price et al. (2010), Warren and Chick (2013), and Webster et al. (2012b). Supplement-supported activities are denoted by (S*).

1.2. Parcel- to Regional-level Decision Making: CWT LTER research takes place in the rapidly urbanizing Piedmont Megapolitan region and its expanding *Ring of Asphalt* (Shepherd et al. 2013). Stream health and water quality are heavily influenced by land use decision-making at the parcel level as former agricultural lands are fragmented into residential developments (Kirk et al. 2012). Home and road construction have caused erosion and increased stream sedimentation (Price et al. 2010, Kirk et al. 2012). While residents regard "stream muddiness" as a pressing issue, landowners regularly remove riparian vegetation and large woody debris from streams on their properties (S*) (Evans 2013, Long and Jackson 2013). Landowner riparian zone management impacts stream health and water quality emphasizing the need to reconcile the impacts of behavior at the local scale with the hydrologic processes at the watershed scale (Jackson and Pringle 2010, Evans 2013).

Our recent willingness-to-pay survey (Allen and Moore) found 86% agreement in the Macon county population (contains the Coweeta Hydrologic Laboratory) for "An ordinance should be put in place to monitor mountain slope development". However, the trade-offs of putting such regulation in place have not yet been resolved (Gustafson et al. 2014, Vercoe et al. 2014). We have also examined the structure of land prices before and after a local conservation activity (Chamblee et al. 2011). Our results indicate that private conservation increases land prices by creating amenity effects and removing land from a market that distinguishes between conservation in fee versus conservation in easement. This means that regional land management strategies must consider local land markets to avoid promoting development near conserved parcels.

1.3. Longitudinal Variation in Hillslope, Riparian and Stream Ecology: We characterized ecological consequences of topoclimate and urban development from valley bottoms across complex mountain terrain in the Upper Little Tennessee River watershed. Our findings illustrate the importance of distinguishing between land cover and land use as predictors of stream flow regimes, and how steep slope development contributes to elevated stream nitrate levels (Webster et al. 2012b). Urban development from valley bottoms to ridge tops increases debris flow, runoff and erosion hazard (Kirk et al. 2012), but our results also showed that topoclimate can be as significant as land use/cover in controlling watershed hydrology. Analysis of remote sensing images showed that hillslope LAI patterns became more uniform over the last three decades in response to climate change impacts on subsurface transport of water and nutrients

(Hwang et al. 2012, Hwang et al. 2014). More uniform cover occurs on lower elevation and south-facing slopes correlating with increased evaporation and reduced runoff. A potential shift to more frequent landslide debris loading from upper slopes into streams is exacerbated by recent increases in extreme precipitation events (Band et al. 2012), and potential expansion of rhododendron which reduces root cohesive strength (Hales et al. 2009).

1.4. Impacts of Climate and Land-use Change on Biodiversity: We contributed understanding to how exurbanization, climate change, and disturbance affect terrestrial and aquatic ecosystems and biodiversity. With our long-term tree phenology records we documented earlier spring leaf-out and more variable, drought-dependent leaf fall (Hwang et al. 2011b, Hwang et al. 2011a). We also identified the most important variables for forest change at individual (Clark et al. 2013a) and continental scales (Zhu et al. 2012, Zhu et al. 2014). The interactions between temperature, drought, and competition for light and moisture vary widely between species and size classes (Clark et al. 2010, Clark et al. 2011b, Clark et al. 2013c, Clark et al. 2013a), but high forest diversity is promoted by individual responses to landscape variation in moisture, temperature and competition (Clark 2010, Clark et al. 2010, Clark et al. 2012a, Clark et al. 2013c, Clark et al. 2013b). Demographic data from tree species on the *Gap Plots* in the Coweeta Basin and elsewhere (Ibanez et al. 2007, Ibanez et al. 2008, 2009, Zhu et al. 2012, Zhu et al. 2014) indicate that trees at regional and continental scales across eastern North America are not migrating fast enough to keep up with their putative climate envelope.

We showed that changes in land cover and species composition due to nonrandom species loss or land management decisions can alter key hydrologic and biogeochemical processes. Low forest cover removal rates affect infiltration, storage, and hence stream flow (Price and Leigh 2006b, a, Leigh 2010, Price et al. 2010). The rapid loss of eastern hemlock from riparian forests due to hemlock wooly adelgid (Elliott and Vose 2011, Ford et al. 2012a) altered carbon (C) (Nuckolls et al. 2009, Ford et al. 2012a) water (Ford and Vose 2007, Brantley et al. 2013, Brantley et al. In press), and nutrient cycling (Knoepp et al. 2011, Block et al. 2012, Block et al. 2013). It also affected terrestrial (Ball et al. 2008) and aquatic litter decomposition (Kominoski et al. 2007, Kominoski et al. 2009, Kominoski and Pringle 2009), and stream temperature and trophic processing (Webster et al. 2012a) shifting stream metabolism towards greater heterotrophy (Northington et al. 2013). Forest management results in vegetation changes that mitigate or exacerbate the streamflow response to extreme precipitation events due to differences in species' sensitivity to climate variability (Ford et al. 2011b).

Our research demonstrated how land use legacies and contemporary landscape patterns affect invasion biogeography, radiation, and dominance of non-native understory herbs (Albright et al. 2009, Anderson et al. 2013, Kuhman et al. 2013), while heterogeneity in the distribution of soil resources depends on disturbance history (Fraterrigo et al. 2005, Fraterrigo et al. 2006d). We used modeling and field manipulations to show how spatial heterogeneity in disturbance and resource availability affect the dispersal, persistence, and abundance of native and non-native plants (Fraterrigo et al. 2009a, 2009b). Our studies in the French Broad River Basin demonstrated that land use history was locally important (Kuhman et al. 2010, 2011), while a multi-year seedling and germination study demonstrated that a thin leaf litter layer and moist soil conditions promote non-native plant invasion (Kuhman et al. 2013).

We demonstrated that plant reproductive and growth strategies are affected by climate and other niche variables across gradients (Warren 2009, Warren and Bradford 2010). Our research also showed that native understory species decline in old stands through reduced fecundity and in young stands through reduced growth (Jackson et al. 2013). Our research established that the shift in ant distribution to higher elevations corresponds with minimum, not maximum, temperature tolerance (Warren and Chick 2013), while insect pollinator abundance and community composition vary with elevation and land-use legacies (Jackson et al. 2012). Finally, our research demonstrated declines in forest interior avian species and Neotropical migrants with the expansion of residential development because edge species increase predation on nests (Lumpkin et al. 2012, Lumpkin and Pearson 2013).

1.5. Baseline Data and Temporal Reconstruction: We analyzed 85 years of long-term climate and streamflow records from the Coweeta Basin to show increasing temperature, and increasing precipitation variability and streamflow since 1980 (Ford et al. 2011b, Laseter et al. 2012). Our analysis of regional meteorological data showed that temperature increases are variable across the southern Appalachian Mountains (Warren and Bradford 2010). We developed a hierarchical Bayesian model to simulate streamflow under a doubled CO_2 climate scenario. The results indicate reduced soil moisture in summer and fall at both low and high elevations, uncertain changes in summer streamflow, and increased streamflow in winter at both low and high elevations (Wu et al. 2011, 2012). The data we will obtain by upgrading and expanding our sensor network to retrieve meteorological and soil measures in near-real time (NSF-FSML 1226983) will be used to resolve issues of coherence and validate scenarios.

1.6. Synthesis and Scaled Integration: We used terrestrial and aquatic ecosystem models, separately and integrated, to study the dynamics of water, C and N in watersheds of the Little Tennessee River Basin. The RHESSys model (Band et al. 1993, Band et al. 1996, Band et al. 2001, Tague and Band 2004, Hwang et al. 2009) is a hillslope hydrology model suitable for first through sixth-order watersheds that includes coupled biogeochemical and productivity models. We demonstrated that root tensile strength differences between woody species compounded by their ecological sorting along a water-stress gradient, alters the susceptibility of slopes to mass wasting (Hales et al. 2009). We then extended the RHESSys model to predict landslide vulnerability as a function of root strength, extreme weather, and lateral throughflow redistribution (Band et al. 2012).

We also used RHESSys to integrate terrestrial and stream processes to calculate lateral inputs of water and N to a stream reach that are then processed by a stream metabolism model (Lin 2013). Our results demonstrate the combined influence of terrestrial and in-stream processes in controlling the timing and magnitude of nitrate concentrations and mass export from forested watersheds. Nitrogen export was more sensitive to in-stream processes when terrestrial inputs were low, but when N loading was high, in-stream processes were saturated and had little impact on watershed export (Lin and Webster 2013). We are extending the model to predict the effects of mountainside development on N export in the Little Tennessee River, and preliminary results suggest that high density near-stream residential development in the absence of buffer zone protection results in higher N export (Lin 2013).

1.7. Education and Outreach: We developed educational activities in the Coweeta LTER Schoolyard program (S*) that meet state curriculum standards and create numerous opportunities for students and teachers. We held 60 events since 2008 that engaged 4,589 students from 14 schools across three states. Our signature events include "Migration Celebration" and "Kids in the Creek", that we organize in partnership with Land Trust for the Little Tennessee, Southern Appalachian Raptor Research, US Fish and Wildlife Service, NC Natural Heritage Program, NC Wildlife Resources Commission, and NC Division of Water Resources. Our Science Study Boxes, filled with science equipment and activities covering diverse topics, served over 7,000 students in western North Carolina and north Georgia. In coordination with the USDA Forest Service Coweeta Hydrologic Laboratory, we offered 259 tours and events to 3,296 people for 1,395 contact hours. During three summers, area high school teachers with RET funding (S*) worked with CWT LTER researchers on curriculum development and student activities. Six University of Georgia students with REU funding (S*) worked with CWT LTER researchers on projects examining salamander predation, hydroclimate effects on fauna, and citizen-science engagement in North Carolina, and an ILTER project in France.

The Coweeta Listening Project (CLP) was established in 2011 to translate CWT LTER science for diverse audiences. Members of the collaborative publish a bi-weekly column in a local newspaper under the by-line "Science, Public Policy, Community" to foster community connections and awareness of CWT LTER research. The CLP help create a partnership with the Land Trust for the Little Tennessee to identify vulnerable streams for use in public education, and collaboratively develop the citizen-science tool we

call the *Southern Appalachian Stream Visual Assessment Protocol* (saSVAP). An area high school student helped field-test the saSVAP through a summer RAHSS (S*) internship.

1.8. Cross-site and Collaborative Activities: The *Long-term Forest Demographic (LTFD) Analysis* network was established in 1991 in the Coweeta Basin (*Terrestrial Gradient Plots* see Facilities) to understand how climate and competition interact to control change in eastern forests (Clark et al. 1998, Clark et al. 2004). These plots were supplemented in 2002 with the *Gap Plots* in the Coweeta Basin (see Facilities), and the network now includes scientists from eight institutions, three LTER sites (Coweeta, Harvard Forest, Luquillo), and other sites across eastern North America and Central America. Observations are made at member sites on natural variation in space and time that are combined with experimental manipulation of competitive environments. Results have generated new understanding of how individual tree responses govern demographic trends at the landscape scale (Clark 2010, Clark et al. 2011b, Clark et al. 2012b, Clark et al. 2013a).

CWT LTER scientists participated in the *Lotic Intersite Nitrogen Experiment* (LINX I and LINX II) with members of eight other LTER sites and demonstrated the role of streams in watershed N export (Mulholland et al. 2008, Hall Jr. et al. 2009, Mulholland et al. 2009, Bernot et al. 2010, Helton et al. 2011, Johnson et al. 2013). Cross-site research initiatives developed at the 2012 All Scientists Meeting in which CWT LTER scientists participated include: *Legacy Effects*, quantified pre-instrumental signals in sediment and material flux from catchments across the LTER network (Bain et al. 2012); *QUEST*, quantified sources of uncertainty in streamflow and chemistry across LTER and non-LTER sites (Yanai et al. 2012); and *Clim-Hydro*, focused on social and ecological responses to climate change and land-use effects on water availability across LTER sites (Creed et al. in review). The CWT LTER Information Manager contributed to cross-site collaboration by first being a member of the LTER IM Executive Committee (2011) and currently serving as IMC Co-Chair (2012 to 2015). The CWT LTER and GCE LTER Information Managers also partnered (S*) to document use of the GCE Data Toolbox then co-hosted a training workshop for 15 information managers from 11 LTER sites (Chamblee et al. 2013). Now nearly one-half of Information Managers across the LTER Network use the Toolbox for some aspect of information management at their site.

Section 2: Proposed Research

2.1. Introduction

Southern Appalachian forests are highly productive ecosystems and globally rich in biodiversity, having been shaped by the interactions between a wet regional climate and a mountainous topography across evolutionary time scales. Microclimate varies with elevation, slope, convergence, aspect and orographic variation in precipitation and humidity. While forest cover partly stabilizes local microclimates against small-scale climate variation, ecosystems are vulnerable to the effects of global warming and human activities. Forest ecosystems and human systems across the southern Appalachian Mountains are now linked at multiple levels (Figure 1). The challenges are to understand key processes at a range of scales, and to identify interventions to advance management objectives while mitigating and adapting to the forces of change (Jackson et al. 2009, Ford et al. 2011b, Webster et al. 2012b, Zhu et al. 2012). Meeting these challenges requires many years of multi-scale data (Jackson et al. 2009, Clark et al. 2011b, Clark et al. 2012a) and transcending traditional disciplinary boundaries. This places the CWT LTER in a unique position to build on past CWT LTER and pre-LTER research (Swank and Webster 2014) on logging (CWT-I, CWT-II), natural and human disturbance (CWT-III), topographical and climate gradients (CWT-IV), regional land cover change (CWT-V), and exurbanization (CWT-VI).

In CWT-VII we propose developing a mechanistic understanding of the relationships between ecosystems, organisms, and their responses to the forces of hydroclimate variability and human activities on the land. Hydroclimate comprises the scale-dependent, spatio-temporal components of the water cycle



Figure 1. Overview of the CWT-VII Research plan conceptualizing the influence of local and regional land use change upon the hydroclimate template of the S. Applalachian biome and illustrating where the principal research components fit within and across these interactions.

characterized by the means, variability, and extremes of key mesoclimatic and microclimatic variables (Karamouz et al. 2013). Our proposed research furthermore reflects the need to understand ecological processes across broader scales so that we may uncover the feedbacks that link the biophysical and the human realms (Rockström et al. 2009, Chapin et al. 2011, Collins et al. 2011). Our objective in the CWT-VII renewal is to understand: **How do hydroclimate variability and the human-modified landscape separately and interactively alter southern Appalachian Mountain ecosystem processes and biotic communities that, in turn, affect the vulnerabilities of regional socio-ecological systems?**

Our proposed research continues and builds on our long-term studies and monitoring activities across numerous permanent plots within and beyond the Coweeta Basin (Figure 2), including over 20 years of tree demographic data representing more than 350,000 tree-years (Dietze and Clark 2008, Clark et al.



Figure 2. Existing long-term CWT watersheds, research areas, and monitoring network sites providing spatio-temporal data on hydroclimate variability critical to CWT-VII activities as described in the proposal. The locations are described in Facilities, Equipment and Other Resources.

2012a). New activities (Figure 1) will include a large-scale throughfall displacement experiment to quantify ecosystem and tree responses to hydroclimate variability across an elevation-moisture gradient (2.3.1). We will examine performance and abundance of a suite of herb, invertebrate, salamander and bird species across a range of existing and new plots selected to represent the interacting forces of hydroclimate variability and human landscape modification (2.3.2). We will conduct a large-scale rhododendron removal experiment to examine processes at the interface between terrestrial and stream ecosystems in relation to management (2.3.3). We will synthesize existing and new field-sampled information to model (RHESSys) past and present hydroclimate variability, and create future scenarios to estimate system function and risks across square-meter to regional geographies (2.3.4). Each of these activities has a human dimension at parcel to regional levels connected with Coweeta Listening Project (CLP) activities to engage science and society (Driscoll et al. 2012) in the southern Appalachian Mountains.

2.2. Background

Spatio-temporal variation in climate strongly affects southern Appalachian ecosystems. Species composition, organismal interactions, and ecosystem process rates are influenced by ridge to cove gradients in edaphic properties, and low to high elevation gradients in temperature and precipitation (Whittaker 1956, Warren 2010). Closed-canopy forest once dominated the southern Appalachian Mountains, but human alterations of the climate and the landscape over the Anthropocene have been significant (Delcourt et al. 1986, Jacobson et al. 1989, Kozak and Wiens 2010, DelBossu et al. 2013). Hydroclimate variability and human landscape modification are independently and substantially re-ordering the biophysical gradients, and their interaction will bring novel responses that exacerbate vulnerabilities within the region. The long-term, multi-decadal research we propose is essential for anticipating, responding to, and mitigating these changes and vulnerabilities.

2.2.1. Hydroclimate Gradients, Variability, and Southern Appalachian Ecosystems

The terrain and downslope redistribution of soil moisture in the southern Appalachian Mountains create steep local hydroclimate gradients from dry ridges to moist coves that maintain high soil moisture even in dry years (Band et al. 1993, Montgomery and Dietrich 1994, Ford et al. 2011a). Within forest stands, climate variables interact with an organism's physiology to limit the conditions of its growth, survival and reproduction (Jackson et al. 2009, Lavorel et al. 2011). Individual responses to local climate affect interactions among individuals, and aggregate individual responses and interactions to environmental conditions determine population and community dynamics (Clark et al. 2011b, Clark et al. 2012a).

A number of recent studies have shown climate changes from global to regional extents (Mearns et al. 2003) in precipitation (Allan and Soden 2008, Ford et al. 2011b), temperature (Karl et al. 1996, Gaffen and Ross 1999, Ford et al. 2011b) streamflow (McCabe and Wollock 2002, Huntington 2003, Groisman et al. 2005), as well as the frequency and intensity of rainfall events (Niyogi and al 2011, Groisman et al. 2013, Shepherd et al. 2013). Climate records show altered growing season length and increased late-season drought in the southeastern U.S. (Figure 3, Ford et al. 2011b, Li et al. 2012, Wu et al. 2013). Changes in soil moisture, saturation and realized vapor pressure, stream peak and low flows, sediment, and water chemistry have potentially large, cascading effects on terrestrial and aquatic ecosystems as well as human safety, health, and economic systems (IPCC 2013).

Progressive changes in climatic variability such as those forecast for southern Appalachia will affect longterm population growth and community composition of trees and other forest biota (Clark et al. 2011a, Clark et al. 2013a). In a warmer and/or drier future, the combination of impacts may lead to structural and functional changes in dominant overstory vegetation. These will in turn alter unique and diverse vertebrate and understory plant communities, soil microbial activity, biogeochemical cycling, and stream flow and chemistry. Ultimately, these changes will affect the quality and quantity of ecosystem dynamics in southern Appalachia (Ford et al. 2011b). Our proposed research will examine local to regional implications of hydroclimate variability observed at fine scales. We will develop specific understanding of alterations in population and ecosystem processes, and then incorporate process changes into analysis or models that operate across square-meter to regional geographies. Our analyses will incorporate direct and indirect human alterations of landscapes and climate serving our objective to develop the scientific basis for managing regional ecosystems.



Figure 3. Local and regional climate trends: Left panel - CS01, Coweeta Hydrologic Laboratory (Ford et al. 2011); solid lines correspond to a time-series intervention model, and dashed lines are 95% confidence intervals about the modeled mean. Right panel - NCDC Divisional Data for "Southern Mountains" in North Carolina, scaled to 1 stdev units; thick lines are 5 y moving averages, and thin lines are annual means.

2.2.2. Anthropogenic Ecosystem Alterations

The forest matrix in southern Appalachia includes patches of development at suburban to urban densities (Kirk et al. 2012) linked by a sparse road network that are beginning to coalesce (Wear and Bolstad 1998, Kirk et al. 2012). Forest fragmentation combined with alteration of riparian and hillslope areas by road and powerline corridors have many consequences (Band et al. 2012, Cecala 2012, Kirk et al. 2012, Webster et al. 2012b). Human activities contribute to global GHG production, and to micro- and meso-scale climate anomalies (Seto and Shepherd 2013). These in turn are exacerbated by increasing intensity of both wet and dry extremes, and prolonged growing seasons across both the Southeast (Wang et al. 2010, Bernardes 2013) and southern Appalachia (Ford et al. 2011b, Wu et al. 2013).

Land cover can buffer (e.g., forest cover) or exacerbate (e.g., riparian gaps) individual biotic responses to regional climate change. Increased isolation and reduced size of remnant forest patches may reduce a species' distribution and abundance irrespective of climatic suitability (Fraterrigo et al. 2009b). Mechanistic scaling of local effects on individual performance, interactions, and habitat biogeography is needed to forecast changes in regional biodiversity patterns (Jackson et al. 2009). However, human land use practices occurring decades and centuries ago can have residual influences on contemporary biological composition and ecological processes (Harding et al. 1998, Bain et al. 2012). For example, by the early 20th century, nearly 90% of southern Appalachian forests had been cut, many areas had also been burned, and foundation species such as the American Chestnut lost (Ellison et al. 2005, Elliott and Vose 2010).

Urbanization alters surface permeability and forest canopy density, increasing surface flows, decreasing infiltration and evapotranspiration (Pataki et al. 2011), and altering ecosystem function as well as micro- and regional climates (Peters and McFadden 2010, Shepherd et al. 2013). Urbanization also reduces floodplain volume through infilling, increases flooding (Smith et al. 2002), restructures terrestrial and aquatic ecosystems, and creates risks and hazards for human communities that can result in fatalities and property damage (Band et al. 2012). Over the last four decades, the amenity-rich southern Appalachian Mountains have effectively become a recreation exurb of major southeastern urban centers such as Atlanta. The values and priorities for the landscape held by original inhabitants, generational residents, and new comers frequently differ (Vick 2011, Evans 2013). This creates complex governance challenges for dealing with exurban issues (Vercoe et al. 2014) and the vulnerabilities created by the interaction of hydroclimate variability and human activities on the land.

2.2.3. Vulnerability Framework

We define *vulnerability* as the propensity of an ecological and social system to suffer harm from exposure to external stresses or shocks (Turner et al. 2003). Vulnerability is a measure of the susceptibility of a system to a particular type of event or pressure typically expressed as a function of exposure, sensitivity and response capacities (Yusef and Francisco 2009). The *exposure* of a system to a perturbation such as a drought characterized by its severity or frequency differs from the *sensitivity* or degree to which a system is affected by the perturbation. The *response capacity* indicates the ability of a system to cope with the perturbation, and can be scaled from individuals to landscapes. Evidence clearly shows that changing climate and residential development affect hydrology and biodiversity within and beyond the southern Appalachian Mountains (Hansen et al. 2005, Wenger et al. 2011, Webster et al. 2012b). Our proposed research, however, is designed to develop a mechanistic understanding of responses by ecosystems and organisms to hydroclimate variability and human modifications of the land. The goal is to inform ecological understanding, uncover the feedbacks that link the biophysical and the human realms, and help alter the drivers of change by forging environmental solutions at scales relevant to intervention.

2.3: Proposed Research

We will continue long-term monitoring within the Coweeta Basin and beyond (see Facilities), and leverage these activities during CWT-VII to examine how hydroclimate variability and the human-modified landscape separately and in interaction alter southern Appalachian Mountain ecosystem processes and biotic communities. Our research is divided into a portfolio of four interrelated activity sets. Activities include controlled manipulative experiments, monitoring, field sampling and observation within the Coweeta Basin, the Wine Spring Creek Watershed (studied in CWT-IV), and Regional Watersheds across the Little Tennessee River and French Broad River basins (both studied in CWT-V through CWT-VII). We will develop a mechanistic understanding of biogeochemical, physiological, individual, population, and community responses to hydroclimate variability and human landscape modifications. Simultaneous social-scientific research will examine and evaluate the perceptions, actions, and governance issues of property owners that map directly to these ecological responses. Finally, the understanding gained from these activities will be challenged and refined by an ensemble of measurements and models of intact and fragmented landscapes across the Little Tennessee River and French Broad River basins.

2.3.1. Ecosystem Processes & Organismic Interactions

Ecosystem and organism responses to hydroclimate extremes are complex. While individuals respond

to changes in water availability (Emanuel et al. 2007, Clark et al. 2010), an ecosystem response is a product of cascading effects among physiology, demography and biogeochemical cycling. The response may further depend on topography (Emanuel et al. 2011, Riveros-Iregui et al. 2012), the frequency and magnitude of hydrologic inputs (Wullschleger and Hanson 2006), and species interactions (Clark et al. 2013a, Wurzburger and Miniat 2013). We focus in this research on quantifying ecosystem responses to hydroclimatic variability by performing manipulative experiments of both throughfall removal and alteration of wet and dry extreme events across a ridgetop-to-cove gradient for which we propose two possible outcomes. **Ridge top ecosystems will be most sensitive to hydroclimate extremes due to a lack of upslope subsidies and lateral flow. Alternatively, cove ecosystems will be most sensitive to hydrologic extremes because their structure and function reflect adaptations to high soil water availability. We anticipate interacting effects of water status and flow on vegetation response and structure, microbial responses, and feedbacks on ecosystem function from macro- to micro-scales. To capture these interacting effects, our research has three foci: 1) hydrology, 2) biogeochemical cycling, and 3) reorganization of ecosystem properties.**

Predictions of future hydroclimate variability include changes in the magnitude of precipitation and changes in the frequency of rainfall events (O'Gorman and Schneider 2009). To capture responses to increases in variability at both high and low rainfall extremes, we propose experiments at two scales (Figure 4): a large-scale throughfall displacement experiment (TDE) and a series of small-scale throughfall altered-frequency experiment (TAE). The TDE will establish one treatment and control plot (~1600 m² each) paired in first-order catchments at each of three landscape positions representing a continuum of ecosystem properties: ridge shoulders, midslopes, and coves. The TDE will be located in Watershed 10 of the Coweeta Basin (Hewlett and Hibbert 1961) and will remove ~2/3 of throughfall to understand how ecosystems respond to hydroclimate extremes (Figure 5). The level of displacement is greater than previous removals in similar systems (Hanson and Wellschleger 2003) and will ensure a drying effect even during the wettest years (Ford et al. 2012b). It is also consistent with TDEs across the LTER (Smith et al. 2013), allowing us to join in cross-site collaboration.

We also propose small-scale throughfall additions to address potential increases in magnitude and predicted changes in the frequency of rain events. Within and adjacent to each TDE control-treatment pair, we will construct small-scale $(3m \times 3m)$ plots in which treatments will include: ~2/3 reduction in throughfall; control; and ambient throughfall but altered input frequency (i.e., fewer, more intense rain events). Each treatment will be replicated three times within each landscape position. The size of the TAE Plots will be too small to affect the physiology of mature trees, but we anticipate observable responses among soil microbes, seedlings, herbs, and interacting elemental cycles. After one year of pre-treatment data on demographic responses, the TDE and TAE experiments will be carried out for at least five years. The design will consist of plastic sheeting that drains to gutters suspended between rails mounted on support posts to drain off-plot. For the TAE treatments we will collect a designated volume of throughfall in cisterns outfitted with a bell siphon that will then be released back to the plot through irrigation lines. The small-scale altered-frequency treatments will not change the amount of throughfall; rather by altering the frequency and magnitude of throughfall (i.e., fewer small events, more large events), this treatment is expected to alter the temporal variability of soil moisture (Rodriguez-Iturbe 2000, O'Gorman and Schneider 2009, Laseter et al. 2012). A number of recent studies have shown climate changes from global to regional extents (Mearns et al. 2003) in precipitation as well as the frequency and intensity of rainfall events (Niyogi et al. 2011, Groisman et al. 2013, Shepherd et al. 2013).

2.3.1.A. Hydrology: We expect to see overall reductions in soil water content in treatment plots relative to control plots at annual timescales although the degree of change will be influenced by seasonality, time since rainfall event, and upslope subsidy. We expect that upslope subsidies will mitigate exposure to soil drying at downslope positions, such that soil moisture will be progressively reduced as a result of throughfall displacement from cove to midslope to ridge sites. High leaf area index (LAI) and transpira-



Figure 4. Downslope subsidy hypothesis and design of the Throughfall Displacement Experiment



Figure 5. Effects of various levels of throughfall displacement on gross primary productivity (GPP) simulated with RHESSys for WS7, a small, south-facing watershed in the Coweeta Basin.

tion demand could result in large sensitivity in cove sites (Tromp-Van Meerveld and McDonnell 2006). We will measure volumetric soil water content (θ), soil water potential (Ψ_s), and groundwater stage in control and treatment plots at each landscape position. This will allow us to assess the contribution of local throughfall relative to upslope water subsidies across time scales (event, seasonal, annual). We will measure these variables from surface soil to the layer just above saprolite in upslope, central, and downslope locations within each plot. At each location, continuous recording instruments will include time domain reflectometry probes (θ), dielectric permittivity probes (Ψ_s), and pressure transducers (groundwater stage) to compute time series of core and derived variables (e.g., saturation fraction, pore pressure, soil water storage, hydraulic gradients). To independently quantify the influence of upslope subsidies, we will sample throughfall, soil water (using falling tension lysimeters) and shallow groundwater for stable isotope ratios of O and H at regular intervals (L2120i, Picarro, Inc.). Isotope ratios will be used in an end-member mixing model (Genereux and Hooper 1998) of local precipitation and nonlocal subsidy water to quantify their contributions to each slope position, then integrated into a measurement synthesis of TDE plot hydrodynamics using RHESSys. This synthesis will be integrated in research at broader scales described later (2.3.2.B, 2.3.4.B, 2.3.4.D)

We expect that the sensitivity of individual- and species-specific plant water uptake to hydroclimate variability will be determined by plant hydraulic architecture and leaf-level physiological adaptations to limiting soil water (Emanuel et al. 2007). To quantify reductions in plant water uptake along the hillslope gradient, we will monitor water movement from the roots to the leaves using sapflow probe installations on a subset of trees in each plot (Burgess et al. 2001, Ford et al. 2004). We will measure foliar water loss with leaf-level gas exchange and stomatal conductance measurements (LI-6400, Li-Cor Biogeosciences) on sun and shade leaves of the trees monitored for sapflux (J_s) (Ellsworth 1999, Novick et al. 2004). Midday and pre-dawn leaf water potential (Ψ_L) measurements will be conducted with leaf-level gas exchange measurements to quantify the pressure gradient (i.e., $\Psi_s - \Psi_L$) driving soil-to-leaf water flux (Novick et al. 2009). Samples of plant tissue water will be collected regularly and analyzed for stable isotopes of O and H (IM-CRDS, with integrated micro-combustion module, Picarro, Inc.). This will allow us to assess the relative contribution of local throughfall and upslope water subsidies to plant water uptake using an end-member mixing model (West et al. 2011).

2.3.1.B. Biogeochemical Cycling: We expect declines in tree productivity, increases in carbohydrate storage and shifts in root density and distribution to manifest most in ridge and midslope *TDE Plots* due to reductions in plant water availability. LAI, which is a principle control on canopy-scale gross primary productivity (GPP), will be measured in treatment and control sites three times each year (early, mid and late growing seasons) using an LAI-2200 (Li-Cor) and digital hemispherical photography. Monthly leaf-level gas exchange measurements will permit quantification of tree-level dynamics in GPP and water-use efficiency. Leaf N-concentration will be monitored to link photosynthetic capacity to changes in soil nutrient availability. To track allocation of assimilated C, we will measure non-structural carbohydrate concentration (Aubrey et al. 2012), the change in diameter at breast height with dendrometer bands, and annual litterfall. Diameter increment will be used with region- and species-specific allometric relationships to determine aboveground net primary productivity (NPP, Martin et al. 1998). We will also measure changes in coarse and fine root density at various depths every two years, and complement root tensile strength measurements conducted in related research (Hales et al. 2009, Hales et al. 2012) if new species/site combinations are encountered.

Patterns of C assimilation and water uptake in *TDE Plots* will depend on, and feedback to, a number of belowground biogeochemical processes. We expect reductions in θ to constrain microbial transformations of organic matter, and we will conduct both field and laboratory studies to determine how the mechanisms of constraint vary by topographic position. In the field we will measure soil CO₂ efflux (R_{soil}) with a portable infrared gas analyzer (LI-6400), forest floor mass, and decomposition rates (Knoepp et al. 2000). We will conduct seasonal *in situ* soil N mineralization assays and quantify activities of C, N and P-degrading extracellular enzymes using fluorometric procedures (Saiya-Cork et al. 2002). We will conduct a series of controlled lab incubations to quantify N mineralization, R_{soil} and extracellular enzymatic activity under varying moisture regimes that simulate hydroclimate extremes. Because we expect intense rain events following dry periods to flush soluble C and N into deeper soil layers, we will measure in both the *TDE Plots* and *TAE Plots* C and N fluxes in throughfall and soil solutions using combined resin (Block et al. 2012) and tension lysimeters at multiple depths (Knoepp et al. 2011). We will quantify how C and N pools and fluxes are changing both over time and with depth (Knoepp and Swank 1997, Knoepp and Swank 1998).

2.3.1.C. Reorganization of Ecosystem Properties: Transformation of eastern forests in the 21st century will be controlled by interactions between intensifying droughts and prolonged growing seasons with responses mediated by plant climate-competition interactions (CCI) for light, moisture, and N. Measurement of seedling through adult demographies across the imposed treatments and gradients will further our analysis of CCI derived from other 20 years of tree demography on the Coweeta *Gap* and *Gradient Plots* (see facilities, Dietze and Clark 2008, Clark et al. 2012a) by expanding the range of drought for both seedlings (planted from seed) and established trees. We expect that increased hydroclimate variation will

shift recruitment of drought-sensitive tree species downslope towards wetter sites. We will measure shifts in canopy density, plant population distribution, abundance, and fitness in the *TDE Plots* along the ridgeto-cove topographic gradient (Mohan et al. 2007, Clark et al. 2010). Predictor variables for demographic responses will include θ with depth, winter air and soil temperatures, light interception, individual size, and growth history (Clark et al. 2010, Clark et al. 2013c, Clark et al. 2013a). Responses at the individual-year (annual demography) scale will be related to water-use patterns across treatments and seasonal droughts inferred from J_s , θ and gas-exchange measurements. Individual transpiration models will be developed to aid scaling to catchments based on θ , N availability, vapor pressure deficit (VPD), air temperature, and photosynthetically active radiation (PAR) using a state-space framework (Clark et al. 2011b, Ward et al. 2012).

We expect that legacies of tree species, including their individual effects on soil nutrients and microorganisms (Boettcher and Kalisz 1990, Finzi et al. 1998, Averill, 2014 #784) will mediate a given species' ability to increase in abundance within topographic positions and along the hillslope gradient. In year four, after several years of demographic response to the TDE, we will identify species that may increase in abundance at each topographic position or may shift their range distributions to more favorable conditions downslope. We will test the individual and interactive effects of soil legacies and hydroclimate variability on the growth of these species in field and greenhouse experiments. Seedlings will be out-planted under the canopies of the dominant species in treatment and control plots, and will be inoculated by the tree-specific soils in the greenhouse under moisture regimes consistent with those on the TDE and TAE Plots (Wurzburger and Miniat 2013). Since migrations of tree species may further disrupt existing plantsoil feedbacks and biogeochemical cycles (Wurzburger and Hendrick 2009), we will introduce litter from migrant trees to soils of resident or declining midslope and cove species in lab incubations. These experiments will determine the functional response of soil microbial communities to novel litter sources and the subsequent effects on C and N transformations (Strickland et al. 2009). Collectively, these experiments will inform how sustained periods of hydroclimate variability might lead to changes in the composition of forest communities and the reorganization of ecosystem properties along ridge-to-cove gradients.

2.3.2. Organismal & Ecosystem Sensitivity to Hydroclimate and Land Use across Scales

We hypothesize that the vulnerabilities of forest understory species to shifts in hydroclimate and land use will depend on the interaction between individual sensitivities to the local environment and population sensitivities to the effects of habitat fragmentation and isolation. We will examine individual and population sensitivities for a suite of herb, invertebrate, salamander, and bird species that are slow to mature, have low fecundity, exhibit limited dispersal capability, and interact with one another to affect the distribution and abundance of other taxa or ecosystem processes. The selected taxa complement and broaden ongoing long-term research on tree species, serve as models for broader suites of regional species, and will build understanding of the ecological and cultural importance of herbs, invertebrates, salamanders, and birds in the southern Appalachian Mountains. This region is a global hotspot of forest salamander diversity (Duellman 1999) as well as an important nesting and winter habitat for many neotropical and temperate bird species. There are approximately 3000 herb species in the region. Because the distributions of most species are patchy, we will determine community-level biotic changes and feedbacks to ecosystem function by quantifying shifts in plant functional traits and relating them to ecosystem processes. Plant functional traits bridge the gap between plant community structure and ecosystem processes, serving as the basis for understanding spatially and temporally variable community dynamics as well as the broad-scale consequences of changes in biodiversity due to climate and land use (Chapin et al. 2000, Diaz and Cabido 2001, Lavorel and Garnier 2002).

We will focus within herbaceous communities on five native (*Polygonum biflorum*, *Smilacena racemo*sa, Sanguinaria canadensis, Viola pedata, and Uvularia sessilifolia) and one nonnative (*Microstegium* vimineum) species common in eastern deciduous forests. *P. biflorum* and *S. racemosa* appear drought sensitive, but are also subject to intense fungal disease in wetter conditions (Warren and Mordecai 2010). All our focal native herb taxa have animal-dispersed seeds. The local distribution and fitness of *S. canadensis*, *V. pedata*, and *U. sessilifolia* varies in response to the presence and abundance of seed-dispersing ants (*Aphaenogaster* spp.), that in turn are affected by soil moisture and precipitation. *P. biflorum* and *S. racemosa* produce red fruits dispersed by forest birds such as Veeries (*Catharus fuscescens*) and Ovenbirds (*Seiurus aurocapilla*) whose local abundance is affected by weather, forest fragmentation, and residential land use. *M. vimineum* is a nonnative annual C_4 grass that is highly invasive in eastern deciduous forests (Claridge and Franklin 2003) and like many ruderal invasive species is common and abundant in post-agricultural and suburban forests. Under these conditions, *M. vimineum* may exclude or suppress native herbs and tree seedlings (Adams and Engelhardt 2009, Marshall et al. 2009, Flory and Clay 2010, Brewer 2011), alter microbial communities, and accelerate N and C cycling (Ehrenfeld et al. 2001, Kourtev et al. 2003, Strickland et al. 2010b, Strickland et al. 2010a, Fraterrigo et al. 2011, Strickland et al. 2011, Bradford et al. 2012).

Our focal animal taxa are *Aphaenogaster* spp., plethodontid salamanders (notably *Plethodon* spp.), and three forest-associated bird species (Black-throated Blue Warbler, *Setophaga caerulescens*; Veery, *Catharus fuscescens*; and Ovenbird, *Seiurus aurocapilla*). *Aphaenogaster* spp. is the most abundant ant in southern Appalachian forests and a likely keystone seed disperser in eastern deciduous forests (Ness et al. 2009, King et al. 2013, Warren and Chick 2013). *Aphaenogaster* are known to be highly sensitive to drought, and appear limited to wet environments (Warren and Bradford 2011, Yaya et al. 2012). *Aphaenogaster* are also the most abundant and important prey in *Plethodon* diets. *Plethodon* are fully terrestrial and dominate the southern Appalachian vertebrate fauna numerically and in biomass (Burton and Likens 1975, Hairston Sr. 1996). Their complete dependence on cutaneous gas exchange makes their fitness and abundance positively correlated with soil moisture and precipitation (Feder 1983), and their local and regional distribution and abundance appear strictly confined by climate (Bernardo and Spotila 2006, Bernardo et al. 2007, Kozak and Wiens 2010, Gifford and Kozak 2012). The interactions among salamanders, ants, and herbs create a strong and influential food chain that may be highly sensitive to climate and land use and result in local population responses to environmental change that are not predicted by individual performance models.

The three focal bird species are long-distance migrants that reach the limit of their southern breeding range in the southern Appalachians. Black-throated Blue Warblers are shrub-nesting foliage gleaners that feed primarily on Lepidopteran larvae. Veeries and Ovenbirds nest on or just above the ground, and forage for invertebrates during the breeding season; late summer through fall, they switch to consuming fruits. In doing so, they disperse the seeds for many understory herbs including two of our focal herb species. Low precipitation and soil moisture change insect communities (Debinski et al. 2006) and limit the production of ground- and leaf-feeding insects; this should limit nestling growth and survival, thus reducing the local breeding density of all three avian species (Sturtevant 2001, Seagle and Sturtevant 2005, Pearce-Higgins 2010). All three species are vulnerable to high nest failure at extreme high precipitation due to inundation. They are also negatively affected by increased forest fragmentation and historic land use. Veery and Ovenbirds require large tracts of forest (Laughlin et al. 2013) with dense litter and understory shrub layers, which are often diminished by human land practices. Black-throated Blue Warblers are sensitive to eastern hemlock loss as well as removal of *Rhodondendron* from forest understories (Lump-kin and Pearson 2013, Stodola et al. 2013).

We predict that the local spatial and temporal performance (growth, survival, and fecundity) and abundance of the focal species will be regulated directly by interactions between their physiological tolerances and hydroclimate variability, and indirectly via effects on competitors, predators, diseases, and mutualists. Across the wider landscape, we expect habitat fragmentation, isolation, and land use legacies to enhance or overwhelm the local effects of hydroclimate variability on individual performance, although we expect population sensitivity to fragmentation and isolation to vary among species in relation to specific life history traits. For example, we expect the sensitivity of herb species that depend on animals for local or long distance seed dispersal to correlate with disperser sensitivity to climate, fragmentation, and land use. We will measure individual performance of focal taxa and associated biogeochemical processes in existing long-term monitoring plots (see Facilities) and new 1-ha *Focal Taxa Plots* that span a range of soil moisture conditions (Figure 6). We will also measure focal ant performance, and focal herb performance and influence on biogeochemical processes on small plots within the *TDE Plots* (2.3.1). This will complement tree seedling demography, and enable us to examine short-term responses to novel extreme hydroclimate environments.

Plots were individual performance will be measured are or will be instrumented to collect daily microclimate including soil moisture, soil and air temperature, precipitation, and relative humidity (see Facilities description for instrumentation details). Synoptic high-density soil moisture sampling on plot grids and



Figure 6. Research framework to examine organismal and ecosystem sensitivity to hydroclimate variability and land use.

RHESSys models fitted and validated against instrumented values will allow us to estimate historic and current soil moisture at 3 m resolution over all 1-ha *Focal Taxa Plots* and *TDE Plots*. Using well-developed field and modeling techniques we will assimilate annual responses on multiple inputs from all plots, identify the variables responsible for growth, fecundity, and survival of our focal taxa, and quantify the CCI that determines their responses to hydroclimate variation (Clark 2010, Clark et al. 2010).

We will generate models of local population growth or performance in relation to soil moisture, precipitation, and a suite of other microclimatic variables for each focal taxon. We will then select 60, 1-ha forested *Regional Plots* in 24 *Nested Watersheds* (described in 2.3.4.A) within and outside the Coweeta Basin and measure appropriate focal taxa characteristics (e.g., abundance, age structure, reproduction as described below). *Regional Plots* will vary in hydroclimate, surrounding forest patch size, isolation, and prior land use (to be determined from long-term land use records compiled in CWT-V and CWT-VI). RHESSys models and satellite canopy measurements (2.3.4.A) will provide soil moisture and other drivers for focal taxa models. Model-measurement comparisons will identify the relative importance of local climate and larger biogeographic and land use factors in driving individual performance, species distributions and abundances. Biogeochemical processes will serve to identify scalability across a broad range of climatic and land use conditions. Final integrative models of species coupled with RHESSys will be used to generate scenarios to assess regional responses (2.3.4.C) and future vulnerability (2.3.4.D).

2.3.2.A. Individual and Ecosystem Processes across Hydroclimate Gradients: We will use a minimum of nine 1-ha *Focal Taxa Plots* to measure individual performance, abundance, and associated biogeochemical processes across precipitation and soil moisture gradients. These *Focal Taxa Plots* will be based on and extend existing long-term measurement plots. We will use the five existing *Terrestrial Gradient Plots* (see Facilities) stratified on ridge, midslope and cove positions, and select four plots from among the existing *Soil Moisture, Herb*, and *Salamander Mark-Recapture* plots (see Facilities). All *Focal Taxa Plots* will be arrayed along or near microclimate station transects used for the regional RHESSys model development, or synoptic soil moisture transects (2.3.4.B), and matching soil moisture stations on the *TDE Plots*. Station measurements will include hourly air and soil temperature, relative humidity, precipitation throughfall amount and intensity, solar radiation, and soil moisture from 0 to 30 cm. This provides a standard suite of microclimate measurements across all plots, and assures regional RHESSys validation for plot-level analysis and landscape through regional scaling.

We will use biennial transect mapping across each *Focal Taxa Plot* to measure changes in herb distribution and abundance (Elliott and Hewitt 1997, Fraterrigo et al. 2006b, c) compatible with sampling on the *TDE Plots* with allowances for plot configuration differences. We will measure plant species and height, estimate biomass, sample fungal-infected plants for genetic identification, and track interannual survival and seed production. For our three focal myrmecochores (*S. canadensis, V. pedata,* and *U. sessilifolia*), we will also measure clumping (nearest conspecific distance), and dispersal (seedling distance to nearest adult). We will collect foliage samples from ten individuals of each species to determine foliar chemistry and leaf traits, and measure biogeochemical processes associated with herb performance and community traits. Using a 2-cm diameter probe, we will collect and composite 10 individual soil cores per plot at a depth of 0-10 cm. Half of the sample will be sieved to 4 mm and used to estimate microbial biomass C and N using a simultaneous Chloroform Fumigation-Extraction (CFE) procedure (Fierer and Schimel 2003), enzyme activities (Finzi et al. 2006, Sinsabaugh, 2010 #941), and active microbial biomass based on substrate induced respiration (Fierer and Schimel 2003). The remaining sample will be air-dried and used to determine pH, total C and N by combustion, and soil texture.

Bulk density (g soil cm⁻³) of both coarse fragment and <2 mm fractions will be determined for each plot by averaging values obtained from four 5.08 cm diameter soil cores per plot. We will additionally deploy five ion-exchange resin bags to quantify N availability. Concurrent with herb sampling, we will measure the composition and abundance of ant species using repeated seasonal counts at bait stations (Warren et al. 2010, Warren et al. 2011). We will estimate the number, size, and health (workers, worker:alate ratios) of *Aphaenogaster picea* colonies, and assess dispersal services (seeds removed from bait stations). We will designate two, $10m \times 10m$ plots 30 m apart within each 1-ha plot to conduct salamander mark-recapture. We will use a robust sampling design consisting of 3 consecutive nights of sampling (secondary periods) each month (primary periods) during the active season (March to October, Pollock 1982, Bailey et al. 2004d, Bailey et al. 2004b, 2004c). Captured salamanders will be measured (length and wet mass); females will be candled to determine if they are reproductively active and marked uniquely using a Visible Implant Elastomer (VIE). We will estimate seasonal survival and growth, and estimate fecundity from clutch number/mass to body length/mass relationships in developed females collected nearby, within the 1-ha *Focal Taxa Plot*, but outside the salamander subplots.

We will measure bird nest success, nest provisioning, insect abundance, and territory size for our focal bird species on the *Focal Taxa Plots*. We will band up to 10 adult pairs per focal species per site (presence dependent), locate and monitor nests daily for eggs and nestlings, and track fledglings for 3 days post-fledge to calculate nest success and fledgling rates (Marshall and Cooper 2004). We will map territory size by following banded adults. We will estimate Lepidoptera abundance in each territory with sampling every two weeks of larvae on three 0.04 ha plots per territory and collecting 50 leaves from 2 stems of each tree species present in the understory. Forest floor insect communities will be sampled using 0.25m² litter samples processed with Tullgren funnels and stored in 50% ethanol (Streby and Andersen 2013). We will estimate nest provisioning rates and prey delivered (caterpillars vs. exoskeletal) using digital video (Stodola et al. 2009).

The output of our within-basin plot studies will be Focal Taxa Plot population growth or abundance models related to mean and variation of local hydroclimate components, modeled or measured at 3-10 m. For each focal taxon, we will estimate individual performance or plot density to generate algorithms relating vital rates or transition probabilities to microclimatic variables. These will be variables we can estimate or predict at fine grains (10 m cell or smaller) across regional extents (e.g., climate network/RHESSys for air and soil temperature, precipitation frequency and amount, soil water content; or canopy LAI from satellite and field data). These algorithms will be integrated into matrix or integral population projection models (e.g., herb height and measured survival and fecundity rates) to estimate population growth (Easterling et al. 2000). For salamanders, we will use both hybrid age-stage structured population models to estimate instantaneous population growth rates and population size and structure, and individual energetic models using estimates of weather effects on surface foraging activity, caloric intake (from existing data), and growth and fecundity (Gifford and Kozak 2012, Gifford et al. 2013). We expect that conditions that support negative energy budgets result in negative population growth, low abundance, and local extinction. For birds we will develop statistical models relating insect abundance and timing to soil moisture and vegetation. We will model population growth rates as a function of adult survival estimated from yearly recapture-resight data. Nest productivity will be estimated from field measurements as a function hydroclimate and associated insect abundance.

2.3.2.B. Modeling Forest Fragmentation and Land Use Effects: The population models developed from the *Focal Taxa Plots* within the Coweeta Basin will be applied to *Regional Plots across* the disturbed landscape beyond the basin. This will require us to incorporate effects operating at larger scales (dispersal, habitat fragmentation and isolation) and related human land use activities. Using PRISM models of mean annual precipitation and RHESSys estimates of mean daily soil water content for the past 10 years along with measures of forest area, isolation, and historic (50 year) and current land use we will select 60, 1-ha *Regional Plots* within our 24 *Nested Watersheds* across the Upper Little Tennessee River and French Broad River basins. Selected sites will represent variation in hydroclimate, fragmentation, isolation, and land use. Using the models generated in the previous section (2.3.2.A) and the 10-year historic climate, we will predict focal taxa population growth, energetics, abundance, and associated biogeochemical processes for each *Regional Plot*.

We will use a subset of methods described in the previous section to test model predictions. Replicate transects will be used to estimate herb abundance, size structure, and individual size, fecundity, and fungal disease prevalence as well as microbial biomass and biogeochemical processes. We will use timed searches of coarse woody material and colony collections to estimate the number, size, and health of *Aphaenogaster* colonies. We will establish 2 replicate $10m \times 10m$ plots and conduct a robust capture-mark-recapture over three consecutive nights in April and May (spring), July and August (summer), and October and November (fall) to estimate plot population size and age-size structure and occupancy among all *Regional Plots*. We will use point count surveys to estimate breeding bird community structure and occupancy among all *Regional Plots*, and breeding pair presence and abundance for our focal taxa. We will use spatially explicit integrated population models to make population estimates from occupancy data (Chandler and Clark 2014). We will measure a suite of structural measurements on all 60 plots including LAI (LiCOR 2200), dominant overstory species and height, tree basal area, and soil moisture (30cm, CS655) to aid in measurement interpretation and test RHESSys performance.

For each focal taxon, we will compare the performance of hydroclimate-only models to models that only include biogeographic and land use information, or models that integrate both hydroclimate and biogeographic data. We will use hierarchical general and generalized linear or logistic models to estimate the relative importance of past hydroclimate, fragmentation, isolation, and land use on individual performance measures, abundance estimates, and species occupancy (Cecala 2012). For herb models, we will include data on soil fertility related to land use, and the presence and abundance of dispersers (ants or birds) and invasive species (e.g., *Microstegium*). We will use an information theoretic approach to select and evaluate models and determine whether models that include biogeographic information only or integrate hydroclimate and biogeographic information outperform models strictly based on hydroclimate (Cecala 2012). We will use our top-selected models to explore future scenarios of regional vulnerability to climate and land use change (2.3.4.C).

2.3.2.C. Co-Mapping Biology and Landowner Values: Ecosystem management depends on knowledge of human land use processes and their cascading effects on biodiversity (Jackson et al. 2009, Nielsen-Pincus 2011). The idea that people are embedded within an environment giving shape to it as well as responding to its changing conditions underlies place-based explanations of land use processes (Zube 1987, Brown et al. 2002, Nielsen-Pincus 2011). Southern Appalachian residents have historically exhibited strong attachment to place bolstered by independent and family-oriented cultural traits. However, these value structures are shifting as a result of increased tourism, rapid development, and in-migration as evidenced by tensions between newcomers, developers, and long-term residents (Vercoe et al. 2014). We will co-map landowner knowledge, beliefs, and values about places and biodiversity on their property relative to the measured importance of biotic elements and processes identified in 2.3.2.A and 2.3.2.B. We predict that variability in the cultural histories and socio-economic characteristic of landowners will explain their decisions about management and use of their property.

Land owners whose property lies within and adjacent to the *Regional Plots* will be subjects in this study. We will first interview them using a combination of closed- and open-ended questions to collect information on their cultural histories, socio-economic characteristics, and land management decisions. We will ask residents about their understandings, beliefs, and attitudes about the ongoing growth and development of the region. We will use public participation GIS (PPGIS) to determine the spatial distribution and density of socially valued places on their property along with measures of the biological productivity of those places (Talen 2000, Ball 2002, Brown and Reed 2011, van Riper et al. 2012). Finally, we will compare responses across property owners to identify "hotspots" where socially defined areas converge with areas of biotic importance. The social values underlying land use will provide information on processes associated with habitat fragmentation and species isolation. This will help explain the land use derived vulnerabilities of the focal herb, invertebrate, salamander and bird species paired to the effects of hydroclimate

variability at larger scales. The results will be used to identify land areas that accommodate distinct human uses and biological productivity versus areas where alternative management approaches are called for either because of conflict between uses or ultimate consequences on biodiversity.

2.3.3. Riparian Land Cover Interactions with Hydroclimate

The broad impacts (e.g., downstream water quality) of climate change and human land use are largely determined by what happens in riparian areas at the interface between terrestrial and stream ecosystems. We hypothesize that riparian land cover changes from management and conservation activities either exacerbate or mitigate the effects of regional climate change by directly altering inputs, outputs, and processing of energy, carbon, and nutrients, that cascade in their effects on ecosystem properties and processes. CWT-VI research documented a mosaic of riparian conditions including lawns, cropped fields, dense shrubs, overstory trees without understories, and forest. This variation in riparian land cover strongly affects local stream temperatures (Long and Jackson 2013), channel morphology (Jackson et al. In Review), nutrient concentrations (Webster et al. 2012a), and biotic assemblages (Kirsch 2011, Cecala 2012). The structure and function of riparian forests in the southern Appalachians have also been significantly affected by eastern hemlock death due to the hemlock woolly adelgid (HWA) infestation (Ford and Vose 2007, Elliott and Vose 2012). Over a decade of research on Hemlock Intensive Plots (see Facilities) shows expansion of Rhododendron maximum (Ericaceae) with understory microclimate and plant-litter-soil biogeochemical feedbacks that inhibit tree seedling recruitment and a sparse overstory of canopy trees (Wurzburger and Hendrick 2009, Ford et al. 2011a). There are also consequences to stream ecosystems because of the low quality of rhododendron leaves as a food source for aquatic insects (Webster et al. 2012a), and the change from hemlock to rhododendron may decrease stream-side land values.

Our previous research suggests that rhododendron has strong localized effects on soil N dynamics. Rhododendron litter is not only recalcitrant, but its leaf and root litter polyphenols have a high propensity to complex organic N, protecting it from microbial degradation (Wurzburger and Hendrick 2007). While rhododendron roots can acquire this polyphenol-complexed-N through a diverse suite of fungal symbionts (i.e., ericoid mycorrhizal fungi, Wurzburger et al. 2012), local tree species show a reduced capacity to access this N (Wurzburger and Hendrick 2009). The expansion of rhododendron will therefore extend this plant-soil biogeochemical feedback across the landscape and reduce available N to trees and microbes. It is thus critical to understand how the presence of rhododendron may change the total flux and species of N transported across the terrestrial-aquatic boundary. We expect that N fluxes will be determined by both the chemistry of rhododendron litter and the abundance and activity of soil microorganisms. The presence of rhododendron is likely to increase stable soil organic N, reduce N mineralization, reduce soil pH, increase the dominance of fungi relative to bacteria and the dominance of archaeal ammonium oxidizers relative to bacterial nitrifiers (Norman and Barrett 2013). Ultimately, we expect these changes to manifest in reductions of the total flux of N and DIN:DON to streams.

The USDA Forest Service and CWT project investigators will collaborate on a large-scale experimental removal of rhododendron and its associated O-horizon leaf litter (Figure 7). The manipulation will occur in riparian corridors once dominated by eastern hemlock into which rhododendron has since expanded. We will collaborate to examine the effects of rhododendron removal on a suite of ecosystem properties and processes in riparian forest and their adjacent stream reaches. The research will involve intensive field experiments at the plot scale and extensive measurements at the reach scale. For the intensive study, we will establish sixteen $20m \times 20m$ plots with rhododendron treatment at two levels (removal or not) and forest floor litter treatment at two levels (removal or not). Eight of the sixteen plots have been monitored for vegetation dynamics, carbon and nutrient pools and fluxes, and soil solution chemistry since 2004 (Hemlock Intensive Plots, Nuckolls et al. 2009, Knoepp et al. 2011, Ford et al. 2012a). Eight additional plots with similar site characteristics will be established in the Wine Spring Creek Watershed (see



Figure 7. Experimental design of the terrestrial and in-stream components of the Rhododendron Removal Experiment.

Facilities). We will randomly apply the rhododendron treatments to all 16 plots, and remove the forest floor litter with a prescribed burn. We will measure for each treatment the rate of recovery in vegetation dynamics (growth and recruitment), soil microbial community shifts, soil extracellular enzyme activity, and nutrient pools and fluxes. The extensive treatments will consist of four, 305-m reaches on 2nd and 3rd order perennial streams at 670-1000 m elevation in the Wine Spring Creek Watershed where we will remove rhododendron and its associated O-horizon leaf litter as above. Terrestrial measurements will be overlapped with in-stream measurements to identify cascading effects on properties and processes within and between terrestrial and stream ecosystems.

2.3.3.A. Terrestrial Processes: We expect that removal of rhododendron, with and without the removal of the O-horizon, will allow recruitment of trees and herbs; increase litter decomposition rates; increase soil pH, N mineralization, nitrification and the pool of DIN in soil. For each treatment, we will measure microclimate, rates of change in vegetation dynamics (growth and recruitment) as well as N pools and fluxes. We will measure soil water content, soil temperature, and available light throughout each plot (Ford et al. 2012a). N pools and fluxes will be measured on each plot before and after treatment, and every 2 years thereafter. Sample collections using standard techniques will include forest floor (O-horizon), soil and soil solution, and litterfall total C and N. Total C and N will be determined by combustion, and total Ca, Mg, K, and P will be determined by dry-ashing, acid digestion and spectrophotometric analysis (Brown et al. 2009).

Net nitrification and N mineralization rates will be measured seasonally using a 28-d, in situ, closed core incubation (Knoepp and Swank 1998). In situ incubations and assessment of microbial communities and extracellular enzymes (Sinsabaugh et al. 1993, Sinsabaugh et al. 2002) will be performed on pre-treatment soils and in two subsequent years. We will characterize the nitrifier communities in subsamples of the 0-d and 28-d soil cores. We will extract the preserved soils using MoBio Power DNA kits, then use qPCR and pyro-sequencing of the ammonia monooxygenase subunit A gene to characterize the bacterial-and archaeal-specific nitrifer communities (Norman and Barrett 2013).

Vegetation dynamics will be assessed with direct measurements of annual diameter growth and recruitment. In each plot, woody stems will be tagged and measured annually, shrubs and tree saplings will be counted and recorded by species, and ground layer vegetation will be sampled seasonally (Whigham 2004). Within each of the four study stream reaches, we will establish six transects aligned perpendicular to the stream and extending from mid-stream to the outer edge of the rhododendron thicket on each side of the stream. Along each transect, we will measure light and soil moisture twice during the growing season, and collect soil samples and measure vegetation one time at peak biomass (July) of each sample year. We will also measure the microenvironment and sample soils and vegetation before and after removal treatments and every two years thereafter. Continuous measurements of soil water content (θ , CS616, CS650, Campbell Scientific Inc. - CSI) and soil temperature (CS105, CSI) will be stored as hourly averages across three locations in the plot. Available light (Q_i) will be measured using GaAsP photodiodes arrayed in an alternating grid pattern throughout each plot (Ford et al. 2012a).

2.3.3.B. In-Stream Processes: We predict that rhododendron removal will result in greater incidence of light and increases in stream temperature and nitrate levels, with increased primary production and consequent cascading effects on stream organisms, nutrient cycling and trophic dynamics. Initial changes are expected to include increased numbers of herbivorous stream insects and vertebrate predators while, over time, increases in the quality and quantity of deciduous leaf litter will result in an increase in the abundance of detritivorous insects. Abiotic and organismal surveys will be conducted above, within, and below the treatment sections, while chemistry and productivity will be evaluated only within the treatment sections. Pre-treatment measurements will be made in summer and fall 2014, and post treatment measurements will begin immediately after rhododendron removal and continue seasonally until the rate of change suggests a different frequency. Canopy cover over the stream channel will be measured each year (n=20 at each study reach) using a spherical densiometer during leaf-on and leaf-off periods (Li et al. 2012). Channel geomorphic surveys (Price and Leigh 2006b, Leigh 2010), including channel width, floodplain width, channel depth, and wood frequency, will be scaled by channel width and conducted at regularly spaced transects above, within, and below the treatment reach. Stream chemistry (16 analytes, pH, DOC and TDN) will be sampled on monthly grab samples above and below each study reach, while the acid neutralizing capacity will be calculated from elemental concentrations. Stream temperature (n=10 per reach) will be recorded hourly throughout each year.

We expect removal of rhododendron will lead to increases in algae and in-stream primary production. Over time, the improvement of allochthonous litter quality will positively affect detrital insect consumers and, vertebrate predators. Algal standing crop (chlorophyll a, AFDM) will be quantitatively measured seasonally (beginning with the pre-treatment year) by sampling epilithon within pools/runs (n=5) and riffles (n=5) of each experimental reach using a modified Loeb sampler (Loeb 1981). Rates of algal standing crop accrual (in both the presence and absence of stream macroconsumers) will be measured over 30 day periods in mid-summer on unglazed ceramic tiles collected every 5 days using previously described methods (Schofield et al. 2004). Litter baskets similar to those used previously (Webster et al. 2012a) will be used to quantify allocthonous inputs. Leaf decomposition rates, fungal biomass, and macroinvertebrates associated with decomposing leaf packs will be measured using air-dried leaf packs anchored in seven pools/runs in each reach. We will measure functional characteristics of the rhododendron removal and reference stream reaches using established techniques we previously used (Northington et al. 2013). We will measure stream metabolism using diurnal single-station oxygen change, with concurrent measurements of nutrient uptake using ammonium uptake as an index of biotic activity (Earl et al. 2006). Benthic macroinvertebrates and fish will be quantitatively sampled (Harding et al. 1998, Price and Peterson 2010) during spring and fall at a minimum of 6 locations distributed above, within, and below the treatment reaches while salamander occupancy will be assessed with regularly spaced refugia bags (Cecala 2012). Terrestrial salamander abundance will be evaluated by capture-mark-recapture techniques in 10m × 10m riparian plots. From these data we will evaluate changes in consumer populations in response to the riparian rhododendron removal, and in particular whether there is an increase in algal abundance and primary production, and then, as the deciduous canopy become more closed, a shift to a spring peak of instream production.

2.3.3.C. Riparian Management as a Function of Landowner Attitudes and Decisions: Eighty-seven percent of forestland in the Southeast is privately owned and 57% of landowners are families, not corporations, who hold land tracts of 9 acres or less (Wear and Greis 2002, Butler 2008, Smith et al. 2009). This trend holds across southern Appalachia as well where estate sales and urbanization are further reducing parcel size in parallel with a conceptual shift in family and corporate use of land and riparian zones. Forestland management is no longer focused primarily on commodity production (i.e., food and fiber), but on producing cultural, aesthetic, recreation, and mitigation benefits (Cardinale et al. 2003, Lai 2004). Changes in stream-side and in-stream uses in particular imply a need to revise outreach efforts to land owners as well as improve understanding about the spatial properties of management activities (Ricketts 2004, Chan et al. 2006). Some ecosystem processes (e.g., soil nutrient cycling) have short temporal and spatial lags so they are effectively private, but other processes (e.g., water quality, C sequestration) have long lags across different landscape areas and effectively constitute public or common-pool resources (Ostrom 1999). Land management policy must take place at multiple scales to account for private and public processes held and transferred between owners across landscapes if it is to anticipate the regional effects of human population increase, climate change and the spread of invasive species (Kauffman 1997, Agrawal 2003).

In response to hemlock loss across the Little Tennessee River basin, landowners have developed management strategies to remove the standing dead wood. The expansion of rhododendron into the spaces created by the loss of hemlock simultaneously created dense "slicks" that limit land use. This transformation is occurring within an historic value context in which land owners create gaps in the riparian zone to enjoy streamside views, fish, etc. Gaps introduce light to an energy-limited system boosting primary productivity and benefiting, for example, salmonids (Hawkins et al. 1983, Hagen et al. 2010), but also increasing maximum local stream temperatures to levels stressful to numerous coldwater species (Burton and Likens 1973). Adjacent land uses may also accelerate sediment and nutrient movement into the stream (Leigh 2010, Evans 2013). Our objective is to isolate the factors that underlie management decisions by property owners about riparian vegetation on their land, and their participation (or lack thereof) in riparian zone restoration. We expect decisions are influenced by: 1) individual attributes (i.e., gender, age, income and education); 2) land owner ego networks tied to local value systems (i.e., family, neighbors, and trusted sources); and, (3) land owner social networks tied to extra-local value systems (i.e., memberships, donations, and subscriptions). We will combine property transaction data from the upper Little Tennessee (1990-Present) with land cover data (1985-present) to test whether hemlock loss and/or high rhododendron density reduces property values. Results will then be used to investigate the social, cultural and economic processes that drive riparian management decisions. Riparian restoration can mitigate the detrimental effects of hydroclimate variability and improve habitat conditions for native species, but to be effective, restoration efforts must incorporate the heterogeneity of processes that drive owners to participate in interventions or respond as intended to policy.

2.3.4: Consequences of Hydroclimate Variability and Landscape Development

Our previous research quantified many consequences of land use change and climate on biodiversity and ecosystems (Bolstad 1997, Harding et al. 1998, Pearson et al. 1998, Wear and Bolstad 1998, Turner et al. 2003, Fraterrigo et al. 2006a, Gragson and Bolstad 2006, Kuhman et al. 2011, Jackson et al. 2012, Jackson et al. 2013). However, the regional consequences of increased hydroclimate variability are less well known. For example, the effects of the observed increase in late summer drought may be exacerbated or mitigated by present or future land uses. Previous work also identified key uncertainties in how land use legacies affect hydrologic response as well as how our current land use categorizations only coarsely reflect underlying impacts on ecosystem structure and function (Webster et al. 2012b). Our objective is to determine how hydroclimate variability and land use may cause shifts in southern Appalachian ecosystems, generating a series of hypotheses to be addressed by activities described below.

First, humans are a dominant modifier of regional ecosystems, and we hypothesize that the geography of human modifications depends explicitly on social, economic, and migration characteristics of human inhabitants, in addition to commonly studied physical and biotic drivers (Turner and Robbins 2008). Previous work has documented exurbanization as a primary force acting on ecosystems in southern Appalachia (Hansen et al. 2005, Kirk et al. 2012), but modeling the effects of human land modifications requires a more detailed characterization of the agents themselves (Verburg et al. 2004). We hypothesize that coupling micro-to-meso-level social science data with multi-level physical and biological data is necessary to estimate cumulative effects across space (Veldkamp and Lambin 2001, NRC 2013), and distinguish between the forces behind development that range from a "cabin nestled in the woods" to the "treeless turf" suburban archetype. Next, we hypothesize that the overarching hydroclimatic effect will be via increased soil moisture extremes (drought and saturation events) across the cove to ridge gradient. This will result in periodic increases in hydraulic stress that lead to nonlinear responses in overstory leaf area, productivity, and community population metrics that in the aggregate increase flood and landslide risk. Finally, we hypothesize large shifts in ecosystem structure and function under future climate scenarios with corollary changes in social/human vulnerability due to higher flood and drought frequencies. We expect that exurbanization will account for a larger proportion of change than the shift in climate while vulnerabilities may not be reflected or accounted for in human governance or risk-balancing mechanisms.

We will quantify hydroclimate variability and land use from 1880 to 2080 by synthesizing previously assembled information (CWT-IV to CWT-VI) and new field sampling across landscapes. We will integrate new work outlined previously (2.3.4.A) that fills key data and submodel gaps in our regional modeling framework, and test/improve the RHESSys model across the full range of soil moisture, stream flow, and other measurements characterizing our manipulation and monitoring plots. We will then perform and analyze future scenarios based on a downscaled IPCC 5th assessment and human population projections. Earlier research (Sections 2.3.1, 2.3.2, and 2.3.3) will be used to identify key mechanisms by which ecosystems respond to hydroclimate and drainage, and land use and management conditions. Plot-derived, fine-scale models (e.g., ongoing and new tree demography models from the TDE section 2.3.1.C, and salamander abundance models from section 2.3.2.B) will be run across a range of regionally varying conditions. Downscaled IPCC climate drivers will be passed through RHESSys to estimate key drivers (soil moisture, air and soil temperature, precipitation, humidity, LAI, vegetative productivity) in an integrated regional framework. Models will be applied across a range of future climate and land use/population scenarios from Coweeta sub-basins, through our 24 *Nested Watersheds*, to our two large, representative river basins - the Little Tennessee (LT) River and the French Broad (FB) River.

2.3.4.A. Land Use Drivers and Legacies: We will complement previous work emphasizing biophysical and proximity effects (Wear and Bolstad 1998) by examining the intensity of human activities on the land, local vs. extra-regional linkages, and details on land-owner decision-making. Work will concentrate on 24, second- to third-order *Nested Watersheds* that include the existing *Gradient* and *Gap Plots*, the *TDE Plots*, and new plots that will be established in support of this research. Riparian and social/economic sampling will be incorporated to the extent possible, and span climatic, biotic, and development gradients integral to other analyses (e.g., 2.3.2.A and B; 2.3.3.A; 2.3.4.B, C, and D). The *Nested Watersheds* will be selected by comparing all watersheds in the LT and FB across the range of key driving variables (e.g., mean or extreme temperature, precipitation, topography, land cover or fragmentation). For each *Nested Watershed* we will map land use, physical and biotic structure, and human population characteristics using individual-level Census Public Use Microdata Sample (PUMS) data, Census American Community Survey small area data, parcel-level municipal records, and land use and biophysical condition from 1m semi-annual Farm Service Administration orthophotographs, 6 m statewide LiDAR, and Landsat DCM. Biophysical variables will be mapped or downscaled to the 6 to 10m grid cell size, and population characteristics downscaled from block group or larger aggregations to sub-block geographies (Mennis and Hultgren

2006). We will use spatially explicit logistic, multi-level, and standard regression analyses (Aspinall 2004) to relate land disturbance (land use, vegetation type and stature, canopy density) to biophysical (e.g., slope, vegetation type, distance to town) and socio-economic conditions (e.g., human population age, income, household size, commuting distance, migration history).

Ethnographic analyses of participant observation results, social networks and migration histories will be used to extend our understanding of the effect of local and extra-regional linkages on land use decisions that drive larger scale ecosystem change. Co-location of the *Regional Plots* within the *Nested Watersheds* will facilitate integrating the analysis of human land-use motivations to be obtained in 2.3.2.C and 2.3.3.C. This is particularly important in southern Appalachia where county populations have typically grown by 30 to 80% in the past 30 years, with 25 to >50% of the population born in another state or country (U.S. Census). We will build and evaluate models that estimate human modification probability based on current development, socio-economic and site biophysical characteristics, and landscape-to-regional population, including total population and density, age, income, density of local and extra-regional linkages, place of origin, and tenure. Models will be tested using ROC (Pontius and Schneider 2001) on past transitions for *Nested Watersheds* (Kirk et al. 2012) allowing us to test a series of hypothesis on driver dominance in human modification, and to downscale estimated regional population for future scenarios described in 2.3.4.D.

We will quantify legacy effects of agricultural abandonment on hydrologic processes as we hypothesize that land use activities transform the hydrologic connectivity of landscapes, in turn affecting soil moisture, canopy properties, and flow regimes at regional scales. Previous work has shown legacies may dominate ecosystem function, irrespective of current land use (Harding et al. 1998). They may also dominate southern Appalachian surface hydrology in many watersheds (Leigh 2010, Price et al. 2010, Wang and Leigh 2012), shifting hydrologic response from variable source area towards Hortonian runoff (Trimble et al. 1987, Knox 2001, Schwartz et al. 2003). This shift persists after conversion from agriculture to forest for some unknown recovery period (Price 2011, Bain et al. 2012), and most current models ignore these legacies. This can potentially cause gross errors, particularly in southern Appalachia where over 35% of the land area in many 2nd and 3rd order watersheds is reforested, abandoned farms (Kirk et al. 2012).

Past land use has been previously quantified (Wear and Bolstad 1998, Kirk et al. 2012). This information will be used to identify parcels within our *Nested Watersheds* on which to characterize bulk density and infiltration capacity (Singer and Janitzky 1986, Amoozegar 1989, Staff 1992), as well as the mechanical, additive, and cultural activities they were subject to over time (Bolstad and Gragson 2008, Houben 2008, Wilson 2008). Parcel information will be analyzed using Geographically Weighted Regression and Bayesian Weights of Evidence procedures to discriminate between first-, second-, and third-order forces acting on landscape hydrologic connectivity (Fotheringham et al. 2000, Leigh and Webb 2006, Gragson and Bolstad 2007). Recovery trajectories will be estimated as a function of time since abandonment and previous land use, and spatial predictions tested by bootstrap and independent sampling. Results will be inputs for our modeling efforts to estimate hillslope hydrology and flow regime impacts, and assess risks such as flooding and slope failure (2.3.4.D).

2.3.4.B. Regional Ecohydrology: We will use a set of extensive measurements across our *Nested Watersheds* and additional gaged watersheds to test RHESSys model skill in predicting soil moisture patterns. Results will be combined with an analysis of our existing regional satellite record (CWT-VI) to evaluate RHESSys predictions of leaf area and other canopy patterns. We will use an improved RHESSys model to expand our simulations of coupled water, C and N cycling and transport at the TDE plot to hillslope scale, at the *Focal Taxa Plots, Regional Plots* and *Nested Watersheds* through to the LT and FB watersheds. Soil moisture, water flow and chemistry, and productivity will be simulated at 10 m resolution for the Coweeta watershed containing the TDE (WS10), and nearby Coweeta gaged catchments. Models will be compared to TDE measurements (e.g., ET, groundwater depth, soil moisture, leaf area) to constrain model parameter ranges and assess model behavior.

We will add 14 continuous soil moisture and climate stations in the 24 *Nested Watersheds* to broaden our topoclimatic measurements. We will also install nine synoptic soil moisture cove-to-ridge-transects within the 24 *Nested Watersheds* and co-located with *Regional Plots*. Soil moisture samples will be collected monthly at 30 m intervals along the ridge to cove transects, with 3 replicates per interval spaced 6 m perpendicular to the transect direction (CS HS2P/CS655) at 30 cm depth. Dominant vegetation structure compatible with the *TDE* and *Gradient Plots* will be measured at each climate station and transect sample (tree species, basal area, height, LAI, soil depth by horizon, O.M., litter mass, root mass), while retrospective canopy FPAR and LAI will be estimated from 30-year Landsat, MODIS, and AVHRR images (Hwang et al. 2014). All long-term USGS discharge gauges in the LT and FB will be included to diagnose and improve long-term model flow performance, typically representing larger watersheds (4rd and 5th order). Model skill in predicting soil moisture, LAI, and other variables across landscape positions will be tested via Nash-Sutcliffe efficiency and other metrics (Beven 2006), and canopy phenology and density response tested through observed and modeled canopy across the 30-year satellite time series. Model runs across years will provide response estimates to input variables for analysis in 2.3.4.C and 2.3.4.D.

2.3.4.C. Biotic Response from Landscapes to Regions: Models developed on the TDE and Gradient Plots (2.3.1.C and 2.3.2.A) will be used to predict response variables (e.g., presence, dominance) for focal taxa in a full spatial (GIS) framework on the Regional Plots, Nested Watersheds, and then LT and FB watersheds. Model drivers will include detailed land use data from previous and proposed activities (section 2.3.4.A) including roads, structure location and density, vegetation management intensity, permeability legacy effects from previous land use (2.3.4.A), vegetation canopy, age, structure, species (2.3.4.B), and climatic and soil moisture data. This information will be used to generate 10 m RHESSys simulated soil moisture, groundwater, canopy processes, litter dynamics, subcanopy radiation and microclimate fields (2.3.4.B). RHESSys will be used to generate a large set of behavioral realizations exceeding a performance threshold (e.g., Beven 2006) across parametric uncertainty ranges using the GLUE approach. Simulated output fields will be used to drive models of individual and population response (from 2.3.2.B) and the species response/competition models developed at Coweeta and elsewhere (Clark et al. 2010, Clark et al. 2011b, Clark et al. 2011a). All models will be applied across the 24 Nested Watersheds, including the Regional Plots, and the entire LT and FB watersheds to generate uncertainty bounds for focal taxa population characteristics and vital rates. Modeled characteristics will be mapped, and analyzed for extent, connectivity, and source/sink relationships. These outputs will also be used as a baseline to compare spatially explicit impacts in scenarios of future landscape and climatic change (2.3.4.D).

We will use FIA data to evaluate trajectories of overstory tree and seedling change on sites that differ hydrologically. This will provide us the opportunity to examine individual demography over repeated, widely-distributed censuses for thousands of plots, and note that another FIA census will occur during the next funding cycle. We will use the shift in patterns of recruitment, growth, and survival on FIA wet sites/ dry sites to test for patterns documented in the TDE (e.g., greater sensitivity in ridge sites due to lack of subsidies, or greater sensitivity in cove sites due to physiological adaptation to well-watered conditions). The 'physiographic' variable in FIA is related to local drainage and explains variation in abundance at the plot scale. We will quantify species migration upslope/downslope and patterns of growth and mortality with elevation, and compare these to models driven by RHESSys modeling described in 2.3.4.B.

2.3.4.D. Hydroclimatic and Land Use Scenarios: We will test coupled ecohydrologic/socio-economic system responses to determine how well current economic signals reflect land use risk due to functional ecohydrology. We will then create a set of scenarios to estimate future system function and risk to pursue the regional implications of hydroclimate variability across square-meter to regional geographies. We will begin by examining how perceived risk of hazards and associated regulations affect land prices and development patterns, and how well these patterns reflect modeled risk. Flood ordinances associated with the National Flood Insurance Program affect development throughout the region. Buncombe County (FB basin) recently adopted and Macon County (LT basin) recently rejected steep-slope ordinances designed

to address landslide risk. We will use multi-decadal data describing land transaction prices in Buncombe County to test the influence of exogenous measures of flood, landslide and fire risk on land prices as relate to insurability (Chamblee et al. 2009, Chamblee et al. 2011). We will then test for the effects on land prices of the adoption of a steep slope ordinance in Buncombe County in 2010. For Macon County, we will use data on individual building permits and test for preemptive development from landowners trying to avoid compliance with new potential regulations (Dehring and Halek 2013). We will integrate ecosystem responses to increased hydroclimate variability generated from 2.3.1.A through 2.3.1.C and previous work (Hales et al. 2009, Hales et al. 2012), e.g., species shifts or tree density changes resulting in a change in aggregate hillslope root tensile strength, and hence changes in landslide vulnerability. RHESSys runs across hydroclimate conditions will identify ecosystem conditions (canopy and root density and strength) indicating landslide susceptibility, and whether current economic or policy systems integrate this changed risk (Figure 8).

RHESSys will be used to estimate response and vulnerability to long-term, regional hydroclimatic change across a state-space that integrates down-scaled IPCC 5th assessment and downscaled ICLUS population and development scenarios. We will assess differential vulnerability in different landscapes to distinct development and climate scenarios. IPCC point and regional climate means for the A1 and B2 scenarios will be converted to stochastic weather time series and spatially downscaled to 10 m cells using landscape extrapolation methods already incorporated into RHESSys. ICLUS human population will be downscaled to sub-watersheds based on relationships identified in 2.3.4.A that incorporate current development and population, and site biophysical characteristics, with and without slope ordinances using current flood-plain delineations. Combined climate/development sets will be generated to a) model important ecohydrologic variables (soil moisture, stand transpiration, forest productivity, and streamflow); b) model canopy C, water and N cycling response; c) couple biotic models from 2.3.2 to estimate demographic and distributional responses for trees and focal taxa; and d) estimate place-based ecosystem and human vulnerabilities to landslide and flooding (RHESSys modules developed in CWT-VI) to future climate extremes.

Key taxonomic, biogeochemical, and social indicator responses will be estimated on decadal or finer intervals through 2080 on the 24 *Nested Watersheds* at 10 m resolution, and for the LT and FB basins at 30 m resolution. RHESSys will directly output variables of interest, or RHESSys output will drive models developed in previous sections (e.g., soil moisture will in part drive tree demography models). Specific response variables representing system structure, function and vulnerability will include mean daily low and high flow frequencies in 1st through 5th order streams. In addition, stream temperature, overstory species composition, ecosystem production, canopy height and density, focal taxa distribution and abundance, index of critical slope saturation and landslide and flooding likelihood will be overlain with other spatial data to identify the amount and extent of vulnerable natural and human populations. We expect land use change will be most important for species richness of non-tree taxa, depending on their range and dispersal characteristics, while habitat loss and fragmentation associated with land use change may amplify the effects of climatic changes (e.g.Lumpkin et al. 2012, Lumpkin and Pearson 2013). Spatially, we expect cove positions to be most vulnerable to changes in species composition due to the combined effects of hydroclimatic sensitivity and higher frequencies of land fragmentation, hence dispersal limitation.

2.4. Synthesis

How do hydroclimate variability and the human modified landscape separately and interactively alter southern Appalachian Mountain ecosystem processes and biotic communities? How do these alterations, in turn, affect the vulnerabilities of regional socio-ecological systems? Disturbance has been the organizing concept for CWT LTER research that originated in a 1974 study of the effects of perturbation on nutrient circulation in WS7 in the Coweeta Basin (Swank and Webster 2014). From the simple engineering notion that disturbance was an impulse function representing an instantaneous change in initial conditions (Waide and Webster 1976), ecology now seeks to understand ecological processes across broader scales





Figure 8. Water table depths, root zone saturation, and factors of safety for shallow rapid landslides simulated with RHESSys for Cartoogechaye Creek and five subwatersheds in September 2004 after tropical storms Frances and Ivan passed through the study area. Colored points represent climate stations (WINE, NWAY, and CS01) and USGS gauge stations (Cartoogechaye Creek near Franklin, NC; ID 03500240); black points represent observed landslide locations from North Carolina Geological Survey.

and to uncover the feedbacks linking the biophysical and human realms (Rockström et al. 2009, Chapin et al. 2011, Collins et al. 2011). Forestry no longer has the economic importance in the southern Appalachian Mountains it did 40 years ago when the WS7 manipulation was carried out, but the CWT LTER program continues to link the results of systematic research to their practical implications.

The southern Appalachian Mountains are a biodiversity hotspot undergoing rapid development. They harbor unique species and assemblages, and are the source of freshwater as well as a recreational destination for human populations in nearby metropolitan areas. The total rural and urban population of areas within and surrounding the southern Appalachian region is expected to continue growing at double-digit rates for the foreseeable future, accompanied by conversion of forested land to developed areas (Wear and Greis 2002, Gustafson et al. 2014). Other studies conclude reduced water inputs slow ecosystem processes (Wu et al. 2011), and that mesic forests as those in southern Appalachia may be particularly susceptible to increased drought frequency, duration, or depth, having developed under moisture-surplus regimes. This hydroclimate variability is not simply a "natural" process. We have found that the Coweeta Basin lies within a *Ring of Asphalt* that experienced a 15.5 percent increase in urban land cover from 1992-2006 (Kirk et al. 2012, Shepherd et al. 2013). The urban chains forming along transportation corridors constitute spokes into the interior resulting in urban rainfall effects in rural southern Appalachia.

Past CWT research has demonstrated the significance of spatial and temporal variation in hydroclimate conditions on the distribution of species and ecosystems. Our proposed research is designed to address the complexity of organismal responses to increasing hydroclimate variability in a world-of-use (Figure 1). We will conduct two experiments manipulating aspects of climate or vegetative cover (throughfall displacement and rhododendron removal), diversify the use of the CWT long-term plots to explore the influence of spatial hydroclimate variability on organisms and ecosystem processes, and examine the landowner value systems underlying land use. Knowledge gained by these studies will be synthesized and integrated into our regional modeling effort and combined with previous CWT results to generate scenarios for how climate and land use may affect key drivers and characteristics of the biome including soil moisture, air and soil temperature, precipitation, humidity, LAI, vegetative productivity, tree demographics, streamflows, and landslide risk.

These proposed research activities tie directly to past CWT research on hillslope flow processes, downslope subsidies, forest demography, and riparian controls on stream processes. Our focused set of mechanistic experiments and activities will allow targeted insights that connect spatio-temporal components of the water cycle across a range of scales to discover feedbacks linking the ecological, biophysical, and human realms. Rapid development of the southern Appalachian Mountains motivates the development of strategies to buffer against climate-driven vulnerabilities across regional socio-ecological systems. Ascertaining as many of these key relationships now, prior to extreme ecosystem change, is timely, necessary and the point of LTER research. A distinguishing characteristic of the Coweeta LTER has been our increasing ability to speak to the human modifications that effect ecological systems in a way that strengthens, rather than weakens, ecological science. Understanding the relationships between ecosystems, organisms, and their responses to the forces of hydroclimate variability and human activities on the land are essential if ecological science is to anticipate, respond to, and mitigate these changes and the associated vulnerabilities.

Section 3: Related Research Projects

CWT LTER research funded by NSF is strongly leveraged by USDA-FS work, and by a range of projects funded by other sources. CWT LTER and USDA-FS have an effective partnership that develops new information on forest ecosystem science that is then translated and demonstrated at diverse levels. USDA-FS scientists and technicians will be involved in all major proposed initiatives, and in particular the Throughfall Displacement Experiment (2.3.1) and the Rhdodoendron Removal Experiment (2.3.3). They will work with National Forest System land managers to coordinate project activities, in addition to continuing to sample the *Intensive Hemlock Plots*. They will also lead collection of core data extensively used in CWT LTER research including weekly grab samples from WS18 and WS27 for stream chemistry analysis; they will also maintain the station and calibrate sensors that serve to sample climate in the valley floor (CS01). Throughout the project, the USDA-FS will facilitate access to the Coweeta Hydrologic Laboratory field sites (see Facilities), as well as host a minimum of two meetings per year on-site for LTER project investigators and students to share findings of research, and to plan and coordinate research.

In *Consequences of Stand Age and Structure on Water Yield* (PI: Ford, 2012-2016), USDA-FS and CWT LTER investigators are examining how changing forest condition affect hydrologic processes in the southern Appalachian Mountains. The objective is to quantify the age and structural dependence of the hydrologic cycle in eastern deciduous forests by measuring the variation in hydrologic components across an early succession to old-growth hardwood chronosequence (i.e., shelterwood harvest site <2 years, 10 years, 30 years, 85 years, and >200 years). The 30-year old stand is located in Watershed 7 while the 85-year old stand is located in Watershed 5, both in the Coweeta Basin (see Facilities). The other three sites are in the Nantahala National Forest. Sites, measurements, and data from this project are central to activities in 2.3.4.

The *Long-term Forest Demographic (LTFD) Analysis* network was established at the Coweeta Hydrologic Laboratory in 1991 (*Terrestrial Gradient Plots*) to understand how climate and competition interact to control change in eastern forests (Clark et al. 1998, Clark et al. 2004) and now includes a network of sites across eastern North and Central America. Early studies quantified basic demographic rates and introduced the hierarchical Bayes paradigm organized as state-space models (Clark 2005), while new modeling innovations have played a large role in quantifying the interactions between temperature, drought, and competition for light and moisture between species and size classes (Gelfand et al. 2013, Ghosh et al. 2013, Wu et al. 2013). Twenty-plus years of demographic data from 40,000 trees representing >350,000 tree-years serves a critical role in the activities described in 2.3.1, 2.3.2, and 2.3.4.

Coweeta investigators are involved in collaborative activities with the NASA Integrated Precipitation and Hydrology Experiment (IPHEX) program to characterize the relationship between precipitation regimes and hydrologic processes in complex (mountainous) terrain. IPHEX includes two major activities: 1) development, evaluation and improvement of remote-sensing precipitation algorithms in support of the Global Precipitation Measurement Mission; and, 2) evaluation of Quantitative Precipitation Estimation products for hydrologic forecasting and water resource applications in the Upper Tennessee, Catawba-Santee, Yadkin-Pee Dee and Savannah river basins. Both activities have direct relevance to activities proposed in 2.3.1, 2.3.2, 2.3.3, and 2.3.4 as well as improving the predictive capacity of RHESSys.

In *Dynamics of Social Spaces and Mountain Environments* (PIs: Hautefeuille & Gragson, 2015-2019), French researchers and CWT LTER investigators are comparing the co-evolution of agropastoralism and soils across the French Pyrenees Mountains and the Southern Appalachian Mountains. Multi-proxy evidence from bio-geoarchives, historical records, pedestrian survey, and ethnography are being used to develop millennial histories of the human transformation of mountain landscapes and in particular how management practices relate to soil fertility, pedogenic processes, and the stratigraphy of land parcels and small watersheds. Activities described in 2.3.2.C, 2.3.3.C and 2.3.4.A are closely associated with this international collaboration.

In activity initiated at the 2012 ASM, investigators from the CWT, JOR and AND LTER sites are using the Coweeta Listening Project (CLP) model to meet the science needs of environmental managers, local environmental organizations and land owners. CWT and GCE LTER investigators are also using the CLP model in a partnership with Georgia Sea Grant and the Georgia Coastal Research Council to promote science-based management of Georgia coastal resources. These cross-site efforts are central to activities described in 2.3.2.C and 2.3.3.C.

Section 4: Education and Outreach Activities

We will continue ongoing educational and outreach activities described below while enhancing our ability to provide information to the general public including the Eastern Band of the Cherokee as described under future plans.

Educational Activities comprise field-based environmental education programs and in-classroom support for middle school students, and university student education and mentoring. Our field-based education targets 5th through 8th grade students, and consists of four annual multi-day field trips that draw about 1,000 students/y from 14 schools in North Carolina, Georgia and South Carolina. These trips involve collaborators from the US Fish and Wildlife Service, NC Natural Heritage Program, NC Wildlife Resources Commission, NC Division of Water Resources, Land Trust for the Little Tennessee and Southern Appalachian Raptor Research. Our main programs include **Migration Celebration, Kids in the Creek, Bird Monitoring**, and **Invasive Species Awareness Day**.

We support environmental science in the classroom by providing **Science Study Boxes** that deliver ecological content for teachers to meet state curriculum requirements. This effort benefits approximately 2,500 students/y. We additionally engage between three and six undergraduate research interns each year through REU and other funding. Our graduate students organize an annual symposium each summer at which they present results of their ongoing research. Many of those located at UGA are also involved in the Integrative Conservation (ICON) PhD program run jointly by Anthropology, Ecology, Forest Resources and Geography. Two CWT project investigators teach the core ICON seminar in which students collaborate with practitioners in southern Appalachia (e.g., Vercoe et al. 2014) to bridge research into public outreach.

Public Outreach. Our partner in outreach is the Land Trust for the Little Tennessee (LTLT), the leading non-profit conservation organization in the southern Blue Ridge. We support the LTLT in three areas. **Aquatic Biomoni-toring** is a citizen-science program that has coordinated thousands of volunteers over the last 25 years to monitor freshwater fish across the upper Little Tennessee River. The CWT LTER website hosts the fish monitoring data that includes hundreds-of-thousands of observations on all known fish species in the watershed. The Coweeta Listening Project working with ICON students and LTLT science-practitioners developed the **Southern Appalachian Stream Visual Assessment Protocol (saSVAP)** to enable volunteers to document stream conditions in relation to land use, water quality, and habitat. The **Shade Your Stream** program incorporates CWT LTER results and educates landowners in the Little Tennessee watershed on the importance of riparian corridor integrity, and includes workshops to restore riparian areas through live staking.

Media Interactions. The Coweeta Listening Project engages the western North Carolina community in a process that links science, policy and management. One of the key activities to date has been a collaborative of CWT project investigators and graduate students who publish a bi-weekly newspaper column in the *Franklin Press* (first issue: January 2012) that translates and communicates community-relevant CWT LTER science. Our support for public outreach and media interactions materially contributed to the recent designation of the Little Tennessee River Basin as North America's 1st "Native Fish Conservation Area".

Future Plans. We will continue providing field-based environmental education for middle school students, in-classroom support for middle-school environmental science, summer undergraduate internships, and making publically available the Aquatic Biomonitoring data. Each year, a minimum of two REU students will be recruited and mentored by project investigators to develop independent, place-based research supporting the CWT LTER project. We will create a graduate certificate program in science communication in tandem with the ICON PhD and engage the Cooperative Institute for Climate and Satellites in Asheville, NC, using the bi-weekly newspaper column as an internship opportunity. We will help LTLT deploy and train users in the application of saSVAP, thus equipping students with tools to address grand challenges in global environmental change (Ledee et al. 2011). We will also support expansion of the Aquatic Biomonitoring and Shade Your Stream programs to the Tuckaseegee watershed.

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Project Management

Composition & Governance. The Coweeta LTER is a regional project with a large number of participating scientists who bring diverse disciplinary backgrounds to the project. Project management ensures the proper balance between productivity, disciplinary and methodological approach, and scientific vitality. The project philosophy is that LTER base funding and infrastructure provide a research platform to enable individuals to leverage additional resources. We follow a consultative approach to project management in which decisions, the right to vote, and the responsibilities that go with them are vested in the Lead Principal Investigator, the Science Advisory Committee, Project Investigators, and LTER Staff. Our bylaws describe the roles and responsibilities of individuals associated with the project, along with the provisions for adding and removing individuals. Voting may be done either electronically or in person, with a quorum consisting of two-thirds of the CWT LTER voting membership. The project membership list is posted to the CWT LTER web site.

The organization of the CWT LTER consists of a Lead Principal Investigator (T. Gragson, LPI) at the University of Georgia who coordinates with the USDA Forest Service Project Leader (C. Miniat, PL) at the Coweeta Hydrologic Laboratory; together they are the Project Directors. The PL is responsible for: setting priorities for and supervising FS and FS contract personnel; review and approval of research activities in the Coweeta Hydrologic Laboratory. The LPI is responsible for setting priorities for an supervising FS and FS contract personnel; review and approval of research activities in the Coweeta Hydrologic Laboratory. The LPI is responsible for setting priorities for an supervising LTER personnel; managing the LTER budget, resources, facilities and equipment across the project area; and, representing the project to the LTER Network, NSF, and the lead academic institution. The Project Directors together are responsible for the overall administration of the CWT LTER Project including final authoring and submission of the proposal and its supplements; conducting and completing CWT LTER annual and mid-term reviews and reports; and, making staffing and support decisions.

The Science Advisory Committee (SAC) provides scientific input on a myriad of decisions to the Project Directors that ensure project continuity over time. The SAC is composed of nine Project Investigators (plus the LPI, PL, Information Manager and Site Manager) who are outstanding in their fields and have demonstrated their commitment to place-based research in southern Appalachia. SAC members are responsible for coordinating draft subcomponents of NSF LTER Renewal Proposals and assist as necessary with project execution by: recommending and recruiting Project Investigators and when appropriate their removal; mentoring new and early career scientists; and, recommending the allocation of funds. SAC membership is organized around the execution and completion of a six-year LTER funding cycle. They meet at least twice each year and more frequently according to project needs.

Project Investigators (PIs) are listed as research participants during a funding cycle. They are expected to play a key role in the writing of a CWT LTER renewal proposal and engage in place-based research within southern Appalachia in support of project objectives. This includes leveraging the CWT LTER to seek additional funding, publishing in appropriate outlets to their discipline, mentoring students, and participating in education and outreach opportunities. Project Investigators submit data obtained with direct or indirect CWT LTER funding in accordance with the Data Management Plan, submit annual reports in a timely manner, acknowledge CWT LTER support in relevant presentations and publications, and routinely attend CWT LTER meetings. Project Investigators for this renewal include faculty from: University of Georgia, University of Minnesota, Duke University, University of Wisconsin, Virginia Polytechnic Institute, Indiana University, Mars Hill College, University of Illinois, University of North Carolina at Chapel Hill, North Carolina State University, and Buffalo State College as well as USDA Forest Service scientists based at the Coweeta Hydrologic Laboratory.

Graduate students (MS and PhD) conducting research within the CWT LTER domain and mentored by a CWT LTER PI are considered CWT LTER graduate students. They submit data obtained with direct or indirect CWT LTER funding in accordance with the Data Management Plan, acknowledge CWT LTER support in relevant presentations and publications, and are encouraged to participate in education and

outreach opportunities. Graduate student representation takes place through the Graduate Student Council, which consists of three to 10 students with a maximum of one member from each project-affiliated university. One member is selected as the representative to the CWT LTER and the LTER Network.

Key staff positions include: the Site Manager (SM) who is stationed at the Coweeta Hydrologic Laboratory and is responsible for field research support and managing field resources; and, the Information Manager (IM) who is station at the University of Georgia and is responsible for project data and information management systems, and serves as CWT-LTER IM representative to the LTER Network.

Meetings & Communication

The CWT LTER meets at least twice each year on dates determined by the Science Advisory Committee. A 1-2 day Winter Meeting (typically end of January) is attended by the Project Directors, Project Investigators, Information Manager, and Site Manager to discuss CWT LTER progress, calendar-year activities, and future directions. A 2-3 day Summer Meeting (typically late June) is attended by the full membership and guests to present results and coordinate working groups. Online forms are used for reserving equipment and initiating research projects. A teleconference service is available for investigators to meet on demand, and is used to hold regular SAC meetings.

Non-LTER Scientists & New Scientists

We encourage non-LTER scientists to become involved with CWT LTER research as Affiliated Investigators (AI). They do this by collaborating and engaging with Project Investigators on research and thus benefit from CWT LTER logistical or other support. Affiliated Investigators submit data obtained with direct or indirect CWT LTER funding according to the Data Management Plan, and acknowledge CWT LTER support in relevant presentations and publications. Becoming an AI is often the first step to becoming a Project Investigator. All FS scientists and staff at the Coweeta Hydrologic Laboratory are involved to some degree in LTER research, and numerous non-LTER and non-FS researchers have ongoing projects within the Coweeta Basin or the surrounding area. This provides regular opportunities for interaction and collaboration, and many of these individuals regularly attend the CWT LTER Summer Meeting. We are adding new scientists to the CWT LTER this cycle from Indiana University, Virginia Polytechnic Institute, Buffalo State College, and University of Georgia.

LTER-USDA Collaboration

The CWT LTER through the University of Georgia has had a long-standing Memorandum of Agreement (MOA) with the USDA-FS Coweeta Hydrologic Laboratory. This MOA ensures research access to the Coweeta Basin, and use of facilities such as the Residence, the Conference Center and the Analytical Laboratory. The FS provides office and analytical space for LTER staff based the Coweeta Hydrologic Laboratory as well as salary support for FS scientists and staff involved in LTER research.

Diversity

From 2008 to the present, the CWT LTER has supported, mentored, and variously engaged in research 626 individuals (exclusive of Schoolyard activities reported elsewhere) including: 117 senior scientists, 18 post-doctoral scientists, 203 graduate students, 97 undergraduate students, 3 high school students, 144 technicians, 6 Research Experience teachers, and 38 other professionals. Of these, 331 were males, 253 were females and 40 chose not to identify their gender. While the majority were white (n=520) and 52 chose not to identify their race, 31 were Asian, 16 were African-American, 3 were American Indian, and 2 each were Pacific Islander and biracial. Finally, 543 individuals claimed no disability, 73 chose not to report, and 10 individuals reported having a recognized disability. During CWT LTER VII there will be 20 males and 11 females Project Investigators; of this total, 15 will be early career and 16 will be senior investigators. Professional information on each participant is available on his or her Biographical Sketch.

Succession Plan

The SAC provides stability and redundancy in the event of unexpected changes in leadership. T. Gragson has served as LPI of the CWT LTER since 2002 and will step down during the next funding cycle, pending successful renewal. According to the CWT LTER bylaws, the SAC nominates candidates for LPI who demonstrate: a) an ability to create the transdisciplinary linkages expected in LTER research; b) the leadership qualities for maintaining a harmonious and productive work environment in an institutionally complex setting; c) a commitment to place-based research in southern Appalachia; and, d) experience managing large and complex research projects. The SAC in adherence to CWT LTER bylaws has selected Rhett Jackson (UGA) to serve as CWT LTER LPI beginning with the 2017 mid-term review.

Budgeting & Accountability

The CWT LTER is fiscally administered at the University of Georgia by the Daniel B. Warnell School of Forestry & Natural Resources, the staff of which unit carry out project-related purchasing, travel, payroll, human resource management, and other activities in accordance with University and State guidelines and policies. CWT LTER research teams are dynamic and form to address specific questions, fostering discussion among Project Investigators to collectively address emerging topics. Once UGA overhead return is accounted for, approximately 45% of project funding is allocated to core funding including long-term measurements, information management, and equipment maintenance; approximately 28% of funds directly support investigator and graduate student research activities.

PIs submit proposals for new research through an online system that are screened for feasibility by the SM and IM, then reviewed and approved by the Project Directors subject to the activity being in compliance with project research objectives and the Data Management Plan. Project Investigators are evaluated each year on the basis of the progress report they submit to the LPI to develop the NSF annual report. Factors considered in the evaluation of PIs are: the number and impact of publications, need for their particular expertise, participation in program planning, cooperation with information management practices, graduate student mentoring, cross-site activities, and ability to attract complementary funding.

Data Management Plan

Overview

The CWT Data Management Plan ensures site-based data is highly available and adheres to the LTER Network's strategic mission for Information Management, providing "long term data stewardship through development and implementation of data and design practices" (LTER Network 2011). The CWT Data Management Plan revolves around the collection, archiving, and publication of Core Data, defined as paired data and metadata packages that address both the LTER Network's Five Core Areas and the Project Description's major theoretical questions. Core Data activities are supported by the CWT LTER Information Management System (CWT IMS), consisting of a connected suite of "micro services," in which hardware and software modules are deployed for specific tasks (cf. Abrams et al. 2010 and 2011) in a service oriented computing environment (cf. Papazoglou and D. Georgakopoulos 2012).

Collaboration is a key component of our approach to developing the CWT IMS (Chamblee and Sheldon 2011; Cary et al. 2013), and our most important collaborator is the Georgia Coastal Ecosystems (GCE) LTER. CWT adopted much of GCE's core software in 2009 and we maintain an ongoing relationship to both advance the software's development and encourage its adoption at other LTER sites, where appropriate. We also take full advantage of collaborative opportunities provided by the University of Georgia community for software development, system administration, back-ups, and co-location by working with the Office of Information Technology in the Franklin College of Arts and Sciences, the Center for Teaching and Learning, and the Laboratory of Archaeology, as well as several private sector contractors.

Support for Site and Network Science

The CWT IMS supports site science by facilitating the collection, archiving, and publication of Core Data; by ensuring that investigators integrate data management best practices in their research designs; and, by providing feedback to the CWT LTER Science Advisory Committee (CWT SAC) on participant compliance with local, Network, and NSF data policies. The CWT IMS also supports both science and outreach activities by providing a high-quality, up-to-date, and content rich web site presenting CWT LTER data, publications, and findings to the scientific community and the public at large. It also provides site-specific content for the LTER Network website when requested and richly documented data packages for the Provenance Aware Synthesis And Tracking Architecture (PASTA) that underlies the LTER Network Data Catalog

We recognize three use-case scenarios for Core Data collection, archiving, and publication: 1) data collected by CWT LTER information management and field personnel via the CWT Streaming Data Network; 2) data manually collected by CWT LTER field personnel; and, 3) data collected and submitted by CWT LTER investigators. These use cases define the personnel, policies, protocols, hardware, and software needed to fulfill both the research objectives as well as data availability policies. Services in the CWT IMS match our primary tasks so that three separate data submission pathways converge on a single site-based data warehouse that ensures our efficient submission of data packages to PASTA. As of March 14, 2014, the Coweeta LTER has published 132 data packages through PASTA. An additional 21 packages from recently completed research projects have been registered with the CWT IMS. Fifty-one data more packages have been recently received and are awaiting processing by information management staff and an additional 44 have been promised by CWT LTER co-PIs. All packages will be published into PASTA within two years of collection.

Although the CWT IM office uses a set of "mission critical" software for processing much of our Core Data, investigators use a widely varied and constantly changing set of tools to generate and manage data. In order to balance their need for flexibility with the project's need to maintain high data availability at the lowest possible cost, the CWT LTER Project Management Plan requires investigators to meet with the CWT Information Manager prior to beginning their research to discuss data management needs and

best practices. The Project Management Plan also requires the Information Manager to provide feedback to the CWT SAC concerning investigator cooperation in information management. The timeliness, quality, and outcomes of pre-research activity meetings and post-research activity data submissions are the metrics for reporting cooperation.

Data streaming, research review, and data submission enhance research activity. Near-real-time workflow-generated data increases the quality of and speed at which data are available for use. This in turn increases the rate at which scientists can assess the results and move on to the questions generated by their previous results. In addition, when researchers adopt information management tools early in the research cycle, they can lower the cost of data processing, analysis, and collaborative sharing. Over the long-term, the Digital Object Identifiers (DOIs) provided by PASTA also make it easier for scientists to increase the visibility and usability their data by the scientific community as a whole.



Figure 1. Schematic of the CWT LTER Information Management System.

Data & Information Management Systems

<u>Hardware</u>: Figure 1presents a schematic of the hardware and software comprising the CWT IMS. The primary on-site repository for digital data (e.g. submissions, processed data, and archived data) is a virtual machine server that is built on a redundant disk array with fail-over support that is maintained in a locked cabinet. Our three virtual machines respectively provide local file and printing, database, and web services. A second and similarly configured server provides disk-to-disk file and database backups and is located in the Curation Vault of the University of Georgia's Laboratory of Archaeology, over two miles away from the main system. Data loss extending beyond a single day would only result if we experienced simultaneous disk failures of three drives on each of our file and backup servers. The GCE LTER provides hosting for our software subversion repository and our windows-based database-driven web

applications, and the GCE Information Manager executes back ups for the services they provide using the protocols outlined in their data management plan (see Alber et al. 2012).

Other elements of the CWT IMS include the data collection and transmission elements of the streaming sensor network, as well as the network hardware, workstations, and laptops the Information Manager deploys and maintains at the Coweeta Hydrologic Laboratory in compliance with the USDA Forest Service requirement that an independent system be maintained for non-Forest Service personnel. These resources include a centralized file server for LTER personnel that is backed up on a weekly basis to an external hard drive stored in the USDA Forest Service file vault. (Ongoing field data collection projects are backed up quarterly to the primary file server in Athens.) The file server and the sensor network are both linked through network security and transmission systems (installed in the most recent funding cycle) that reduce maintenance and travel costs by allowing information management staff to remotely resolve the majority of troubleshooting requests from the University of Georgia campus.

<u>Software</u>: We use micro services to maintain our web presence, provide services to CWT LTER participants, and manage and publish our data and metadata. The rationale behind this modular, adaptive system relates to cost and sustainability. Micro-services are easier to develop and deploy, and less expensive to maintain than a monolithic system because modularity allows for replacement as needs change (Abrams et al. 2010:176). Table 1 lists and describes mission critical software service components in the CWT IMS.

Application	Service Provided
Drupal	Web content management system and organizing framework
OpenLDAP	Authentication and user management for web services
KBPublisher	Knowledge base for field and information management protocols
Subversion (SVN)	Software version control repository for all CWT IMS code
Trac	Software development Wiki and bug tracking for CWT IMS code
PHPScheduleIT	Reservation system for shared physical resources
GoToMeeting	Teleconferencing support for a distributed environment
GCE Metadata MMS	Site Based Management of NIS related content
Loggernet	Retrieval of data from remote sensor sites
GCE Data Toolbox for MATLAB	Streaming, QA/QC, and review of data.
GCE / CWT Excel Template	Submission of data sets from PIs and students

 Table 1. Mission-critical service components of the CWT IMS

We use Drupal as the "Landing Pad" or primary public point of entry for the CWT LTER website. It also provides the scaffolding for all other web services including the more static portions of our web content such as project background, leadership, facilities and policies. LTER NIS related content is managed through our implementation of the GCE Metabase Metadata Management System (MMS), which presents our personnel directory, our searchable publication and data catalogs, and links to photo galleries and reference GIS data. The most important function of the Metabase MMS, however, is that it allows us to dynamically generate XML metadata fully compliant with EML version 2.1 to accompany the data packages we submit to PASTA. Other web-based services include on-line equipment reservations, teleconferencing, and cloud storage that authenticate against our LDAP server and increase our capacity for collaborative work in a distributed setting.

The data collection, archiving and publication use cases described above are supported by three software packages. We use Campbell Scientific's LoggerNet Software and the GCE Data Toolbox for MATLAB for end-to-end processing of all streaming sensor data. We created training documents for the GCE Data Toolbox, and LTER field personnel use the system for submitting manually collected data. Investigators who do not wish to use the Data Toolbox can submit data for final publication using a customized Excel spreadsheet template that supports importing and reviewing data in the Data Toolbox.

<u>Documentation and Training</u>: KBPublisher provides our "knowledge-base" or repository of information management and field technician workflows that cannot be fully recorded in software comments or the subversion repository. The knowledge base is a crucial tool for ensuring service continuity during personnel changes. TRAC SVN, hosted by the GCE LTER, secures our micro-service application code by maintaining backups and past versions of the executable code underlying our software. For training new information management staff, technicians, students, and PIs, we rely on the documentation we helped write, now provided at the GCE Data Toolbox for MATLAB Wiki (cf. Cary et al. 2013).

Anticipated Changes

As a system organized around micro-services, the CWT IMS is designed to change with the evolution of scientific questions and priorities, as well as developments in information technology. The Information Manager discerns needs and prepares for change through active participation in both the CWT SAC and on the LTER Network Information Management Committee. The expression of change lies in the Information Manager keeping systems up to date, providing data-related training and education for CWT LTER participants, and seeking new technological and cultural ways to address emerging challenges for site and network science. Although not discussed in detail, our adherence to University of Georgia standards for asset management and software maintenance ensures we can anticipate routine changes in the hardware and software supporting our IMS and budget accordingly.

We recognize four specific challenges requiring changes to the CWT IMS. 1) Our research questions continue evolving with the successful conclusion of each research project, but our current project tracking system does not allow us to digitally link data, publications, personnel and projects in a way that reflects the strong ties that exist between individual research efforts and Coweeta's more than thirty-year emphasis on the relationships water, climate, ecosystem structure, population dynamics, and anthropogenic change. 2) While research designs increasingly require manual collection of complex field data, the tools for field data recording are not as efficient as they could be. 3) Regional modeling efforts like those based on RHESsys (Tague and Band 2004) are a key component of the present proposal. However, researchers in many domains struggle with technical solutions for the sharing, storage, and publication of model output data and large spatial data sets - Massive Online Data Sets (MODS). While some individual domains have developed solutions, (cf. Tarboton et al. 2011), there are ongoing challenges for contexts involving heterogeneous data (cf. Tuarob et al. 2011). 4) New technologies for data collection and overall data availability requirements come with costs for both information managers and researchers. Reducing these costs requires the training to both acquire s new skills and, when dealing with the challenges associated with "big data," to shift mindsets (cf. Cukier and Mayer-Schoenberger 2013; Hampton et al. 2013; Lindenmayer and Likens 2011).

Milestones and Deliverables

Routine Work.

- 1) We will continue publishing data to the LTER NIS and PASTA.
 - *Deliverables:* All known data packages will be published into PASTA within two years of collection. Streaming data from our core monitoring sites will continue to be updated on the CWT LTER website daily and annual updates of these data will be published to PASTA, as will all investigator-driven data sets related to the core elements of this proposal. These efforts will result in yearly increases in the number of CWT data sets in PASTA.

2) We will assess hardware and software on a continuing basis, making upgrades and modifications, as needed.

Deliverables: We will publish an annual report on the state of the CWT IMS, emphasizing data submissions, system changes, and IT-related challenges and opportunities.

3) In recognition of the fact that information technology changes at time scales much shorter than six years, we will conduct on overall strategic assessment of the CWT LTER IMS at the project midpoint.

Deliverables: We will publish a comprehensive review of the CWT LTER Data Management Plan in at the beginning of year four. This plan will document the strategic planning efforts and technical judgments of the Information Manager; outcomes related to the current Data Management Plan; feedback received, SAC, the CWT LTER community, and the CWT-LTER mid-term review; and any changes required in the Data Management Plan for the remainder of the project.

Proposed Changes.

- We will implement a new research tracking system by modifying and implementing a module of the GCE Metabase MMS designed for that purpose, but not previously part of the CWT IMS. This sub-system gather user input in such a way that we can explain link data, publications, personnel, and projects, presenting those materials in the context of our larger research efforts. *Deliverables:* Prototypes for the system will be deployed in the first six months of year one. The system will be in full production by the end of the first year.
- 2) We will work with field personnel to increase the efficiency of data collection by developing an integrated, database-driven, data entry and management system for manually collected Core Data. We will focus especially on data sets involving spatial location, population and demography measures, physical samples, and phenology. This system will allow data entry in the field, and will use controlled vocabularies, real-time range checks, and other application logic to ensure that data are entered as accurately and efficiently as possible. It will also leverage controlled vocabularies and real-time range checks to improve data quality. *Deliverables:* Prototypes for all Core Data modules will be deployed by the end of year one. All systems will be in production by the end of year two.
- 3) The CWT Information Manager will actively engage with researchers to address problems related to the sharing, storage, and publication of MODS, from both a research and technical perspective. *Deliverables:* The CWT Information Manager will develop an operational plan for MODS data by the CWT LTER Mid-term Review and will actively support LTER scientists who are engaged in the search for funding to support and maintain MODS-related projects.
- 4) Experience has shown that investments in data management training yield dividends in data submission and data availability. CWT information managers will continue to collaborate with GCE information managers by publishing new training documents, creating new podcasts, and conducting instructional sessions to help PIs and students adjust to the demands associated with "big data".

Deliverables: In the first year, the group will produce five additional podcasts and update the Data Toolbox User Guide (Cary et al. 2013) to include materials focused on the near-real time streaming of sensor data. In year two, we will develop instructional guides using feedback received from the Data Toolbox user community. In addition, the CWT Information Manager will teach a one-hour graduate seminar on environmental informatics beginning in the Fall Semester of 2014. These materials will be consolidated into an on-line course offering by the fall of 2015, at which time possibilities for cross-university instruction will be explored.

Coweeta LTER Data Sets Deposited in the LTER Network Information System

Data Package Identifier	Creators	Year	Title
			Habitat suitability and the distribution of species:
			Polygonatum biflorum demography data from the
knb-lter-cwt.1002.14	Pulliam	2008	Coweeta Hydrologic Laboratory from 1998 to 2006
knb-lter-cwt.1003.13	Beckage	2003	Seedling recruitment in artificial gaps
	Ū		
			Growth-mortality relationships for southern Appalachian
knb-lter-cwt.1004.13	Clark	2003	trees from the Coweeta Hydrologic Laboratory in 1995
			Tree seedling densities across an elevation and
			moisture gradient from the Coweeta Hydrologic
knb-lter-cwt.1005.13	Clark	2003	Laboratory from 1996 to 1999
			Seed bank densities across an environmental gradient
			from the Coweeta Hydrologic Laboratory from 1995 to
knb-lter-cwt.1006.1	Clark	2003	1998
	0.001		Rhododendron maximum cover across an elevation
			gradient from the Coweeta Hydrologic Laboratory from
knb-lter-cwt 1007 13	Clark	2003	1997 to 1999
	Clark	2000	
knb-lter-cwt 1008 13	Clark	2003	Seed production and dispersal for Tsuga canadiensis
	Chain	2000	Cross-site decomposition of leaf litter in terrestrial and
			aquatic habitats CWT and LUQ 2000 (species
			Buchenavia capitata Dacryodes excelsa Guarea
kpb-lter-cwt 1010 13	Coleman	2005	quidonia Quercus prinus)
knb-lter-cwt 1011 22		2003	Climate Station 1 Climate Data
	Laselei	2013	Gradient throughfall (thrufall) collection at the Coweeta
kph ltor out 1012 11	Miniat	2002	Hydrologic Laboratory from 1002 to 1007
KID-Iter-CWL1012.11	Iviii liat	2003	Terrestrial gradient microclimate measurements at the
kph ltor out 1012 101	Knoopp	2012	Coweeta LTEP. North Carolina, 1000-2012
KID-Iter-Cwt. 1013.101	Кпоерр	2012	Nitrogen transformation along an elevational and
			vegetative gradient from the Coweeta Hydrologic
kph ltor out 1014 12	Knoopp	2002	Leberstery from 1001 to 1005
KID-ILEI-CWL 1014.13	Кпоерр	2003	Laboratory from 1991 to 1995
kep tor out 1015 12	Hainaa	2002	Compare Hydrologic Laboratory from 1002 to 1002
KND-Iter-cwt.1015.13	Haines	2003	Litterfell on the elevational gradient (Crown 2) focusing
			Litterial on the elevational gradient (Group 2) locusing
high then such 4040 40		0000	on Rhododendrum lear litter from the Coweeta
KND-Iter-CWt.1016.13	Haines	2003	Hydrologic Laboratory from 1994 to 1995
		0000	Litternali on the elevational gradient (Group 3) from the
KND-Iter-CWt.1017.13	Haines	2003	Coweeta Hydrologic Laboratory in 1995
			Litterrail on the elevational gradient (Group 4) with a
			focus on greenfail from the Coweeta Hydrologic
knb-lter-cwt.1018.13	Haines	2003	Laboratory in 1995
			Litterfall on the elevational gradient (Group 5) from the
knb-lter-cwt.1019.13	Haines	2003	Coweeta Hydrologic Laboratory in 1995
			Litterfall on the elevational gradient (Group 6) from the
knb-lter-cwt.1020.13	Haines	2003	Coweeta Hydrologic Laboratory from 1995 to 1996
			Litterfall on the elevational gradient (Group 7) in the
knb-lter-cwt.1021.13	Haines	2003	Coweeta Hydrologic Laboratory from 1996 to 1998

cowceta Eren Data Sets Deposited in the Eren Network information System

Data Package Identifier	Creators	Year	Title
			Dendrometer Band Measurements from the Coweeta
			LTER Terrestrial Gradient Sites, Coweeta Hydrologic
knb-lter-cwt.1022.13	Vose	2011	Laboratory, Otto, North Carolina.
knb-lter-cwt.1023.83	Vose	2010	Terrestrial gradient soil moisture measurements
			Nitrogen transformation along an elevational and
			vegetative gradient from the Coweeta Hydrologic
knb-lter-cwt.1024.13	Knoepp	2003	Laboratory from 1991 to 1995
	••		Fine root dynamics along an elevational gradient in the
			southern Appalachian mountains in the Coweeta
knb-lter-cwt.1025.13	Haines	2003	Hydrologic Laboratory from 1993 to 1994
			Fine root dynamics along an elevational gradient in the
			southern Appalachian mountains in the Coweeta
			Hydrologic Laboratory from 1994 to 1995 (lengths of
knb-lter-cwt.1026.11	Haines	2003	fine root segments)
			Fine root dynamics along an elevational gradient in the
			southern Appalachian mountains in the Coweeta
knb-lter-cwt.1027.11		2003	Hydrologic Laboratory from 1993 to 1994
knb-lter-cwt.1028.13	Hunter	2005	Canopy gradient throughfall.
			Canopy gradient frass from the Coweeta Hydrologic
knb-lter-cwt.1029.11	Hunter	2005	Laboratory from 1996 to 1998
			Soil chemistry along the canopy gradient from 1997 to
knb-lter-cwt.1030.13	Hunter	2005	1999
			Hourly gap microclimate measurements from the
knb-lter-cwt.1032.13	Vose	2003	Coweeta Hydrologic Laboratory in 1993 and 1994
			Gap dendrometer band measurements at the Coweeta
			Hydrologic Laboratory from 1992 to 2000
knb-lter-cwt.1033.13	Vose	2003	(Circumference measurements)
			Gap soil moisture at the Coweeta Hydrologic Laboratory
knb-lter-cwt.1034.13	Clinton	2003	from 1993 to 1996
			Gap PAR (Photosynthetic Active Radiation) at the
knb-lter-cwt.1035.13	Clinton	2003	Coweeta Hydrologic Laboratory from 1993 to 1997
			Effects of Hurricane Opal on foliar chemistry and insect
			herbivores at the Coweeta Hydrologic Laboratory in
knb-lter-cwt.1036.13	Hunter	2003	1997: foliar chemistry data
			Probing the mechanisms by which sub-canopy
			evergreen shrubs inhibit tree seedling recruitment at the
knb-lter-cwt.1037.13	Clinton	2006	Coweeta Hydrologic Laboratory from 1999 to 2003
knb-lter-cwt.1039.13	Kloeppel	2007	Macon County, NC Middle School Climate Data
			Continuously measured forest soil moisture at four sites
knb-lter-cwt.1040.11	Bolstad	2012	in the Coweeta basin.
			Trapping system for longhorn beetles at the Coweeta
knb-lter-cwt.1043.11	Miller	2006	Hydrologic Laboratory from 2000 to 2003
			Soil respiration in treatment boxes on canopy gradient
			sites at the Coweeta Hydrologic Laboratory from 1997
knb-lter-cwt.1054.13	Hunter	2003	to 1998
			Soil respiration at resin bag sites at canopy gradient
knb-lter-cwt.1055.13	Hunter	2003	sites

Coweeta LTER Data Sets De	posited in the LTER I	Network Information Sv	ystem
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Data Package Identifier	Creators	Year	Title
U			Soil respiration and precipitation data at resin bag sites
			on canopy gradient sites at the Coweeta Hydrologic
knb-lter-cwt.1056.13	Hunter	2003	Laboratory in 1998 (dataset 1056)
			Nematodes in canopy gradient sites at the Coweeta
knb-lter-cwt.1057.13	Hunter	2003	Hydrologic Laboratory from 1997 to 1998
			Nematode functional groups in quadrat treatments on
knb-lter-cwt.1058.13	Hunter	2003	canopy gradient plots
			Litter decomposition in canopy gradient plots at the
knb-lter-cwt.1059.13	Hunter	2003	Coweeta Hydrologic Laboratory in 1998
			Litter decomposition in quadrat treatments along
			elevation gradient for canopy herbivore input study at
knb-lter-cwt.1060.13	Hunter	2006	the Coweeta Hydrologic Laboratory from 1997 to 1999
			Variation in the relative effects of top-down and bottom-
			up forces on herbivores and herbivory along an
			elevational gradient in the southern Appalachian
knb-lter-cwt.1062.11	Chamblee	2005	mountains in 2001
	Hunter		
knb-lter-cwt.1064.11	Kloeppel	2003	Watersheds 1 and 17 white pine survey in 2001
			Nematode total numbers in greenfall and litterfall
knb-lter-cwt.1066.13	Hunter	2003	exclusion quadrat treatments on canopy plots in 1998
			Examining the potential effects of phytophagous insect
luck then such 4000 44	Livertan	0005	trass on forest nitrogen cycling at the Coweeta
KND-Iter-CWt.1069.11	Hunter	2005	Hydrologic Laboratory from 1999 to 2001 Medeling Viebility of Avien Deputetions in the Southern
			Appelophions: Detential impacts of Climate Change
kph ltor out 1072 12	Chambles	2006	from 2002 to 2004
KIID-ILEI-CWL 1072.15	Champlee	2000	
			Coweeta Watershed 1 Litter and Soil Temperature for
knb-lter-cwt 1073 13	Kloeppel	2003	White Pine Decomposition Study from 2002 to 2004
	Ricoppor	2000	Summary of lysimeter ion concentrations at Coweeta
			Watershed One at the Coweeta Hydrologic Laboratory
knb-lter-cwt.1078.13	Swank	2003	from 1985 to 1988
			Bulk throughfall at Coweeta White Pine, Watershed
			One at the Coweeta Hydrologic Laboratory from 1985 to
knb-lter-cwt.1079.13	Swank	2003	1988
			Bulk stemflow at Coweeta Hardwoods, Watershed Two
knb-lter-cwt.1080.13	Swank	2003	from 1985 to 1988 (Coweeta Hydrologic Laboratory)
			Bulk throughfall at Coweeta Hardwoods, Watershed
			Two (Coweeta Hydrologic Laboratory) from 1985 to
knb-lter-cwt.1081.13	Swank	2003	1988
			Bulk stemflow at Coweeta White Pines, Watershed One
knb-lter-cwt.1082.13	Swank	2003	(Coweeta Hydrologic Laboratory) from 1985 to 1988

Data Package Identifier	Creators	Year	Title
			Remeasurement of permanent hectare plots at Hocking
knb-lter-cwt.1083.13	Clinton	2003	College 1998 (Coweeta Hydrologic Laboratory) in 1998
			Recruitment potential of southern and local tree species
			at the Coweeta Hydrologic Laboratory from 2003 to
knb-lter-cwt.1086.13	Clark	2006	2005
			Comparison of polyphenol degrading enzyme activities
			between forest types and soil horizons from 2003 to
knb-lter-cwt.1088.13	Hendrick	2007	2004
			Forest floor mass and nutrient content by laver in
knb-lter-cwt 1090 13	Kloeppel	2004	Coweeta white pine watershed 1 from 2001 to 2003
	racoppor	2001	
			Litter decomposition rates and litter nutrient content in
knb-lter-cwt 1091 13	Kloeppel	2004	Coweeta white pine watershed 1 from 2001 to 2004
	Косррсі	2004	Herb coverage on southern pine beetle and non-
			southern nine beetle impacted permanent plots in
kph-ltor-cwt 1002 13	Klooppol	2004	Coweets white pipe watershed 1 from 2001 to 2003
KID-Iter-Cwt. 1092.13	Nioeppei	2004	Coweeta white pine watershed 1 from 2001 to 2003
			Soudling regeneration density on southern nine beatle
			and non nouthern pine beatle impacted permanent plate
kep lter out 1002 12	Kleennel	2004	in Cowaste white sine wetershed 1 from 2001 to 2002
KND-Iter-Cwt. 1093.13	кіоерреі	2004	In Coweeta white pine watershed 1 from 2001 to 2003
			Photosynthetically active radiation (PAR) on southern
			pine beetle and non-southern pine beetle impacted
			permanent plots in Coweeta white pine watershed 1
knb-lter-cwt.1094.13	Kloeppel	2004	from 2002 to 2003
			Percent soil moisture on southern pine beetle and non-
			southern pine beetle impacted permanent plots in
knb-lter-cwt.1095.13	Kloeppel	2004	Coweeta white pine watershed 1 from 2002 to 2003
			Physical characteristics and GPS data for 21
			permanent plots in Coweeta white pine watershed 1
knb-lter-cwt.1096.13	Kloeppel	2004	from 2003 to 2004
			Causes and effects of ant community structure in
knb-lter-cwt.1100.13	Chamblee	2007	Hemlock Forests in 2005
			Elevational gradient in ant diversity in the Coweeta
knb-lter-cwt.1105.13	Chamblee	2007	Hydrologic Laboratory in 2005
			Continuous soil moisture and microclimate
			measurements at a forest gap site in the Coweeta
knb-lter-cwt.1114.101	Clark	2008	Hydrologic Laboratory, North Carolina, 2007-2012.
			Measurements of Soil pH and Soil Cations Along an
knb-lter-cwt.1120.73	Knoepp	2010	Elevational Gradient
			Leaf litter weights, Coweeta LTER, Terrestrial Gradient
knb-lter-cwt.1121.73	Knoepp	2010	Sites, 1994-2009
			Forest floor weights along an elevational and vegetation
knb-lter-cwt.1122.13	Knoepp	2010	gradient
			Measurements of Soil Bulk Density at the Coweeta
knb-lter-cwt.1123.13	Knoepp	2010	Terrestrial Gradient Sites

Coweeta LTER Data Sets Deposited in the LTER Network Information System

Coweeta LTER Data Sets	Deposited in the LTER	Network Information S	ystem
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Data Package Identifier	Creators	Year	Title
			Measurements of Soil %C and %N at the Coweeta
			LTER Terrestrial Gradient Sites, Coweeta Hydrological
knb-lter-cwt.1124.13	Knoepp	2010	Laboratory,
			Measurements of Soil Nitrogen Transformations at the
knb-lter-cwt.1125.13	Knoepp	2010	Coweeta Terrestrial Gradient Sites
			Measurements of Soil Water Chemistry at the Coweeta
knb-lter-cwt.1126.13	Knoepp	2010	Terrestrial Gradient Sites
knb-lter-cwt.1127.13	Knoepp	2010	Terrestrial Gradient Throughfall Collections
			Goodyera pubescens plant demography from 1999-
		0044	2003 at the Coweeta Hydrologic Laboratory,
knb-lter-cwt.1200.13	Pulliam	2014	Chattahoochee National Forest, and Whitehall Forest
			Hepatica nobilis (Anenome americana) plant
			demography 1999-2006 at the Coweeta Hydrologic
			Laboratory, Chattanoochee National Forest, and
knb-lter-cwt.1201.13	warren	2014	
			Hexastylis aritolia (Asarum canadensis) plant
			demography 1999-2006 at the Coweeta Hydrologic
	10/	0044	Laboratory, Chattanoochee National Forest, and
Knb-Iter-cwt.1202.13	warren	2014	VVnitenali Forest
KND-Iter-cwt.1203.13	vvarren	2014	Tipularia discolor plant demography 1999-2004
kab ltar out 2000 42	Vachlau	2002	Ripanan study: nouny microclimate data from the
KND-Iter-cwt.2000.13	теакіеу	2003	Coweeta Hydrologic Laboratory from 1994 to 2007
luck then such 0004 44	Veelderr	0000	Ripanan study of dissolved organic carbon at the
Knd-iter-cwt.2001.11	reakley	2003	
			Piparian Study: Sail Maisture (TDP) from the Cowasta
kph ltor out 2002 12	Vooklov	2002	Hydrologic Laboratory from 1002 through 1005
KID-IIEI-CWI.2002.13	reakiey	2003	Litter decomposition data from the Coweeta Hydrologic
kph-ltor-owt 2003 11	Coloman	2003	Laboratory from 1003 to 1005
RID-ILEI-CWL2005.11	Coleman	2003	Microbial biomass at the Coweeta Hydrologic
kph-ltor-owt 2004 11	Coloman	2003	Laboratory in 1997
KID-IIEI-CWI.2004.11	Coleman	2003	Riparian zone seedling establishment growth
			dynamics and the influence of Rhododendron
			maximum soil moisture: forest floor data at the Coweeta
knb-lter-cwt 2007 13	Beckade	2007	Hydrologic Laboratory from 1997 to 2000
	Decikage	2007	Riparian study: soil water chemistry (lysimeters) yearly
			data (1993 to 1997) at the Coweeta Hydrologic
knh-lter-cwt 2010 13	Yeakley	2003	Laboratory
	Teakiey	2000	Geomorphology of Ball Creek and Coweeta Creek in
knb-lter-cwt 3004 13	Webster	2003	1989
		2000	Dissolved organic carbon (doc) in stream water at
			watersheds 7 14 and 27 at the Coweeta Hydrologic
	Maxar	2004	Laboratory Otto North Carolina USA
knb-lter-cwt 3005 2	wever	////4	
knb-lter-cwt.3005.2	weyer	2004	Fish collections at Coweeta LTER 100 m stream sites

Coweeta LTER Data Sets De	posited in the LTER I	Network Information S	ystem
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Data Package Identifier	Creators	Year	Title
			Habitat availability estimates of LTER 100 m stream
knb-lter-cwt.3007.13	Grossman	2003	sites at the Coweeta Hydrologic Lab from 1991 to 1998
			Leaf decomposition along the Ball Creek / Coweeta
			Creek elevational gradient at the Coweeta Hydrologic
knb-lter-cwt.3008.11	Benfield	2003	Laboratory from 1991 to 1992
			Benthic organic matter (BOM) standing crops along the
	Descal	0000	Ball Creek / Coweeta Creek elevational gradient at the
KND-Iter-CWt.3009.11	Benfield	2003	Coweeta Hydrologic Laboratory from 1991 to 1992
			Age, growth and reproduction of mottled sculpin (cottus
kph ltor out 2016 12	Crossman	2007	
KND-ILET-CWI.3016.13	Grossman	2007	1996
			Spatial and temporal patterns of habitat use and
kpb-lter-cwt 3018 11	Grossman	2007	availability in upper Coweeta Creek from 1996 to 1998
	Crocoman	2001	Mesoscale variation in fish populations in two small
			Appalachian streams (fish population data) at the
knb-lter-cwt.3026.13	Grossman	2007	Coweeta Hydrologic Laboratory in 1996
			Mesoscale variation in fish populations in two small
			Appalachian streams (light data) at the Coweeta
knb-lter-cwt.3029.13	Grossman	2007	Hydrologic Laboratory in 1996
			Shope Fork of Coweeta Creek streamflow at the
knb-lter-cwt.3032.14	Swift	2003	Coweeta Hydrologic Laboratory from 1934 to 1999
knb-lter-cwt.3033.21	Laseter	2013	Watershed 18 daily stream discharge
knb-lter-cwt.3034.21	Laseter	2013	Watershed 27 daily stream discharge
			Predatory impact of benthic fishes in an Appalachian
knb-lter-cwt.3035.13	Grossman	2007	stream at the Coweeta Hydrologic Laboratory in 1998
knb-lter-cwt.3046.13	Grossman	2007	Microhabitat use in a stream fish assemblage
			Stream lish assemblage stability in a southern
kep tor out 2047 12	Crassman	2007	Appalachian stream at the Coweeta Hydrologic
KND-ILET-CWI.3047.13	Grossman	2007	
			Assessment of parentage relationships in Cottus bairdi
kpb-lter-cwt 3048 13	Grossman	2007	at the Coweeta Hydrologic Laboratory in 1999
	Crecoman	2001	Ecology and Evolutionary Biology Field Trip at the
			Coweeta Hydrologic Laboratory (Watershed 18) in
knb-lter-cwt.3060.13	Courtnev	2006	2004: Aquatic Invertebrates (Adult) data
			Nutrient effects on a detritus-based stream ecosystem
			at the Coweeta Hydrologic Laboratory from 1998 to
knb-lter-cwt.3062.13	Rosemond	2006	2003
knb-lter-cwt.3080.13	Maerz	2014	Milanovich salamander cage experiment in 2009
			Milanovich desmognathus quadramaculatus excretion
knb-lter-cwt.3081.13	Maerz	2014	rate data from 2008
			A multi-scaled approach to evaluating the fish
			community structure within southern Appalachian
knb-lter-cwt.3100.14	Kirsch	2014	streams, 2011

Coweeta LTER Data Sets Deposited in the LTER Network Information System

Data Package Identifier	Creators	Year	Title
			Joyce Kilmer Memorial Forest - microclimate station -
			midslope plot at the Coweeta Hydrologic Laboratory
knb-lter-cwt.4000.13	Kloeppel	2007	from 1996 to 2008
			Stem temperature in watershed 02, ridge plot at the
knb-lter-cwt.4001.13	Bolstad	2007	Coweeta Hydrologic Laboratory from 1996 to 1998
			Stem temperature at watershed 18, cove 218 gradient
			plot at the Coweeta Hydrologic Laboratory from 1996 to
knb-lter-cwt.4002.13	Kloeppel	2007	1999
			Stem temperature in watershed 27 ridge climate 77
			station plot at the Coweeta Hydrologic Laboratory from
knb-lter-cwt.4003.11	Chamblee	2007	1996 to 1999
			Aboveground biomass and nitrogen allocation of ten
			deciduous southern Appalachian tree species at the
knb-lter-cwt.4004.13	Kloeppel	2003	Coweeta Hydrologic Laboratory in 1997
			Acclimation common garden microclimate at the
knb-lter-cwt.4018.13	Bolstad	2013	Coweeta Hydrologic Laboratory from 1999 to 2002
			The importance of crayfish in the breakdown of
			rhododendron leaf litter at the Coweeta Hydrologic
knb-lter-cwt.4022.13	Prinale	2006	Laboratory in 1999
	v		Direct and indirect effects of increased bedload on algal
			and detrital-based stream food webs at the Coweeta
			Hydrologic Laboratory from 1997 to 1999: Tile/
			sediment addition experiment. Summer 1997:
knh-lter-cwt 4023 14	Pringle	2006	Chlorophyll AFDM inorganics (days 5-40)
	, mg.c	2000	Top-down interactions in streams draining human-
			modified landscapes at the Coweeta Hydrologic
knb-lter-cwt 4024.13	Pringle	2006	Laboratory from 1997 to 1998: Gradient algae data
	1 1119.0	2000	Post-burn study of herbaceous understory plots at
knb-lter-cwt 4025.13	Clinton	2004	Jacobs Branch and Devils Den burn sites, 1992
		200.	Post-hurn survey of Blazed Creek herbaceous
knb-lter-cwt.4026.13	Clinton	2004	understory plots. 1991
	••••••		
			Post-burn study of herbaceous vegetation at Jacobs
knb-lter-cwt 4027.13	Clinton	2004	Branch and Devils Den burn sites, 1990-1994
			Post-burn study of woody plants at Jacobs Branch and
knh-lter-cwt 4028 13	Clinton	2004	Devil's Den hum sites in 1991 1992, and 1994
	Omitori	200.	Post-burn study of woody plants at Devils Den burn site
kph-lter-cwt 4029 13	Clinton	2004	1001-1002
	Omitori	200.	Pre and post-burn forest floor survey of Jacobs Branch
kph-lter-owt 4031 13	Clinton	2004	and Devils Den hum sites 1990-1992
	Omitori	200.	Post-burn study of herbaceous understory plots at
kph-lter-cwt 4032 13	Clinton	2004	lacobs Creek and Devils Den burn sites 1990
	Olinton	200-,	Post-burn study of woody vegetation at Jacobs Branch
kph-ltor-cwt 4033 13	Clinton	2004	East hurn site 1001-1002
KIID-Iter-Cwt.4000.10	Ciriton	2004	Post-burn study of woody vegetation at Jacobs Branch
kph ltor out 1021 12	Clinton	2004	Fact 1004
KIID-ILEI-CWL4034.13	CIIIIIOII	2004	Lasi, 1994

Data Package Identifier	Creators	Year	Title
			Post-burn study of woody plants at Jacobs Branch West
knb-lter-cwt.4035.13	Clinton	2004	burn site, 1991-1992
			Post-burn study of woody plants at the Jacobs Branch
knb-lter-cwt.4036.13	Clinton	2004	West burn site, 1994
			Pre-burn survey of overstory vegetation at Jacobs
knb-lter-cwt.4037.13	Clinton	2004	Branch and Devils Den burn sites, 1989
			Climate and Terrestrial Microclimate Measurements at
			Mars Hill College, Buncombe County, North Carolina,
knb-lter-cwt.4038.14	Pearson	2013	2004-2012.
			Hedonic Modeling Data for Land Use Regulations and
knb-lter-cwt.4043.13	Dehring	2009	Water Quality in Buncombe County, N.C.

Coweeta LTER Data Sets Deposited in the LTER Network Information System

Facilities, Equipment, & Other Resources

The Coweeta Long Term Ecological Research (LTER) Program is based on a collaborative agreement between the University of Georgia Research Foundation in Athens, Georgia, and the USDA Forest Service (FS) Coweeta Hydrologic Laboratory in Otto, North Carolina. The Coweeta Hydrologic Laboratory was established in 1934 and is located in the Nantahala Mountain range of western North Carolina within the Blue Ridge Physiographic Province. The 2185 ha laboratory is comprised of two adjacent, east-facing, bowl-shaped basins. The Coweeta Basin (1626 ha) has been the primary site for watershed experimentation, while the Dryman Fork Basin (559 ha) has been held in reserve for future studies. The Coweeta Basin is drained by two fourth-order streams, Ball Creek and Shope Fork that join within the boundaries of the Laboratory to form Coweeta Creek, a tributary to the Little Tennessee River.

The research program at the Coweeta Hydrologic Laboratory uses watersheds as landscape units. The laboratory includes 26 well-defined watersheds ranging in size from 3 ha to 760 ha, with over 72 km of streams of which 16 contain weirs to collect stream flow data. The elevations across the Coweeta Basin range from 675 m in the administrative area to 1592 m at Albert Mountain. The collaboration between the University of Georgia and the Coweeta Hydrologic Laboratory began with a cooperative study of mineral cycling on four watersheds within the Coweeta Basin in 1968. The resulting 37-year partnership in national and international research is what ensures the availability of facilities, equipment and resources to carry out the proposed research.

Facilities, equipment and other resources necessary for the research are located at the Coweeta Hydrologic Laboratory (Otto, NC) and surrounding areas, and the University of Georgia (Athens, GA). Coweeta LTER staff members are stationed in Otto, North Carolina and in Athens, Georgia (approximately 90 miles apart). Their activities in support of the project are tightly integrated and coordinated through redundant communication pathways.

Coweeta Hydrologic Laboratory

Field operations are coordinated and supported from facilities jointly staffed by LTER and USDA-FS personnel at the Coweeta Hydrologic Laboratory. Coweeta LTER staff include an LTER Site Manager, two full-time field technicians and three full-time analytical laboratory technicians. The Site Manager supervises all LTER on-site staff as well as two-to-three LTER summer undergraduate interns; coordinates field research activities in consultation with LTER investigators and the FS Project Leader; and coordinates Coweeta Schoolyard LTER activities. USDA-FS staff includes: a professional chemist who manages the Chemical Analytical Laboratory, a professional hydrologist, a biological scientist-technology transfer specialist, five field technicians, an office manager, a business manager, one post-doctoral research ecologist, three research scientists, and the research Project Leader. USDA-FS contractors employed by the University of Minnesota are also on-site and include one GIS-specialist and one post-doctoral research ecologist.

On-site facilities include a state-of-the-art analytical chemistry laboratory, a residential facility, a greenhouse, and a conference center. While owned by the USDA-FS, their current configuration and operational capacity reflect financial investments since 1999 by NSF (FSML, LTER), USDA-FS and the University of Georgia.

The **Coweeta Analytical Chemistry Laboratory** (4,000 ft²) provides processing, analytical, and archiving space for all water, soil, and plant samples collected for USDA-FS and Coweeta LTER research. Sample preparation and storage infrastructure includes a walk-in refrigerator and a walk-in drying oven; tissue grinders; and filtration, digestion, and freezer facilities. The Analytical Laboratory contains the following analytical instrumentation:

Instrument	Analytes
Dionex ion chromatograph	NO ₃ -N, PO ₄ , Cl, NO ₂ -N, SO ₄
Thermo-Fisher ICS-4000 capillary HPIC	Br, NO ₃ -N, PO ₄ , Cl, SO ₄
Astoria autoanalyzer	NO ₃ -N, PO ₄ , NH ₄ -N, SiO ₂
Thermo Flash EA1112 CN analyzer	Plant and soil total C and total N
Shimadzu TOC/TN analyzer	Dissolved organic carbon and nitrogen DOC, DON
iCAP 6300 ICP-OES spectrometer	Na, Ca, K, Mg, +
Shimadzu GC-2014 gas chromatograph	N ₂ O, CO ₂ , CH ₄

The **Coweeta Residence** $(2,980 \text{ ft}^2)$ can house up to 20 investigators, students, and visitors in a modern and fully ADA compliant facility that was completely renovated and expanded in 2003. The facility reduces travel time and expense of working in the field, and increases interaction among investigators working on diverse research projects.

The **Greenhouse** was built in 2007 and has 944 ft^2 of climate-controlled growing space and a headhouse (386 ft^2) with an equipment bench space, refrigerator for samples, and sinks. Greenhouse light levels are controlled with high-pressure sodium lamps; air temperature is controlled with a four-stage, evaporative cooling systems and a furnace; and, soil water and air humidity are controlled with irrigation and misting systems.

The **Coweeta Conference Center** (7,000 ft²) was built in 2003 and includes an 80-person conference room, a central meeting/reception area, nine offices, a kitchen, and a library. All large-group Coweeta LTER meetings are held at the Conference Center so there is no need to rent meeting facilities. The Conference Center is used for USDA-FS and Coweeta LTER educational and outreach workshops, and has also been used for regional and national meetings increasing exposure to on-site research and creating opportunities for collaboration.

There are, in addition: two office buildings (4,300 ft^2 and 2,145 ft^2) for scientists and staff; a house for visiting scientists and summer interns (2,500 ft^2); a maintenance/repair shop; and a vehicle shelter/storage shed (14,700 ft^2). The vehicle shelter is used to house both the USDA-FS and Coweeta LTER fleet, the latter of which is comprised of six four-wheel drive vehicles (two SUVs and four pick-ups) - available for Coweeta LTER investigators to use on the steep and rugged terrain of the study area.

Additional equipment and resources available at the Coweeta Hydrologic Laboratory for use in field research include: YSI 30 salinity/conductivity/temperature probe (1); Hach 2100P turbidimeter (1); Hach Hydrolab MS5 sondes with DO, conductivity, temperature and turbidity sensors (14); Teledyne ISCO 6712 water samplers with pressure transducers (12); Topcon total station (1); Trimble GeoXT differential GPS (1); Campbell Scientific CR200x (21) and CR10 (15) data loggers; and, Campbell Scientific Hydrosense II soil moisture measurement unit (3).

Numerous experimental plots and watersheds located within the Coweeta Basin or the surrounding area are used for long-term monitoring as well as ongoing and proposed research activities.

Watershed 5 is a north-facing reference catchment 2.5 ha in area adjacent to the administrative area. It is drained by Creasman Branch and contains a cove hardwood forest that has been undisturbed since 1927. In 2012, an eddy covariance tower was installed on the watershed making it one of the most topographically complex sites in the Ameriflux network. Measurements taken within Watershed 5 include: overstory transpiration using sapflux probes; understory transpiration using leaf gas exchange and understory eddy covariance tower; litter interception and soil evaporation using a combination of

half-bridge circuits, soil moisture and temperature probes, and relative humidity sensors; streamflow using an H-flume; canopy and open-field climate and precipitation using micromet sensors; and interception using forest structure measurements and throughfall collectors.

Watershed 7 is a south-facing treatment catchment, 59 ha in area, drained by Big Hurricane Creek. The elevation ranges from 722 m at the weir to 1077 m. The lower portion was grazed by an average of six cattle during a 5-month period each year from 1941–1952. It was commercially clear-cut and cable-logged in 1977 as part of a multi-investigator study examining the response of terrestrial and aquatic communities to commercial clear-cutting. Dissolved organic carbon (DOC) has been measured since July 1, 1979.

Watershed 14 is a northwest-facing reference catchment, 61 ha in area, drained by Hugh White Branch. The elevation ranges from 707 m at the weir to 992 m. The watershed has been undisturbed since 1927; and DOC has been measured on this watershed since July 1, 1979.

Watershed 18 is a northwest-facing reference catchment, 13 ha in area, drained by Grady Branch. The elevation ranges from 726 m at the weir to 993 m. The watershed has been undisturbed since 1927; stream discharge has been continuously recorded at the 120° V-notch weir since July 3, 1936.

Watershed 27 is a northeast-facing reference catchment, 39 ha in area, drained by Hard Luck Creek. The elevation ranges from 1061 m at the weir to 1454 m. The watershed was partially defoliated by a fall cankerworm infestation from 1972 to 1979. Stream discharge has been continuously recorded at the 120° V-notch weir since November 2, 1946; DOC has been measured since July 1, 1979.

Long-term core data are collected in five 80m × 80m **Terrestrial Gradient Plots** established in 1991 in Watersheds 18 (n=3) and 27 (n=2) that represent a gradient of elevation and plant communities: #118 low elevation (782 m) pine-oak, #218 low elevation (795 m) cove hardwood, #318 low elevation (865 m) mixed oak, #427 high elevation (1001 m) mixed oak, #527 high elevation (1347 m) northern hardwood. Soil water content is measured from 0-30 cm, and from 30-60 cm at the upper (#527) and lower plots (#118); soil temperature is measured at 5, 20, and 50 cm below the surface; and air temperature is measured at 1 m above the surface. Tree demographic data has been collected every two years since 1991 on: a) DBH of trees >2m in height, b) tree canopy, c) tree reproductive status, and d) census of seedlings on within-plot transects. In addition, seeds are recovered from seed baskets 5 times each year. Total throughfall has been measured since 2013. Microclimate data are related to forest dynamics and tree demography (seed, sapling, and tree measurements), soil and forest floor chemistry, leaf litter dry mass and chemistry, and coarse woody measurements. The USDA-FS makes daily stream discharge, and stream and precipitation chemistry data collected on watersheds 18 and 27 available.

Twelve $20m \times 20m$ **Intensive Hemlock Plots** were established in low elevation (730-1040 m) cove hardwood riparian zone forests in 2003. The experimental design had three main treatments: plots with girdled eastern hemlock trees (girdled in 2004), plots with hemlock woolly adelgid (HWA) infested hemlock trees (infested in 2005), and plots with no eastern hemlock trees. In 2003, eastern hemlock comprised more than half of total basal area in the girdled and infested plots, and rapidly experienced mortality. Plots have been measured annually for litterfall, tree growth and mortality; every two years for herbaceous cover and seedling recruitment; and intermittently for forest floor and litter mass, soil solution chemistry, soil respiration, and transpiration.

Two **Hillslope Sites** were established in 2011 to link land use impacts to streamwater quality in the southern Appalachian Mountains. One subsurface flowpath following the elevation gradient is instrumented at each site with a Campbell Scientific CR200X data logger that is used to monitor groundwater well stage, soil moisture at 0-30 cm and 30-60 cm, and soil temperature at 5 cm. Measurements are taken every 60 seconds and output as hourly averages for use in the Regional HydroEcological Simulation System (RHESSys). One site is located in Watershed 14 in the Coweeta Basin (described above). The other site is located in a mixed-oak forest on Fall Branch, a tributary to

Cowee Creek in the Nantahala National Forest.

Three long-term plots were established in 2013 in Great Smoky Mountains National Park (**GSMNP Plots**). One is located at Purchase Knob (high elevation, old-growth northern hardwood forest), one is located near Clingman's Dome (high elevation spruce fir), and one is located near Noland Divide (high elevation spruce-fir). All trees >2m in height are tagged and will be measured every other year; seed traps and seedling transects will be recorded annually; and, forest floor and soil samples were collected. Microclimate stations will be installed in 2014 to continuously record air temperature, soil temperature, and soil moisture.

Four continuously measured volumetric soil water content stations were established on the **Soil Moisture Plots** in 2000 in the Coweeta Basin across a range of elevations: Plot #1, low elevation mixed oak; Plot #2, low elevation xeric oak-pine; Plot #3, high elevation mixed oak; and Plot #4, high elevation northern hardwood. At each location, soil water content is measured from 0-30 cm and from 30-60 cm. Air temperature is measured at 1 m above the surface and soil temperature is measured at 5 and 20 cm depth. Photosynthetically Active Radiation (PAR) is continuously measured below the canopy (~2 m above the surface) and above the canopy (~20 m above the surface) at two stations (#2 and #4). These two stations also have 20 m walk-up towers used to assess spring and autumn phenology.

Ten **Gap Plots** were established in 2002 in the upper reaches of Ball Creek between Watershed 27 and Watershed 28 in the Coweeta Basin by pulling dominant canopy trees until they either snapped or uprooted. Two size gaps were created: four, 20 m (small) diameter gaps from pulling 5-to-12 trees, and six, 40 m (large) diameter gaps from pulling 25-to-40 trees. Soil moisture, and soil and air temperature data have been continuously collected since 2007. Manually collected soil moisture measurements have been recorded every two weeks during the growing season since 2000. Tree demographic data has been collected every two years since the gaps were established on: a) DBH of trees >2m in height, b) tree canopy, c) tree reproductive status, and d) census of seedlings on within-plot transects. In addition, seeds are recovered from seed baskets 5 times each year.

Twelve **Herb Plots** were established in 2006 in the Coweeta Basin and on Whitehall Forest (UGA campus) to assess the fundamental niche of shade-tolerant evergreen herbs. Three plots at each site were established on north-facing slopes and three on south-facing slopes. On each plot, $1m \times 1m$ quadrants were planted with one of three evergreen herb species then manipulated one of four ways: 25% shaded light, ambient light, enhanced moisture, ambient moisture. Plots were subsequently used (2010) to examine the seed-dispersal mutualism of evergreen herbs with ants as a function of climate; and, the effect of leaf litter disturbance (2011) on plant phenology and performance. Soil moisture and temperature are monitored on these sites.

Long-term **Salamander Mark-Recapture Plots** were established in 2011 at three locations along an elevation gradient (two plots at each site) adjacent to Ball Creek in the Coweeta Basin to examine the effects of climate on salamander foraging, competitive interactions, hybrid zone dynamics, and dispersal rates. The target species are *Plethodon teyahalee* and *P. shermani*. While the former occupies lower elevation forests and the latter occupies higher elevation forests, they hybridize in the overlap zone.

The **Throughfall Displacement Experiment** will be established on **Watershed 10** within the Coweeta Basin. This is a southeast-facing 86 ha treatment catchment drained by Camprock Creek. The elevation ranges from 742 m at the weir to 1159 m. Streamflow data were collected from March 7, 1936 to October 1954; and the headwall for the weir was removed in 1976. The watershed was subjected to an exploitive commercial timber and pulpwood cut during 1942-56 that was representative of common forestry practices across southern Appalachia. This involved removal of 65,000 ft³ of material, reducing basal area by 30%, and skidding the timber off the watershed thus disturbing the soil surface. The watershed has been undisturbed since this treatment and is now covered by a 57-year old second-growth mixed hardwood forest.

Rhododendron Removal Experiment will use the Intensive Hemlock Plots (described above) as well as reach-scale plots located in the Wine Spring Creek watershed on the Nantahala National Forest in western North Carolina. This 1820 ha watershed has a mix of hardwood forest types. Three tributaries (Wine Spring Creek, Bearpen Creek, and Indian Camp Branch) converge and drain into Nantahala Lake at the western edge of the watershed. The USDA-FS Coweeta Hydrologic Laboratory and its partners have performed several research projects within the watershed ranging from the effect of prescribed burns on water quality to the impact of in-stream coarse woody debris on trout populations. The Rhododendron Removal Experiment reach-scale sites will be located along Wine Spring Creek.

University of Georgia

Information management activities are coordinated and supported by LTER staff on the University of Georgia campus. Staff includes a full-time Information Manager (IM) and a full-time Assistant Information Manager (AIM). The IM supervises the AIM and between three and five part-time student and non-student workers to ensure maintenance of a highly accessible, and appropriately secure data management and distribution system. This entails: development and maintenance of the information technology (IT) infrastructure that supports the Coweeta Information Management System (CWT IMS); administration of the CWT IMS; deployment and management of the CWT Sensor Network; and populating the CWT IMS with site data. A four-wheel drive SUV is stationed at UGA and used for transporting and deploying equipment in the field.

Information management activities are based out of the **Sustainable Human Ecosystems Laboratory** (SHEL, 2400 ft²), which contains office spaces for the IM and AIM as well as 10 duty stations for additional personnel. The **IT Infrastructure** consists of the Ethernet backbone supporting network connectivity, the server systems, and the workstations that support LTER activities at the Coweeta Hydrologic Laboratory and in the Sustainable Human Ecosystems Laboratory. The IM acts as the liaison to the Franklin College of Arts and Sciences, which is the institutional entity responsible for maintaining the backbone for the IM lab and the Ethernet at the field station. As a Federal installation, USDA-FS policy dictates that the Coweeta LTER maintain a parallel, non-overlapping network that does not interact or interfere with USDA-FS network activities.

The **SHEL Network Infrastructure** at UGA consists of 10 personal work stations with high-end computers organized into a scalable network that provides password-protected redundant RAID 5 backups for any computer with access privileges to the UGA campus network (on or off campus). The infrastructure consists of the UGA backbone; an 8 TB RAID 5 virtual machine host consisting of a 2 TB web server and a 6 TB file server; a 12 TB RAID 5 backup server; and 14 workstations and four laptops.

Within the Sustainable Human Ecosystems Laboratory is a state-of-the-art teleconferencing room (SHELTR) with seating for eight that includes two 40" LCD monitors and a teleconference server that staff, investigators and students regularly use to coordinate Coweeta LTER research activities. The teleconference service is through a subscription to GoToMeeting.

The **CWT Network Infrastructure** at the Coweeta Hydrologic Laboratory includes ten 10/100 switches distributed across six buildings; a Cisco 1800 Series router that serves as the LTER broadband connection; a Cisco 5505 Adaptive Security Appliance that provides firewall, Dynamic Host Client Protocol (DHCP), and Virtual Private Network (VPN) services; a centralized Cisco WLAN controller to provide wireless network access in every building with LTER personnel; and a 1 TB file server, a 1 TB RAID 1 backup server, and 11 workstations and two laptops.

The **CWT Sensor Network** comprises a flexible network of monitoring stations for sampling microclimate, weather, and stream flow data at the scale of the watershed, river basin and southern Appalachian region. In 2012 we began switching from manual data downloads to streaming data directly from stations using cellular, radio, and satellite transmissions. Thirteen long-term monitoring stations

have been upgraded, seven new regional stations have been installed, and at least 10 more stations will be added by June 2014. Whenever possible, we use Campbell Scientific equipment and retrieve field sensor data using Campbell Scientific's Loggernet Software. Data are automatically post-processed, given quality assurance checks, and published to the Internet in near real time using the GCE Data Toolbox for Matlab. The sensor network configuration can be altered in response to long-term project goals, shortterm mechanistic research needs, and unanticipated event-driven research opportunities.

In addition to the facilities already mentioned, the Coweeta LTER Schoolyard regularly hosts activities at several sites in Macon County (North Carolina) through the auspices of partners and collaborators. Several tours for K-12 students are organized each year at the **Coweeta Hydrologic Laboratory**. Activities range from catching salamanders in one of the many small creeks to catching butterflies with aerial nets near the administrative building.

Tessentee Bottomland Preserve is owned and managed by the Land Trust for the Little Tennessee (LTLT). It consists of a 28-ha tract featuring second growth forests and early successional bottomland habitat at the junction of Tessentee Creek and the Little Tennessee River. The site is used for the annual Migration Celebration as well as serving as a Monitoring Avian Productivity and Survivorship (MAPS) bird banding station during the summer that is staffed by Southern Appalachian Raptor Research (SARR) volunteers and local students.

Macon County Rec Park is managed by Macon County Parks & Recreation and is the location of the annual Kids in the Creek event. The park contains the Cartoogechaye Creek, the water source for Franklin (Macon County, North Carolina), as well as restrooms and a large parking space for buses.

Cowee Mound is owned by the Eastern Band of Cherokee Indians and jointly managed with the LTLT. This 29-ha tract along the Little Tennessee River is one of the most significant Mississippian Period (800-1500 CE) archaeological sites in North Carolina as well as a major 18th century Cherokee diplomatic and commercial center. The tract was added to the National Register of Historic Places in 1973. SARR uses the site in the summer as a MAPS bird banding station.

The **Little Tennessee River Greenway** follows the Little Tennessee River and its tributary, Cartoogechaye Creek, through wetlands, railroad cuts, and alongside pastures and upland forest. The Tassee Shelter is the location for the annual Invasive Species Awareness Day.

Fires Creek Recreation Area is located on the Nantahala National Forest in Clay County, NC. It serves as the location for the annual Kids in the Creek event.