RENEWAL PROPOSAL

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Southern Appalachia on the Edge –
Exurbanization & Climate Interaction in the Southeast

PROJECT SUMMARY

Multi-scale process-oriented research is proposed on the consequences to the southern Appalachian socio-ecological system of the interaction between changing climate and land use. Landscapes in the southeastern U.S. are expected to change profoundly in the next five decades as the socioeconomic factors driving the dramatic exurbanization of the past three decades persist, and the changes to the rates, frequencies, and intensities of important climatic factors occur. Climate and land use change will especially impact the rural and quasi-rural lands that still characterize much of southern Appalachia where this research is centered.

The proposed research will extend long-term measurements, field experiments and interdisciplinary modeling from small watershed studies to regional-scale analyses so as to account for increases in resource demand and competition from adjacent and more distant areas. The research focus will be on the provisioning service of water quantity, the regulating service of water quality, and the supporting service of maintaining biodiversity. The overarching question that guides this research is: How will key ecosystem processes and the focal ecosystem services of water quantity, water quality, and biodiversity be impacted by the: (1) transition in land uses from wildland to urban and peri-urban; (2) changes in climate; and (3) interactions between changes in land use and climate including both on-site and off-site feedbacks?

INTELLECTUAL MERIT: These are unprecedented times and the environmental challenges faced by society demand novel approaches to the production, dissemination and application of knowledge to protect essential ecosystem services and meet human needs. Traditional experiments provide limited understanding of the complex interactions between exurbanization and climate change prevalent at regional scales, while correlation-based models omit the relevant processes about which much is already known. At a regional scale, assimilation of sparse observational and experimental data from multiple scales becomes the overwhelming challenge, and process-based models are the best option for meeting this challenge. The sampling, experimental manipulations and modeling proposed in this research are designed to capture interactions within a range of distinct landscapes reflecting the flowpaths, habitats, and human communities characteristic of southern Appalachia. It does this by working across a range of scales from coarse to fine consisting of (1) regional basins, (2) sub-basins, (3) headwater catchments, and (4) hillslopes and riparian zones.

BROADER IMPACTS: Although the most consequential effects of climate and land use change will appear on the rural and quasi-rural lands of southern Appalachia, scientific effort to date has largely concentrated on the urban and wildland end-members of this transformational gradient. This limits understanding of the complex interactions between climate change and exurbanization that is vital to the near-term and long-term quality of life within the region. It also circumscribes the capacity to continue providing the ecosystem services of water quantity, water quality, and biodiversity within and beyond southern Appalachia. The results from this research will be of considerable interest to policy makers, planners, and regulators in southern Appalachia and the Piedmont Megapolitan Region as they struggle to maintain the properties of place that make the region both a ‘water tower’ to the Southeast and one of the most biodiverse temperate regions in the U.S. if not the world.

SECTION 1. RESULTS OF PRIOR SUPPORT - DEB AWARD #0218001

1.1. Introduction. Coweeta LTER research in 2002-08 enhanced understanding of social-ecological dynamics in southern Appalachia from local to regional scales centered around three major initiatives: (1) characterizing the social-natural template, (2) ecosystem responses to variation in the social-natural template, and (3) forecasting future ecosystem conditions. Highlights from each initiative are presented below. Total productivity during this funding cycle was high with a total of 269 publications and 48 dissertations and theses. This brings our cumulative total since the site was established in 1980 to 1,247 publications and 205 theses. With the recent signing of a book contract with Oxford Press, a second Coweeta synthesis volume will appear toward the end of 2009 (Swank and Webster n.d.). A comprehensive list of LTER-supported publications (Table 1.1) and data sets (Table 1.2) produced this funding cycle are presented in the Supplementary Documentation for this proposal.

1.2. Characterizing the Social-Natural Template. We synthesized understanding of major 18^{th}, 19^{th} and 20^{th} century land-use changes including the transition from Native American to EuroAmerican occupation, abandonment of extractive resource uses, and increases in housing density and forest cover for southern Appalachia. The results of these efforts give the proper context for understanding how the past helps define the present and constrains the future in southern Appalachia (Gragson and Bolstad 2006). We developed a long-term chronology of fluvial and colluvial sedimentation and demonstrated how human-induced sedimentation rates since the beginning of the 19th century are an order of magnitude greater than the same rates prior to this date (Leigh and Webb 2006). This research also indicated that the entrenched condition of southern Appalachian stream channels may be inherited from the middle Holocene rather than a product of contemporary land-use practices.

Historic settlement and deforestation led to a narrowing of stream channels and an increase in fine-textured streambeds (Price and Leigh 2006b). The increase in fine textured material is highly correlated with biotic integrity in southern Appalachia although few conclusions can be drawn about the morphological response of streams to the level or the intensity of impact. This could be because the level of disturbance is below the threshold of morphological sensitivity or because it has not persisted long enough for a morphological response to be evident. The water quality of these streams is very good by comparison to streams in the Piedmont, but even moderate reductions in forest cover are associated with degradation of stream water quality (Price and Leigh 2006a). This carries important implications for stream management in this rapidly developing region. From a policy standpoint, morphological adjustment to disturbance may be more effectively addressed system-wide (i.e., regionally) than at the reach scale (i.e., county or community).

Quantification of land-use/land-cover trajectories has enhanced understanding of the ecological consequences of changing land use. For example, we overlaid changes in housing density with the potential distribution of forest communities to determine whether development might differentially impact distinct forest types. Cove hardwood forest communities, which are located in sheltered slopes at middle elevations and are naturally fragmented, were particularly vulnerable to increasing development (Turner et al. 2003c). To give greater time depth to our understanding of disturbance patterns in forest stands we conducted dendrochronology studies in the Coweeta Basin and the old-growth Joyce Kilmer Memorial Forest along topographic and compositional gradients (Butler 2006). The average decadal disturbance rate (calculated as percent of plot area affected per decade back to the mid-1700s) was 8.7% to 18.3%. This rate is both similar to rates across eastern temperate forests (5% to 20%) and indicates a disturbance history of low, but fluctuating rates resulting from recurring small canopy gaps (Clinton et al. 1993).

The patterns of land use that pre-date European settlement in southern Appalachia are poorly described. Using the first true census of the Cherokee Nation and the first detailed English map of North America's southern frontier, we examined Cherokee town placement and population across the region (Gragson and Bolstad 2007). We then modeled the constraints and trade-offs to meet individual settlement needs for selected resources and so determine the "resource demand footprints" for the entire Cherokee territory in the early 18th century (Bolstad and Gragson 2007). This provided a critical benchmark for evaluating pre-settlement land use and extended our understanding of the regional historic land-use mosaic.

1.3. Ecosystem Responses to Variation in the Social-Natural Template. Our efforts in this initiative fall into three main categories: (A) ecological response to variable environments, (B) effects of past and present land use on contemporary ecosystems, and (C) functional consequences of changing species composition.

1.3a. *Ecological Response to Variable Environments*. Long-term monitoring of environmental gradients (1991 to the present) and experimental manipulations were used to determine how life history stages (seed production, dispersal, germination, growth, maturation, survival) of dominant tree species respond to variation in light, temperature, soil moisture and soil pathogens (e.g., Wyckoff and Clark 2002, Beckage and Clark 2003, Ibáñez et al. 2007a, Ibáñez et al. 2007b). Theoretical studies complemented this empirical research and demonstrated that neither low-dimensional niche nor neutrality models explain the high observed diversity (e.g., Clark et al. 2007a). A simulation model was developed to directly implement these observations to prediction for use in experiments (Govindarajan et al. 2007). Observations made during extreme climate events – droughts of 1985-1988 and 1998-2001, and Hurricane Opal in 1995 – complement the previous life history research and provide critical insights on environmental variability from infrequent disturbances. Our results indicate that ecosystem recovery to pre-disturbance conditions was relatively rapid (months to years) in consequence of the vegetative diversity, deep soils, dense forest, and riparian canopy of the region (e.g., Kloeppel et al. 2003, Yeakley et al. 2003).

We carried out synthetic studies on the long-term Coweeta gradient plots by measuring ecosystem process indicators such as forest floor mass, coarse woody debris, and soil nitrogen transformation. Results indicate that biotic site variables regulate N availability whereas abiotic variables regulate canopy N cycling (Knoepp et al. 2007). Analysis of forest inventories from permanent plots established in 1934 and re-sampled in the 1970s and 1990s, reveal a significant increase in tree species diversity following the demise of chestnut (*Castanea dentata*) (Elliott and Swank 2007). Building on the Coweeta tradition of studies designed to relate ecological patterns and processes in terrestrial and aquatic ecosystems, we completed studies of: fine-root dynamics along an elevational gradient (Davis et al. 2004); the role of insect herbivory and frass deposition on soil N and C fluxes (Frost and Hunter 2004); the effects of turbidity on foraging in stream fishes (Zamor and Grossman 2007); and, the role of labile carbon in the food web of headwater streams (Wilcox et al. 2005). These diverse studies collectively provide a firm foundation for understanding the mechanisms that underpin local and regional environmental change in southern Appalachia.

1.3b. *Effects of Past and Present Land Use on Contemporary Ecosystems*. Most contemporary observers of forest-dominated southern Appalachia are unaware of the degree to which land uses prior to 1950 transformed land cover and imposed legacies that still influence regional ecosystems and land use. During this funding cycle we focused on key land-use legacies representing the persistent influence of historic land use across the region (a.k.a. the “ghost of land-use past” sensu Harding et al. 1998). For example, agricultural land use from the middle of the 19th through the middle of the 20th centuries and timber harvests from the early 20th century had long-lasting effects on carbon (C) pools and fluxes in the region of which differences in aboveground C pools are the most persistent (Bolstad and Vose 2005, Vose and Bolstad 2007).

The mean size of soil nutrient pools also displays differences according to land-use history, but the most striking is the difference in soil nutrient variance (Fraterrigo et al. 2005). Previously farmed sites have less total variance since most variance is among rather than within plots. In reference sites, however, total variance was greater within plots (i.e., at finer scales) rather than among plots. In this case, the spatial structure of soil nutrients was a key indicator for the legacy of agricultural land use. In a parallel study, soil microbial communities were shown to vary across land-use histories *decades* after agricultural abandonment. In this case, neither total microbial biomass nor litterfall varied, it was that previously farmed sites had less fungi and more Gm-bacteria while unfarmed reference sites had more fungi (Fraterrigo et al. 2006b). We also demonstrated that fungal abundance and soil bulk density effectively predict mineralization rates (Fraterrigo et al. 2006a), which effectively decrease over the long term. This result is in contrast to typical expectations about microbial community resilience to change.

1.3c. *Functional Consequences of Changing Species Composition*. How changes in community composition may affect streams, riparian zones and terrestrial ecosystems remains an important ecological question and a long-standing theme of Coweeta LTER research. Introduction to southern Appalachia of the non-native hemlock woolly adelgid (*Adelges tsugae*) sparked new studies on the potential impact of removing a foundation species (hemlock, *Tsuga canadensis*) from the landscape (Ellison et al. 2005). In related work, we demonstrated it is possible to scale from the sap flux probe to watershed evapostranspiration in a single-species southern Appalachian system with a fair amount of confidence (e.g., within 7% and 14% of watershed ET estimated from water balance P-Ro Ford et al. 2007). This methodology was then used to quantify the transpirational flux of eastern hemlock in southern Appalachia and estimate the potential impact of its loss on hydrology without replacement (Ford and Vose 2007). Mortality of eastern hemlock would reduce annual stand-level transpiration by ~10% and reduce winter and spring stand-level transpiration by ~30%, which would result in persistent increases in discharge, decreases in the diurnal amplitude of streamflow, and increases in the width of the variable source area. These changes will present a real challenge to land managers to develop strategies that restore function or mitigate impacts.

Several Coweeta PIs (Pringle, Bradford, and Hunter) joined forces in a study to understand the effects of non-random tree species losses caused by factors such as altered climate, land-use patterns and N deposition on litter decomposition. The experiment used a full-factorial design with all possible combinations of four dominant litter species and compared decomposition in both riparian and stream ecosystems. Initial results show that effects of species loss are not predictable from our knowledge of single species in a stream system (Kominoski et al. 2007). Non-random tree species loss may have large and *predictable* effects on decomposer community structure, but large and *unpredictable* effects on ecosystem nutrient cycling. We looked for additive and non-additive effects of litter mixing on mass loss, nutrient dynamics, and the decomposer community using a full-factorial litterbag experiment of four deciduous leaf species (Ball 2007). Our results suggest a potentially large impact of non-random species loss with high-quality litter species (e.g., *L. tulipifera*, *A. rubrum*) supporting larger, more diverse decomposer communities resulting in increased rates of mass loss; low-quality species (*R. rubrum*) tend to decrease decomposer abundance and diversity thus slowing the rate of mass loss in mixture.

Finally, we developed a spiraling-based model for particulate organic C dynamics in the Little Tennessee River to synthesize existing data and illustrate our current understanding of river ecosystem processes (Webster 2007). For the whole river system, leaves accounted for 19% of inputs, primarily near the headwaters, and almost ½ of the input was respired. The model illustrates that a consequence of downstream transport is that much of the particulate C in streams is metabolized a considerable distance downstream from where it enters the stream, and this longitudinal linkage is essential to our understanding of stream ecosystems.

1.4. Forecasting Future Ecosystem Conditions. Research was initiated to integrate results from our observational and experimental data and move toward forecasting future ecosystem conditions using alternative scenarios. Basic research at fine scales is a critical step in generating the scientific knowledge for building scenarios although it seldom provides the requisite knowledge on interactions and processes required for planning and decision-making. We focused on the conceptual and methodological developments, and parameterization of selected components.

We made many methodological advances contributing to an understanding of how forests will respond to global change including modeling and computational tools to infer relationships between demographic rates and the climate variation and disturbance that influence them. Specific examples include synthesis of fecundity and dispersal (Clark and Bjornstad 2004), growth rates (Clark et al. 2007b), competition in canopies (Wyckoff and Clark 2005), mortality (Wyckoff and Clark 2002), and the sensitivity of recruitment to environmental variation (Hille Ris Lambers et al. 2002, Clark et al. 2003b, Beckage et al. 2005, Ibáñez et al. 2007a, Ibáñez et al. 2007b). Potential vulnerability of freshwater supplies to climate change is underscored by the widespread North American droughts of 2007. Soil moisture and streamwater flow at Coweeta was modeled under a doubled CO^2 climate scenario for water yield in small, headwater streams that ultimately determine water supply to the southeastern U.S. Using a hierarchical Bayes framework to account for uncertainties in different data sources (Wei and Clark n.d.), we were able to show not only an increase in the frequency of extreme drought with substantial decrease in summer and fall flows, but an increase in the frequency of floods in western North Carolina.

Macon County officials have struggled over measures to control and direct land development, so we examined the hypothetical use of conservation easements as an alternative land-use policy. We estimated that a household's willingness to pay to participate in an easement program ranges from $10.97 to $21.79 per year per household, suggesting 53-175 acres entering an easement program per year (Cho et al. 2005a). This would be equivalent to a 14-46% decline in the rate of land conversion relative to the rate between 1987 and 1997. We also applied spatial statistics to census block data to develop a coherent multi-scale econometric model of housing demand in southern Appalachia based on estimating the marginal effects of household, community and environmental characteristics (Cho and Newman 2005, Cho et al. 2005b). Results indicate that housing development in urban communities is more responsive to increased population density than housing development in rural communities; on the other hand, safety and education level are a greater concern to urban households. There are distinctively different growth drivers that demand managing growth according to community type. For example, policy makers could guide urban development by focusing on programs that lower crime rates and increase community stability, while in rural areas they would need to focus on improving air quality.

A new conceptual framework, the Land-Cover Cascade (LCC), was introduced to quantify the transfer of land-cover-disturbance effects to stream biota in southern Appalachia (Burcher et al.

2007). Disturbance was hypothesized to propagate through key variables that transform disturbance and translate effects to the next hierarchical level ultimately cascading to a biotic effect. Analyses were conducted using 31 hydrologic (e.g., discharge), geomorphic (e.g., stream bank height), erosional (e.g., suspended sediments), and substrate (e.g., size) variables along with 26 biotic responses in two large watersheds that varied in level of exurbanization. Results indicate that biota were influenced by near-stream urban, agricultural, and forest land cover as propagated by hydrologic, geomorphic, erosional and depositional streambed features along LCC pathways (Burcher et al. 2007). This suggests that communities are influenced by land-cover change indirectly through a hierarchy of associated abiotic components that propagate the disturbance to biota. The general concept about the effects of past and present land use on contemporary ecosystems may be applicable to other regions.

1.5. Data-Compilation in Support of Regionalization & Cross-Site Collaboration. We undertook three important data compilation efforts. 1) We developed and populated the Coweeta Geographic Network (COGENT), an interactive GIS map viewer and data downloader for the Coweeta LTER study region (http://coweeta.ecology.uga.edu/ecology/cogent.html). 2) We developed a 1986-2001 land cover classification (2006 is in process) with 5 yr time steps using a standard methodology (http://coweeta.ecology.uga.edu/ecology/gis/landcover.html). 3) We compiled human population and economic data for all counties within the Coweeta LTER study region (as well as for all continental LTER sites in collaboration with the EcoTrends project) from 1790 to 2000 (http://coweeta.ecology.uga.edu/trends/catalog_trends_base2.php).

1.6. Cross-Site and Collaborative Activities. Coweeta researchers have participated in numerous intersite collaborations, and we continue to provide leadership in promoting improved integration of natural and social sciences within the LTER Network. Coweeta was represented in the special feature on LTER in *BioScience* (Turner et al. 2003b). Ted Gragson (CWT) and Morgan Grove (BES) edited a special issue of *Society and Natural Resources* to highlight social science dimensions of research across the LTER network (Gragson and Grove 2006). With Laura Ogden (FCE), they also taught an internet-based course on socio-ecological methods that involved researchers from across the network and was accessible to any participant from any site (http://coweeta.ecology.uga.edu/ecology/web_learning/intro.html). Coweeta researchers have also been involved in collaborative studies beyond LTER boundaries (e.g., Webster et al. 2003, Oleksyn et al. 2007).

SECTION 2. PROPOSED RESEARCH

2.1. Research Direction. We propose multi-scale process-oriented research on the consequences to the southern Appalachian socio-ecological system of the interaction between changing climate and land use. We expect landscapes in the southeastern U.S. to change profoundly in the next five decades as the socioeconomic factors driving the dramatic exurbanization of the past three decades persist, and the changes to the rates, frequencies, and intensities of important climatic factors occur (**Figure 2.1**). Climate and land use change will especially impact the rural and quasi-rural lands that still characterize much of southern Appalachia (Gragson and Bolstad 2006), which is both a 'water tower' (c.f. Viviroli et al. 2007) to the Southeast and one of the most biodiverse temperate regions in the U.S. if not the world (Stein et al. 2000).

These are unprecedented times and the environmental challenges faced by society demand novel approaches to the production, dissemination and application of knowledge to protect essential ecosystem services and meet human needs (Sanderson et al. 2002, Theobald 2004, Brown et al. 2005, Collins et al. 2007). The interaction of changes in climate and land use anticipated in southern Appalachia cannot merely be extrapolated from data collected on the experimental watersheds at the Coweeta Hydrologic Laboratory. We therefore propose a research program that builds on the knowledge we have gained in the 40+ year collaboration between the University of Georgia and the Coweeta Hydrologic Laboratory on diverse dimensions of disturbance in southern Appalachia (Hunter and Forkner 1999, Wright and Coleman 2002, Fraterrigo et al. 2006b, Price and Leigh 2006b, Gragson and Bolstad 2007, Webster 2007). The organization of the project and the group of interdisciplinary investigators that make the research described in this proposal possible are described in Section 3, and profiled in Table 3.1.

Our proposed research program will extend long-term measurements, field experiments and interdisciplinary modeling from small watershed studies to regional-scale analyses so as to account for increases in resource demand and competition from adjacent and more distant areas. Our focus is on the *provisioning* service of water quantity, the *regulating service* of water quality, and the *supporting* service of maintaining biodiversity. The overarching question that guides this research is: ***How will key ecosystem processes and the focal ecosystem services of water quantity, water quality, and biodiversity be impacted by the: (1) transition in land uses from wildland to urban and peri-urban; (2) changes in climate; and (3) interactions between changes in land use and climate including both on-site and off-site feedbacks?***

Our proposed research (**Figure 2.1**) will provide critical within-system knowledge across a range of temporal and spatial scales by examining processes associated with Parcel-Level to Regional Decision Making (Subsection **2.5a**), Longitudinal Variation in Hillslope, Riparian, and Stream Ecology (**2.5b**), Impacts of Climate and Land Use Change on Biodiversity (**2.5c**) and Baseline Data and Temporal Reconstruction (**2.5d**). Data and analytical results from each component will be linked through Synthesis & Scaled Integration (**2.5e**). The proposed research will also provide the foundation for comparative analyses, which are increasingly necessary for understanding the local manifestations of global change whether in climate or human settlement, in ways that advance knowledge of complexity about socio-ecological systems (Collins et al. 2007, Liu et al. 2007).

2.2. Conceptual Framework. Southern Appalachia with its abundant low-solute precipitation and dense stream network serves as a 'water tower' (c.f. Viviroli et al. 2007) to the southeastern U.S. The antiquity, north-south alignment, and topographic diversity of the southern

Appalachian Mountains are responsible for the region's remarkable biodiversity (Stein et al. 2000). These *properties of place* result in the overall capacity of southern Appalachia to provide varied ecosystem services linked to seasonal and permanent immigration from Piedmont and more distant populations. The rural and quasi-rural lands of southern Appalachia are being steadily consumed by sprawling development (**Figure 2.2**) from peripheral metropolitan centers such as Atlanta, Greenville, and Charlotte. Southern Appalachian streams are relatively unbuffered and therefore sensitive to atmospheric deposition of varied types; they are also subject to heavy sediment inputs from the high rates of land development, which are difficult to control given the general lack of regional planning. The capacity of southern Appalachia to continue providing the varied ecosystem services for which it is recognized is in peril. This increases the potential for internal competition between human and non-human populations and conflict between human communities within and beyond the borders of the region over provisioning, regulating, and supporting ecosystem services.

Southern Appalachia is now part of a vast trans-metropolitan region growing as "…an irregularly colloidal mixture of rural and suburban landscapes" (Gottmann 1961: 5, Zelinsky 1973, Taylor 2005). As of AD 2000, this so-called Piedmont Megapolitan Region (PMR) had a combined population of over 18 million (6.5% of the total US population), was growing annually at 1.7% (ranked 5th in the U.S.) and covered 236,000 km^2 (the boundary for the PMR is shown on **Figure 2.1**). While there are indications for a quasi-stationary or slightly cooling climate in the Southeast (Lu et al. 2005), predicted variability around climate means suggest a future with few historical analogues that will place a premium on anticipatory environmental decision-making (Heal et al. 2001, Koontz 2001, Evans and Kelley 2004). Six of the ten highest mean July temperatures for the Southeast have occurred in the previous 25 years and extended droughts characterized the summers of 1984-1987, 1997-1998, 2003, 2005 and 2007 (see PSDI graph on **Figure 2.2**). In the future, human and non-human residents alike can expect increased summer droughts, with longer dry-down periods of low base flow in streams, and increased potential incidence of high discharge events in streams during winter and spring that will increase the potential for landslides as steep, high elevation areas are developed (Burkett et al. 2000).

The state of Georgia, which anchors the Piedmont Megapolitan Region socially and economically through the city of Atlanta, grew at an annualized rate of 3.6% between 1990 and 2003 (the most recent available data) making it the fastest growing state east of the Rockies (Lang and Dhavale 2005, Mackun 2005). Atlanta sits on the doorstep of southern Appalachia and over the last decade its metropolitan area increased from 65 miles to 110 miles north to south while metropolitan and micropolitan populations across the Southeast grew respectively by 19.2% and 12.0%. Populations outside defined urban areas grew at the rate of 9.0% between 1990 and 2000. Sprawling urban development is characteristic of the Southeast (Keilman 2003, Mackun 2005, Liu et al. 2007) and is converging on the rural and quasi-rural lands of southern Appalachia by a combination of reductions in development density, segregation of residential and commercial districts, and expansion of transportation networks (Ewing et al. 2003).

Sprawl is not simply a function of the classic monocentric city principle in which land rents decline radially as distance from the Central Business District increases (Can 1990, Orford 2002, Kestens et al. 2004, Lang and Dhavale 2005, Munroe 2007). It is closely associated with a decrease in household size and an increase in the number of dwellings that reflect an aging of the U.S. population and changes in behavioral and social mores (Alig and Healy 1987, MacKellar et al. 1995, Fischer-Kowalski and Amann 2001, Alig et al. 2004). Income and house price are thus interdependent with a variety of spatial externalities including traffic congestion and crime; environmental, cultural and health amenities; ethnic and historical attachment to place; as well as the organizational complexity of the population (Anas et al. 1998, Irwin and Bockstael 2002, Grove et al. 2006b, Gragson and Bolstad 2007).

The regionalization of Coweeta LTER program (2002-2008) expanded the scope of scientific inquiry in space (54,000 km^2) and time (AD 1700 to the present with forecasts out to AD 2040). This led to the development of unique biophysical and socioeconomic data sets that advance our understanding of the dynamics and links between disturbance, forest structure and function, watershed ecosystem processes, and human land use. Our proposed research (2008-2014) will focus on ecosystem processes and services in the same southern Appalachian study area while recognizing their contextual dependence on the Piedmont Megapolitan Region (236,000 km^2).

2.3. Research Overview. In our proposed research, we will focus on forest catchments located on mountainous (colluvial) and valley (alluvial) landscapes within watersheds ranging from those that are characteristic of the Coweeta Basin (<10^0 km^2) through regional drainages (10^3-10^4 km^2, **Table 2.1**). We will synthesize and upscale our observational and experimental research using a process-based approach designed to resolve cross-scale interactions among gradients in moisture, microclimate, settlement intensity, and regulatory environment. Traditional experiments provide limited understanding of the complex interactions between exurbanization and climate change prevalent at regional scales, while correlation-based models omit the relevant processes about which much is already known (Clark et al. 2003a, Gragson and Bolstad 2006, Ibáñez et al. 2006). At a regional scale, assimilation of sparse observational and experimental data from multiple scales becomes the overwhelming challenge, and process-based models are the best option for meeting this challenge (Clark and Bjornstad 2004, Clark et al. 2007b). That a process-based approach is both relevant and productive in regional settings is attested by contemporary ecohydrologic (Baron et al. 1998, Band et al. 2000, Law et al. 2004), biotic (Graumlich 1991, Clark et al. 2003a, Stevens et al. 2006), and socioeconomic research (Groffman et al. 2003, Law et al. 2004, Bolstad and Gragson 2007).

Regionalization of the Coweeta LTER moved our research beyond analysis of the undeveloped mountainous catchments characteristic of the Coweeta Basin to an examination of the human-dominated watersheds and river basins of southern Appalachia (**Figure 2.3**). This required conceptual advances to reach a critical understanding of the environmental *and* human responses to the forces of change within this socio-ecological system (**Figure 2.4**). Our earliest regional research established that history, topography, and civil infrastructure controlled land use change (Wear and Bolstad 1998). More recently, we focused on identifying the patterns associated with geomorphic, biotic, and settlement regimes (Price and Leigh 2006b, Bolstad and Gragson 2007), and the impacts on stream and terrestrial structure and function of particular land use regimes (Harding et al. 1998, Jones et al. 1999, Scott et al. 2002, Turner et al. 2003c, Fraterrigo et al. 2005). From this foundation the proposed research takes up ecosystem processes and focal ecosystem services in the Little Tennessee (~1260 km^2) and the French Broad (~2740 km^2) basins, across four orders of magnitude in drainage area using evidence back to the early 18th century.

The Little Tennessee and French Broad rivers typify the west-flowing, medium-sized, regional rivers of southern Appalachia (Wallace et al. 1992). Such rivers integrate the processes occurring in their watersheds, but they are not simply the accumulation of their smaller tributary streams (Shaman et al. 2004). Farming-related disturbance dominated both river basins until the early 1900s, with settlements clustered in low, near-stream areas (**Figure 2.5**). A decline in row-crop agriculture led ultimately to farm abandonment that progressed over time from the steepest, most isolated sub-catchments to valley bottoms. There was little residential or commercial development between the mid 1930s and the early 1970s, after which immigration steadily accelerated. Regional forests recovered from extensive timber harvesting in the 1920s to reach their cover apogee in the early 1990s and then began to decline as residential construction and land clearing increased.

We have selected the Little Tennessee and French Broad watersheds for focused research because the gradients in development, amounts of private vs. public lands, and regulatory environments make them representative of the socio-ecological variability across southern Appalachia. It also allows us to leverage our existing instrumentation, research plots and experience to partner with local, county, and state government agencies and NGOs. This will help us achieve a regionally relevant understanding of change across southern Appalachia.

2.4. Linking Conceptual, Empirical and Simulation Approaches. The complex interaction between projected changes in climate and land use across southern Appalachia leads us to adopt a nested hierarchical framework to examine provisioning, regulating and preserving ecosystem services. Our sampling, experimental manipulations, and modeling are designed to capture interactions within a range of distinct landscapes reflecting the flowpaths, habitats, and human communities characteristic of southern Appalachia (**Figure 2.6**). It does this by working across a range of scales from coarse to fine consisting of (1) regional basins, (2) sub-basins, (3) headwater watersheds, and (4) hillslopes and riparian zones. This flowpath network with intervening natural and built spaces extends upstream from the perennial stream system through transitional, intermittent and ephemeral phases terminating in unchannelized hillslopes. Stream reaches begin at the base of hillslopes within floodplains (level 4) where fine-scale processes in terrestrial patches and land parcels control the inputs along hillslope, floodplain and channel flowpaths, and collectively constitute catchments (level 3) and watersheds (levels 2 and 1). A critical aspect of the proposed research is that study sites will be co-located so that different groups of collaborating investigators can obtain complementary measures to produce comprehensive descriptions of local system status and dynamics.

Material fluxes are processed as they travel through the flowpath with fluxes of water, carbon, nutrients and particulates affected by forces acting on the intervening spaces of the network. Our field studies are designed to measure and estimate linkage and feedback between the ecohydrological cycling, population dynamics, and socioeconomic subsystems within and across the defined flowpath network. Local scale responses (level 4) will be characterized with a spatial detail relevant to the processes targeted by observational and manipulative approaches. Instrumented sites encompassing elevation and land-use intensity gradients (Levels 2 and 3) will be complemented by extensive sampling at the regional scale (level 1) of ecohydrologic, stream gradient, biotic and socio-economic structure. Site selection and field activities will be guided by results from our current and proposed research including historic environmental reconstruction and long-term environmental monitoring. Extrapolation from site measurements to the region will be accomplished by combining multi-resolution remote sensing products, spatial socioeconomic databases, and government information systems.

Modeling will be used to synthesize measurements from all levels with understanding of how transport and processing operates today and how it could be impacted by future climate and land use change. We will use the Regional HydroEcological Simulation System (RHESSys) that integrates water, carbon and nutrient cycling over complex terrain (Band et al. 1993, Band et al. 2001, Tague and Band 2004, Band and Tague 2005), coupled with models we have developed to understand nutrient spiraling within streams (Webster 2007) and terrestrial biodiversity (Govindarajan et al. 2004, Clark et al. 2007b, Govindarajan et al. 2007). In the next five sub-sections, we outline the questions that motivate our research of processes associated with

Parcel-Level to Regional Decision Making (**2.5a**), Longitudinal Variation in Hillslope, Riparian, and Stream Ecology (**2.5b**), Impacts of Climate and Land Use Change on Biodiversity (**2.5c**), and Baseline Data and Temporal Reconstruction (**2.5d**) that are then linked through Synthesis & Scaled Integration (**2.5e**).

2.5a. *Parcel-Level to Regional Decision Making.* Guiding question: **What are the links between private and public land use decisions and ecosystem services?**

Rapid in-migration to southern Appalachia provides an important opportunity to understand the relationship between ecosystem services and land-use decisions (**Figure 2.7**). Ecosystem services are benefits that humans directly or indirectly receive from the natural environment at different temporal and spatial scales (Farber et al. 2006). Scaling parcel-level decision-making to the regional level connects physically-mediated processes, such as climate change, and socially-mediated processes, such as exurbanization, in policy-relevant ways (**Figure 2.8**). This is because individual awareness of the ecological consequences of land-use decisions changes over time and across populations and is affected by a regulatory overlay at the local, state, and federal levels. The importance of focusing on parcel-level decision-making stems from the recognition that: (1) observed landscapes produced by actual household decisions are much patchier and have more edge than those predicted by utility-maximization models; (2) the diversity of actual decisions made by households exceeds the practical allowance of factorial design experiments; and, (3) there are many unobserved factors that influence utility maximizing decisions ignored in many theoretical models, including historical context and the preference for equity or 'fairness' (Evans and Moran 2002, Cho and Newman 2005, Bolstad and Gragson 2007).

Individual decisions are based on comparisons of the relative value of different options and the marginal benefit and cost of these options, not only the quantity or quality of resources. The economic value of a good or service reflects the marginal value it contributes to an individual's utility or society's welfare, which depends on many different factors, including the availability of substitutes (Bockstael et al. 2000). In some cases, economic value is fairly easy to identify. For example, the value of timber (a provisioning service) can be reasonably inferred from timber prices that reflect many independent individual decisions about the tradeoff between buying or supplying timber and buying or supplying something else. However, many ecosystem services (such as water quantity, water quality, and biodiversity) are not traded in formal markets and thus do not have a competitive market price from which to infer value. This does not mean these services do not have an economic value only that this value is harder to estimate. Valuing non-market goods and services has long been a focus of resource economists working on environmental problems and three recent references (Champ et al. 2003, Freeman 2003, Haab and McConnell 2003) describe the theoretical foundations, practical considerations, and econometric techniques appropriate to this effort.

While private landowner decisions reflect the benefits *the landowner* receives from the property, public land use decisions reflect the net benefits to *the public* of various land use options. Many of the ecosystem services affected by land use decisions are valued by someone other than the individual or group that owns the parcel. For example, upstream riparian zones provide water quality and quantity benefits to downstream urban or agricultural users. Since a private landowner would not receive the full value of these benefits, they would not consider them in their land use decisions. Biodiversity protection is another ecosystem service with significant external benefits that public land managers may not consider in their land management objectives. The diverse and complex arrangement of different types of public land including federal, state, and locally owned, complicates the empirical study of land use decisions and ecosystem services. During our proposed research, we will focus on the presence and management of public land as it impacts private property values, especially in areas with significant second home development.

Our research focuses on changes in the quantity and quality of key ecosystem services from current levels constrained by a finite set of contextually relevant management options (Guo et al. 2000, Heal et al. 2001, Farber et al. 2006). Specific questions to be addressed include:

- How do land prices capture the value of ecosystem services and related regulations?
- How does increased awareness of ecological consequences affect land use decisions?
- Which policies are most efficient in achieving a socially optimal level of ecosystem service provision, e.g., educational campaigns that inspire voluntary responses, command-and-control regulations that impose restrictions on decision making, or incentive-based policies that change decisions?
- How do changes in specific ecosystem services, such as municipal water systems, alter the quantity and quality of other ecosystem services, for instance the quality of non-treated surface water sources?
- What vulnerabilities are created by changes in ecosystem services, how are risks distributed within and among local and regional communities, and what are the rules and/or concepts of equity that govern those allocation decisions?
- Do public land use decisions reflect the full value of biodiversity and water related ecosystem services and how do these decisions impact private land use decisions?
- How does the county level political economy influence exurban in-migration and resulting land use patterns?

In identifying the factors that influence individual decisions, we will consider both market and non-market values of ecosystem services. We will rely on a combination of revealed and stated preference methods to estimate the demand and willingness to pay for these services and predict responses to future changes in the availability and quality of these services. Revealed preference methods (e.g., hedonic pricing models, travel cost models, migration models) rely on observed data from actual transactions in relevant markets to estimate the preferences for a good or service, even if not freely or individually traded (Champ et al. 2003). For example, residential property values reflect the aggregate value of all attributes of the property including air and water quality. The hedonic pricing method uses regression techniques to identify the value of a particular attribute while holding all other parcel attributes unchanged (Taylor 2003). Building on previous Coweeta LTER research (e.g., Cho et al. 2005a), we will use residential sales data and tax records combined with multi-scalar spatial data infrastructure to determine the value of focal ecosystem services to property owners and how land use regulations affect values.

We will also rely on face-to-face interviews and representative surveys (in years 2 and 6). Surveys can reliably record attributes of a household and its land uses at a particular moment in time and while they measure intended rather than actual behavior, they do provide essential information about attitudes and preferences otherwise difficult to obtain. Interviews on the other hand provide critical knowledge on motivations, incentives, and preferences necessary for explaining actual decisions (Langley 1999, Evans et al. 2006, Grove et al. 2006a, Eisenhardt and Graebner 2007). We will rely on stated preference valuation methods (e.g., contingent valuation) and will use surveys to estimate the value of non-market environmental goods (see Louviere et al. 2000, Brown and Peterson 2003). With this method, respondents are asked to make decisions that reflect their willingness to make trade-offs between competing uses of ecosystem services.

Econometric methods (e.g., hedonic pricing) will be used to parameterize and integrate information into a multi-level social model of individual decision-making in response to environmental factors and regulatory conditions (see Chamblee et al. n.d.). We will use discrete choice models to relate individual land use decisions to various individual, property and decision characteristics to improve the power and accuracy of our empirical model (Lubowski et al. 2003). This model will be well-suited to evaluate the impact of land use decisions on neighboring households (i.e., a spatial externality) as well as providing the means for integrating the subjective data obtained by survey methods. We will also use quasi-natural experiments in which some decision-making units are subjected to a non-controlled treatment, for example, a local policy change that affects some units, while others are not. The rich parcel-level data we are collecting (**Table 2.2**) and the continually evolving local and state regulatory overlay in southern Appalachia are ideal for comparing the impact of regulation on individual and social welfare at several levels using a difference-in-difference technique (Galster et al. 2004).

2.5b. *Longitudinal Variation in Hillslope, Riparian, and Stream Ecology*. Guiding question: **How do differences in riparian and hillslope land cover, soils, and infrastructure alter water quality and quantity along flowpaths from hillslopes to small streams to rivers?**

Exurbanization and the parcel-level to regional land use decisions studied in **2.5a** impose abrupt and unique discontinuities in stream energy and mass fluxes (**Figure 2.9**). These alter instream and riparian processing of nutrients and carbon as well as the distribution of instream habitat and biota. By transforming the overlapping physical, biological, and functional continua recognized in forested watersheds (Schumm 1977, Vannote et al. 1980, Robert 2003), exurbanization is a key force that reorganizes rural and quasi-rural landscapes in southern Appalachia (**Figure 2.10**). Mountain stream channels have been classified into domains according to the relative dominance of different physical controls and processes (Montgomery and Buffington 1997, Montgomery 1999). The upper stream channel is governed by colluvial processes within watersheds <2 km^2 in surface, such as the headwaters of Shope Fork and Ball Creek at Coweeta Hydrologic Laboratory. Colluvial reaches, such as Ball Creek and Shope Fork, supply colluvial and alluvial sediment in episodic pulses to transport reaches, such as Coweeta Creek, within watersheds ranging in size from 5 to 30 km^2. Finally, transport reaches grade into alluvial response reaches such as the main channel of the Little Tennessee River, and these reaches are associated with extensive bottomlands and valleys with surface areas in southern Appalachia that exceed 30 km^2.

To understand the longitudinal changes in light, nutrients, carbon and sediment as a function of exurbanization, we propose establishing a network of sites along stream gradients that will be coordinated and co-located with other research sites in the Little Tennessee watershed. These gradients will be laid out in a set of small watersheds ranging in size from 5 to 20 km^2 throughout the Little Tennessee watershed and incorporate some of the *Hazard Sites* established in 1998 for repeat sampling every five years through 2030 (Gardner et al. n.d.). The questions that guide our research into longitudinal variation emerge from recent Coweeta LTER findings about human influences on southern Appalachian streams (i.e., Price and Leigh 2006b, Burcher et al. 2007):

1. What are the longitudinal gradients in contributing watershed characteristics and hydrology, biogeochemical processes, biota, channel form, and sedimentology typical of forested watershed systems?
2. How do anthropogenic changes to soils and vegetation alter these gradients?
3. How can information from representative flowpaths be combined in a modeling framework to provide a regional assessment of ecosystem services?

Land use patterns in southern Appalachia provide an opportunity to separate effects of a) riparian forest removal and nutrient addition from b) exurban land uses that increase peak flow frequencies, magnitudes, and stream power. To separate these effects, we will select study sites in a) fully forested, b) mountainside residential and c) developed and agricultural valley watersheds. This design provides the opportunity to assess longitudinal gradients in primarily forested landscapes and determine how they are altered by exurbanization. Research activities will be divided into two phases (**Table 2.3**). During Phase 1, synoptic sampling of streamwater N and sediment load will be carried out two times in Year 1 throughout the channel networks of selected watersheds in the Little Tennessee basin. Approximately 50 sites will be selected for synoptic sampling based on stream size, land cover, and watershed scale as well as past and ongoing research (e.g., Hazard Sites, LINX). Previous Coweeta research supports the relative value of streamwater N and sediment load for discriminating streams according to land use intensity (e.g. Swank and Bolstad 1994, Clinton and Vose 2003). In Phase 2, results from the synoptic sampling will be used to identify a subset of intensive sampling locations of three types (e.g., Likens and Buso 2006): 1) headwater steam reaches (6 sites) distributed along a development gradient; 2) watersheds (3 sites) in developed and agricultural valleys; and, 3) established USGS gaged sites (3 sites) along the main-channel of the Little Tennessee River.

<u>Riparian and Hillslope Subsystems</u>: Altering or removing upland and riparian vegetation will change hillslope hydrology, biogeochemical processes, and incident solar radiation (e.g., **Figure 2.11**). Sampling points will be associated with a transect that links the hillslope, riparian, and stream subsystems and is also co-located with other studies (see **2.5c**). Vegetation composition, soil morphology and chemistry, riparian groundwater, and soil solution (plant available and exported) will be measured in each transect. Hillslope water chemistry will be collected seasonally based on plant phenology: spring (bud break), summer (full canopy), fall (abscission layer formation and leaf fall), and winter (dormant). Previous Coweeta research has shown variation in stream chemistry and soil solution chemistry for these seasons (Swank and Vose 1997).

Variable source areas and ephemeral channel features will be mapped by field inspection (Dunne et al. 1975); subsurface topography will be mapped using auger holes or tile probes (Leigh and Webb 2006, Tromp-van Meerveld and McDonnell 2006); and soils will be characterized. This information will be used to plan and install a distributed network of shallow piezometers and lysimeters on the hillslope, deeper piezometers on the floodplain, surface water collectors in the variable source areas and ephemeral channels, and hyporheic piezometers to compare geochemistry at different locations in the stream. Following select storms and seasonally, samples of vadose water, saturated interflow, surface runoff, alluvial aquifer, and hyporheic water will be collected from riparian and hillslope soils (organic and upper mineral). The results will be a key input to the RHESSys modeling effort (see **2.5e**).

<u>Stream Subsystems</u>: We expect stream nutrient loading to increase in response to exurbanization, reflecting the influence of forest practices, agriculture, septic systems, the application of imported fertilizers (mineral and organic), and agricultural activities. Forest land uses, whether managed or unmanaged, have extremely low nutrient export relative to all other land uses in southern Appalachia (Swank and Vose 1997, Clinton and Vose 2003). Some land uses remove riparian vegetation that causes increased solar insolation to channels, reduction of woody debris inputs, the alteration of channel morphology, and increases in fine sediment inputs. Septic systems and lawns or small row crop fields can introduce the following to streams bacteria, small soil particles, fertilizers, and other chemicals through subsurface flow and surface runoff. The combined effect is a reduction in the capacity of streams to process nutrient

loads, which we hypothesize will result in a predictable longitudinal pattern of the biogeochemical signal that can be related to land use intensity (**Figure 2.12**).

Phase 1 synoptic sampling will include monitoring three classes of variables related to physical, chemical, and biological stream responses that will serve as the backdrop to intensive study of stream structure and function. Each intensive sampling site will include permanently installed water level sensors to continuously monitor streamflow. Discharge data will be coupled to bi-weekly composite measures of stream chemistry (particulate and dissolved C, N, and P, as well as TSS) to generate material loads at each monitoring site. These data will be used to develop sequential material budgets and address how net material processing responds to land use, climate, and other disturbances. Stream reaches of 100-500 m will be established at each intensive site to study stream N cycling. The uptake and transport of N will be measured seasonally using low-level releases of ammonium and analyzing response curves using a nutrient spiraling approach (Webster and Valett 2006). The coupling of synoptic and intensive data collection will provide us with information for calibrating and parameterizing values for in-stream transport to be used in the nutrient spiraling model (see **2.5e**).

Sediment Sources: The U.S. EPA identifies sediment as one of the top four priority pollutants for the southeastern U.S., and the third most common cause of impairment in North Carolina streams. Land clearing for housing developments, removal of trees from the riparian zone, and removal of woody debris from the stream channels simplifies habitats and increases the supply of fine sediments. This results in a shift to finer bed particle size distributions. Several stream ecology studies in the region correlate stream sedimentation to degradation of biotic conditions (e.g., Roy et al. 2003, Walters et al. 2003, Burcher et al. 2007). We will use sediment sourcing studies to quantify hillslope versus streambank sources of sediment to improve understanding of the processes involved in sediment contamination related to exurbanization.

Streambed and suspended sediment will be sampled at each intensive site during baseflow; storms will also be sampled at each intensive sampling site. Geochemical signatures will be used to model sources based on representative hillslope and streambank sediment characteristics (Collins and Walling 2005). Geochemical signatures for different types of land surfaces within each watershed (i.e., pasture, forest, lawn, cultivated land) will be linked to a landscape model using geographic information systems (GIS) and discriminant statistical analyses (Collins and Walling 2002, Carter et al. 2003, He and Walling 2003, Collins and Walling 2004, Miller et al. 2005, Walling 2005). Key geochemical tracers will include ^{137}Cs**,** multi-element concentrations, and carbon isotopes. ^{137}Cs will greatly facilitate discrimination of streambank-derived, versus hillslope- and soil surface-derived sediment because of their widely different concentrations of ^{137}Cs. We will use multi-element concentrations (30-40 elements) determined by Inductively Coupled Plasma spectrometry to identify “signature” chemical traits by discriminant analyses. For example, iron oxides and other distinctive compounds result from surface weathering on hillslope soils, and automotive lead results from roadside and cultivated localities. Carbon isotopes of ^{12}C and ^{13}C will aid in distinguishing sediment derived from pastures, lawns, corn fields, old pastures and forested lands.

2.5c. ***Impacts of Climate and Land Use Change on Biodiversity.*** Guiding question: **How do climate change and exurban development affect biodiversity at local to regional scales, and what are the implications for ecosystem processes?**

Climate change in the Southeast may lead to shifts in the abundance of mesophytic plants and animals (Currie 2001). We expect upslope range shifts of some species (Parmesan and Yohe 2003, Root et al. 2003, Wilson et al. 2005), as well as local extinctions of montane fauna or species at the southern limits of their ranges (Franco et al. 2006). Superimposed on the anticipated change in regional climate is rapidly changing land use (Parsons et al. 2004, Franco et al. 2006). This exurban development affects patterns of species abundance and distribution (**Table 2.4**). For example, development of forested land is reversing some of the habitat gains by forest species that resulted from 20th century agricultural abandonment and reforestation (Pearson et al. 1998, Mitchell et al. 2002, Foster et al. 2003). It is further altering species dispersal, including accelerating the transport rate of nonnative organisms from urban to rural areas (von der Lippe and Kowarik 2007), which include exotic pests and pathogens that in some cases have already had profound impacts on native communities in our study region (e.g., hemlock wooly adelgid). Resultant changes in biodiversity are likely to affect ecosystem functioning by altering essential processes involved in nutrient cycling (Ehrenfeld 2003), ultimately feeding back to affect future terrestrial and aquatic community structure and function (Levine et al. 2003). Shifts in biodiversity can also change ecosystem processes (Hobbie 1992, Finzi et al. 1998, Lovett et al. 2004). For example, upslope migration of *Liriodendron tulipifera* could accelerate terrestrial and stream nitrogen release from decomposing leaves, (Ball 2007, Kominoski et al. 2007) and soil moisture withdrawal due to high transpiration rates (Ford and Vose 2007).

To address the effects of climate and exurban development on biodiversity and ecosystem processes, we will combine modeling, observational, and experimental studies across regional and local scales in southern Appalachia. The goal of the regional-scale work will be to predict changes in community structure due to the migration and extinction of native and nonnative species, given extant species distributions and abundance patterns, and projections of climate and land use change. It is important that we incorporate mechanistic studies, but logistic challenges often limit direct manipulations at broad spatial scales. Therefore, we will exploit natural spatio-temporal environmental variation and conduct experiments at fine scales to provide mechanistic understanding of the causes and consequences of landscape-scale changes in biodiversity and ecosystem processes. Our proposed studies build directly on ongoing Coweeta LTER research and associated projects that document species abundances across the landscape and their effects on ecosystem processes (see Section 1. Prior Results). Our studies will address two main subquestions:

1. How will climate and/or exurban development affect the growth, reproduction, survival, and spatial distribution of (a) tree seedlings, (b) shade-tolerant invasive species, (c) native understory herbs and (d) forest and riparian vertebrates?
2. How will these species losses and/or gains affect ecosystem processes?

Our proposed research on species responses to climate change and exurban development (Subquestion 1) will combine models and broad-scale spatial sampling informed by fine-scale process studies. We will test a range of hypotheses about biotic response to our key drivers of climate and land use change (**Table 2.5**). Projects will include spatially and temporally replicated monitoring of forest plant communities including trees, exotic and native understory species, and vertebrate communities, notably woodland and stream salamanders. The choice to study tree species and both exotic and native understory herbs is obvious from the perspective of linking biodiversity change to ecosystem function given established impacts of tree and herbaceous species on nutrient cycling in forested systems (e.g., Ehrenfeld 2003, Ball 2007, Ford and Vose 2007, Kominoski et al. 2007). We include plethodontid salamanders because the region is a global hotspot for salamander diversity (Petranka 1998). In addition, they are the dominant vertebrate group in relatively undisturbed forests and associated streams (Burton and Likens 1975, Hairston 1996, Bailey et al. 2004), and their abundance and high metabolic efficiency affects decomposition and nutrient retention (Burton and Likens 1975, Wyman 1998, Johnson et al. 2007). Because plethodotids are lungless (Feder 1983), they are especially sensitive to changes in land cover that affect moisture, temperature, and light penetration to the forest floor and siltation of streams (Pough et al. 1987, Petranka et al. 1993, Ash 1997, Miller et al. 2007). To integrate our biodiversity research with that described in Subsection **2.5b**, we will superimpose biodiversity monitoring onto sites selected for the longitudinal gradient work.

Responses of both plant and animal populations to climate change will be investigated along elevational and topographic gradients, representing gradients in temperature and moisture availability. For example, to investigate climate effects on forest composition, demographic rates for trees and herbaceous species will be obtained on mapped plots that allow inferences based on repeated census data. This work will be complemented by experimental plantings to estimate migration potential and recruitment responses to climate variation. It will build from an initial study involving 14,000 seedlings of resident and potential immigrant species, including species not now present at study sites, but predicted to immigrate on the basis of climate change scenarios (Ibáñez et al. 2007a, Ibáñez et al. 2007b). Given that forest processes are so dependent on forest canopy openings, forest sites will have experimental canopy gaps as part of the design with interdependent hypotheses at each scale (organism, population, community, and ecosystem). Canopy gaps and transplant studies are nested manipulations *within* sites so that we have pretreatment and treatment/control *at each location*. Protocols will follow previous experimental gap treatments (Beckage and Clark 2003, Dietze and Clark 2007) with experimental plantings done in gap treatment and control plots (Ibáñez et al. 2007a, Ibáñez et al. 2007b). Inferences will include responses of recruitment, growth, and mortality to the large variation in soil moisture and temperature variation across the sample locations and that will occur among years (**Figure 2.13**).

For the impacts of land use change on forest plant and animal populations, we will work at sites characterized by low and high exurban development impact identified with intensive sampling above (Subsection **2.5b**). There is co-variation between gradients in climate and exurban development, so we will attempt to pair sites along the exurbanization gradient with fully forested sites experiencing similar temperature and moisture regimes. As in the climate study, we will link observational studies along exurbanization gradients with experimental transplants of focal plant species to sites differently impacted by human development. Response variables for plants will be the same as for the climate gradient work, including survival, growth, flowering, seed production and recruitment; soil temperature and moisture will also be monitored. We will link observational and experimental results to understand how land use history may constrain the response of herbaceous species to climate change by either limiting propagule availability or altering resource levels. For invasive plants, we will focus on two relatively abundant shade-tolerant species (oriental bittersweet - *Celastrus orbiculatus*, and Japanese stiltgrass - *Microstegium vimineum*) and conduct observational studies along environmental gradients of climate and exurban development. Sampling for plethodontid salamanders will be co-located with that for plant populations.

The second subquestion links our biodiversity research to hydrology and ecosystem processes, to better understand, document, and anticipate how water quantity and quality are affected by land use and climate change (**Figure 2.14**). We thus include plant and animal species for which a change in abundance and/or distribution is likely to influence water quantity and quality, which extends current Coweeta research linking species identity with ecosystem processes. We will use fine-scale studies to quantify how species loss and/or gain may affect hydrologic and nutrient regimes. The proposed measurements of ecosystem processes across the exurban gradient outlined above (**2.5b**) will be used to assess the ‘aggregate’ effects of biota and their environment on ecosystem processes. We will carry out additional measurements that will serve to clarify how the aggregate effects arise from the properties of focal taxa by using plant and animal species known or likely to become important in regulating ecosystem processes in southern Appalachia. We will focus specifically on those likely to change in abundance and/or distribution due to climate change or exurbanization. Fine-scale studies within sites across the exurban and climate gradients will help us assess the 'context dependencies' associated with development and/or climate change (see Subsection **2.5e**). Here we summarize three experiments.

Understory Herbs, Pests, and Process. We will use a comparative approach to understand how exotic understory herbs (e.g. *Microstegium vimineum*) and pest/pathogen outbreaks (hemlock woolly adelgid) affect ecosystem processes. We will select comparable locations within the climate and exurbanization gradients where the exotic pests are present or absent. For example, in areas invaded and non-invaded with *M. vimineum* we will combine traditional in situ measurements of nutrient cycling with ^{15}N stable isotope tracer studies to investigate impacts on processes such as plant-microbe nitrogen partitioning. *M. vimineum* is a non-native, understory C4 grass that is rapidly increasing in southern Appalachia. Previous work has shown that it elevates soil pH and nitrate concentrations, increases nitrification rates, and promotes loss of soil carbon (Ehrenfeld et al. 2001). The markedly different quality and timing of litter input from *M. vimineum* may drive some of these effects (Levine et al. 2003), which are likely to alter not only soil nutrient cycling rates, but also dissolved nitrogen concentrations in streams. Regarding pests and pathogens, the hemlock woolly adelgid is already widely distributed across the region and our current work (Ford and Vose 2007) suggests that the decline of hemlock would increase nitrogen availability in the soil, but decrease water flux.

Species Composition, Ecophysiology and Mechanism. Comparative studies will be complemented by manipulative studies designed specifically to identify mechanisms of species impacts on ecosystem processes, and/or the impacts of projected changes in species composition across our gradients. For example, *Phytophthora ramorum* (sudden oak death) has not yet infected forest stands in southern Appalachia, but its arrival will most likely cause mortality and reduced vigor in both northern red oak (*Quercus rubra*) and rhododendron (*Rhododendron maximum*). These dominant species have low rates of transpiration and low nitrate uptake (Lovett et al. 2004), and their loss or reduced abundance and subsequent replacement with other species may decrease water flux and increase nutrient flux (decreasing water quantity and quality). To test these predictions, we will add and expand measurements to a study currently underway at Coweeta where oaks have been girdled and rhododendron has been removed to simulate the impacts of sudden oak death (R.L. Hendrick and J.M. Vose, USDA Forest Service Cooperative Agreement). We will quantify both the biotic responses and changes in decomposition, nutrient cycling and water flux in control and experimental plots.

Manipulation, Observation and System. Other manipulative studies will address how forest change may affect ecosystem processes and biota. For example, we will transplant deciduous leaf litter into terrestrial and stream habitats to measure effects of changes in forest composition on terrestrial and aquatic decomposition and nutrient cycling. Within streams we will also measure stream salamander responses to litter manipulations, extending ongoing Coweeta research into the importance of leaf litter species identity on stream fauna. Finally, we will initiate manipulative research to understand how changes in vertebrate (i.e., salamander) biodiversity may feedback on ecosystem function (**Figure 2.15**). Based on the results of comparative surveys, we will manipulate the density of specific larval salamander species in small sections of headwater streams and measure compensatory responses by other salamander and macroinvertebrate species. We will incorporate standard stoichiometric approaches to determine whether loss of particular salamander species will affect the capture, retention and export of nutrients in headwater streams.

2.5d. *Baseline Data and Temporal Reconstruction*. Guiding question: **What are the long-term (1500 years) climatic, geomorphic, and land use conditions that characterize southern Appalachia, particularly the magnitudes and frequencies of climatic and land use disturbance?**

Our baseline climatic, stream flow, water chemistry, and structural biotic measurements span more than 70 years while our social and economic data span more than 200 years. However, they incompletely explain the drivers of the southern Appalachian socio-ecological system as they fail to capture the major turning points or disturbance frequencies in the record. We will continue our **Environmental Monitoring**, but augment this baseline with **Paleoenvironmental and Forest Disturbance Reconstructions** and **Land Use Reconstructions**. This research will be critical in scaling the processes investigated in Subsections **2.5a** through **2.5c**, and informing our modeling described in Subsection **2.5e**. The work will be guided by the following set of questions:

1. How has the frequency and intensity of extreme events observable through paleochronologies varied over the past 1500 years? Is there evidence for increased variability in the contemporary record relative to the geomorphic and dendrologic records?
2. How do natural disturbance regimes compare and interact with human disturbance and land use regimes?
3. What are the specific spatial extents and intensities of human disturbance regimes, particularly development and land-use decisions, and to what extent have they been influenced by exogenous social or economic factors versus local parcelization and environmental conditions (Subsection **2.5a**)?
4. How do the effects of human disturbance regimes cascade through ecosystem processes (**2.5b** and **2.5c**), and what are the consequences on these factors, projected through models onto future landscapes (**2.5e**)?

Environmental Monitoring. We will continue to collect direct environmental measurements in the Coweeta basin and complement them with climate, atmospheric deposition, stream chemistry, and stream flow data from the regional environmental monitoring network (**Table 2.6**). Basin and regional measurements have already been used to develop the critical baseline to analyze temporal trends (e.g., Swank and Waide 1988, Swank and Vose 1997), identify driving variables (e.g., Swank and Vose 1990/91, Vose and Swank 1993), and develop and validate spatially-explicit models (e.g., Bolstad et al. 1998). The augmentation of existing, long-term instrumentation on hillslopes to catchments described above (Subsections **2.5b** and **2.5c**) will expand environmental measurements to a broader range of land uses and conditions. This will provide information on both *in situ* effects of land use on environmental variables within ecosystem patches; it will also provide information on the effects of the spatial pattern of change relative to civil infrastructure within catchments along hydrologic flowpaths. This will be critical in determining the down-gradient evolution and influence of hillslope and stream water on terrestrial and aquatic ecosystem services.

Paleoenvironmental and Forest Disturbance Reconstructions. Exurbanization and climate change are recognized as global contemporary processes, but it is nevertheless important to resolve the relative magnitude of climatic- versus human-induced changes across space and through time for southern Appalachia (**Figure 2.16**). While the stratigraphic and sedimentologic records we have established indicate major changes in fluvial sedimentation, they are poorly resolved both temporally and spatially. For example, Leigh and Webb (2006) postulated that more frequent flooding occurred during the early to middle Holocene interval of global warming while sedimentation rates during the late Holocene suggest a climate regime much like the present. Other evidence indicates several severe droughts since AD 1500 during the Little Ice Age (Cook 2000, Stahle et al. 2004). However, the resolution on this sedimentary data does not allow us to distinguish human from climatic forcing of the pulses readily evident in our biotic archives. Forest disturbance records after AD 1500 indicate the importance of small forest canopy gaps interrupted by occasional and noticeably higher disturbance peaks – some due to natural events such as hurricanes or drought and others related to human events such as logging and forest clearing for agriculture (Clinton et al. 1993, Butler 2006).

We will increase the resolution on forcing pulses over the last 1500 years through stratigraphic and sedimentologic analyses of cores and backhoe pits (Leigh and Webb 2006, Leigh 2007, Figure 2.17), luminescence and radiocarbon dating, particle size analyses, and sediment source ascription (described in Subsection **2.5b**). We will analyze stable isotope composition ($\delta^{18}O$, $\delta^{13}C$) of biogenic mineral matter (phytoliths and otoliths) preserved in dated sediment columns, and tree-ring cellulose of old growth trees (see below), which are useful techniques for identifying the dominance of tropical-type precipitation (Wurster and Patterson 2001, Roden et al. 2005, Miller et al. 2006). Finally, we will analyze stable isotope and mineral composition of a few speleothems (dripstones) from caves located on the southern edge of the Ridge and Valley Province in eastern Tennessee to reconstruct millennial changes in regional climate using established techniques (Brook et al. 1999, Wang et al. 2001, Webb and Longstaffe 2006, Webster et al. 2007, White 2007)

Understanding the patterns of and the mechanisms behind past forest disturbance provides a context for understanding contemporary forest structure, function, and responses as well as the prediction of future extreme events. Our previous research documented the disturbance histories of local to regional mixed-oak forests (Butler 2006) and found that average decadal disturbance rates (8.7% to 18.3%) were similar to rates across eastern temperate forests (5% to 20%). It also indicated the importance of localized disturbances, such as small canopy gaps in these forests (Clinton et al. 1993). Occasional and noticeably higher disturbance peaks were evident in all stands, and were likely attributable to extreme events such as widespread forest mortality (e.g., loss of the American chestnut), logging, or hurricane wind-throws. However, the uncertainty surrounding the causes of disturbance peaks is still significant. To discriminate among potential event sources, we will analyze annual tree-ring α-cellulose from old-growth trees (~300 years) for signatures of drought ($\delta^{13}C$) and hurricane events ($\delta^{18}O$) (Roden et al. 2005, Miller et al. 2006). Initially using only trees in the Coweeta basin (two sites), we will use a time series statistical approach over the last 70 years to resolve correlations between tree growth and cellulose $\delta^{13}C$ and $\delta^{18}O$ with recorded climate and extreme events. We will then extend the spatial resolution of sampling to old-growth trees in four additional sites to determine regional (e.g., hurricane, drought, insects) vs. localized (e.g., small gap formation by wind, insect defoliation) disturbance events.

Land Use Reconstruction. Our mapping across scales from small watersheds (3-20 km^2) through a broad set of southern Appalachian counties demonstrates how humans have grown to dominate disturbance regimes over the past two centuries. We propose expanding the coverage to coincide spatially with the small watersheds targeted in Subsections **2.5b** and **2.5c** in order to generate estimates of past disturbance rates, intensities, and extents that correspond to mapping epochs (**Figure 2.18**). These epochs would include early USGS surveys and maps (1900-1920s), U.S. SCS mapping (1910-1950), and TVA topographic mapping (1920s-1950s). In addition, we will backcast using developed methods from an 1880-to-present time series of commodity, agricultural, and population censuses (e.g., Bolstad and Gragson 2007), and forecast land use in model catchments. These would then serve as the basis for parameterizing the models described below (**2.5e**).

Parcel ownership is the basis for linking current ecosystem processes and services to both contemporary (Subsection **2.5a**) and historical land use, but little is known about how landscape structure reflects the historical sequence of property systems imposed over time (Thrower 1966, Price 1995, Russell 1997, Bain and Brush 2004, Jurgelski 2004). The legacy of landscape heterogeneity from an original property mosaic may dampen the expression of relative increases in landscape heterogeneity due to urbanization or simply be 'reset' by contemporary exurban development. We thus propose an analysis of parcel trajectories and land use dynamics with models based on our extensive archive of parcel boundaries, tax assessor data, land cover, and physical infrastructure for Macon and Buncombe counties.

To understand the effects of parcel morphology across the nineteenth and twentieth centuries, we will use digital parcel data to model earlier parcel matrices to later ownership patterns (cf. Tatom 2004). If the original mosaic has a strong effect on later land subdivision, we expect a tessellation through internal subdivision; if the original mosaic is not strongly constraining then parcel boundaries will be erased in mass parcel assembly. Incentives for sale and hence parcel transition may also be related to soil degradation, which we have documented from historic soil maps. If so, the highest rates of parcel assembly should coincide with the highest rates of measured soil degradation. Our parcel history and 80-year time series of land cover classification will be used to relate parcel evolution, land cover heterogeneity, deforestation, and reforestation that will then serve as the basis for parcel- and population-based projections of future land use through 2050.

2.5e. *Synthesis & Scaled Integration*. Guiding question: **How can we integrate our understanding of hydrological, ecological and human social processes into a predictive understanding of the dynamics of our key ecosystem services at the small catchment level, and scale that understanding to regional watersheds?**

Previous Coweeta LTER research focused on the patch to small catchment level. There has been significant conceptual progress in hydrologically linking hillslopes, small watersheds, and medium-sized rivers (e.g., McDonald 2003, Shaman et al. 2004, Uchida et al. 2005), but there has been much less progress in making this linkage for nutrient and organic matter dynamics (but see Wolock et al. 1997, McGlynn and McDonnel 2003). In Coweeta V, we expanded our investigations outside the Coweeta watershed to surrounding catchments with a range of land uses in the Little Tennessee watershed. Our project is now in a position to synthesize and upscale the observational and experimental process-based approach we have followed in the Coweeta Basin and surrounding areas. The principle elements of our synthesis include 1) ecohydrologic models of terrestrial water, carbon and nutrient cycling and export to aquatic systems, 2) nutrient spiraling models that describe how processing and transport occurs within streams, and 3) biodiversity models that determine how the combination of climate and land cover change will impact ecological communities. Here we describe each of these synthesis efforts, how they link to one another, and how they can aid our understanding of southern Appalachian ecosystems.

The objective of synthesis and scaled integration centers on the examination of 3-d landscape processes contributing to the provision of ecosystem services within the context of changing climate and land use. We will address cumulative impacts of development over the historic era through present conditions with coupled analysis and simulation of watersheds with areas ranging over four orders of magnitude. This work will be extended to evaluate potential cumulative impacts due to forecasted growth and climate change scenarios through mid-century. This portion of our research will be guided by the following questions:

1. How are ecosystem services (regulation of water quantity and quality) influenced by the form of hydrological connectivity through terrestrial and aquatic ecosystems?
   a. What are the space/time patterns of water, carbon, and nitrogen stores and fluxes that develop along terrestrial and aquatic flowpaths in undeveloped watersheds?
   b. How do the type and spatial arrangement of land cover and infrastructure (transportation, drainage) influence hydrologic connectivity and the storage and flux of these materials?
   c. How, and to what extent does the alteration of flowpath patterns by different landscape structures alter landscape level connectivity and export of water, sediment and nutrients from the terrestrial to the aquatic ecosystem at the small catchment scale, and resulting in retention and processing of carbon, nitrogen, and sediment through larger watersheds?
2. How does temporal variation in hydroclimate interact with the biodiversity of terrestrial and aquatic ecosystems at short to long time scales along hydrologic flowpaths?
   a. How does hydroclimate variability affect the degree and persistence of connectivity of hillslopes and drainage networks for water and nutrients?
   b. How do the space/time variability of available water and nutrients along hydrologic flowpaths interact with the biodiversity of terrestrial and aquatic communities?
3. How do ecohydrological characteristics and connectivity of catchments correlate with socioeconomic variables, such as population density, lot sizes, income levels, migrant status (i.e., long-term resident vs. recent arrival), and education?
   a. Are there scale thresholds at which these functional relationships among socioeconomic and ecological parameters change?

Modeling is used as a framework to link research in the four preceding Subsections (**2.5a** to **2.5d**) by first identifying key interactions among research components at the patch to regional watershed scales. These interactions are then represented by building dynamic feedbacks among the set of models we have developed. An integrated monitoring, experimentation and modeling approach actively adjusts and informs each component. In this section we describe these models and outline their coupling to address the questions posed above.

Ecohydrologic Modeling – RHESSys. Distributed ecohydrologic models provide the ability to derive spatiotemporal dynamics of root zone soil moisture, saturated zone levels, and various processes such as soil biogeochemical cycling, canopy evapotranspiration and carbon cycling. The spatial organization of the model is close to the conceptual and empirical design of our project as it includes a hierarchy of spatial classes (**Figure 2.19**), including the full watershed or *basin*, its component *hillslopes*, and the set of ecosystem *patches* within each *hillslope*. The model operates by explicitly nesting these classes as a spatial hierarchy and associating ecohydrological processes and stores with specific classes. A full ecosystem model operates within each patch that simulates multiple *strata* thus representing different life forms or species that compete for light, water, carbon, and nutrients budgets using a process-based equation set extended from elements of BIOME-BGC (Running and Hunt 1993), CENTURY (Parton and Schimel 1996) and other hydrologic and ecosystem models for canopy and soil processes. Each *patch* is linked as part of a lateral flowpath network within each hillslope (figure E2) using a modified version of the DHSVM routing (Wigmosta et al. 1994) or TOPMODEL (Beven and Kirkby 1979). Model process details are fully described at http://fiesta.bren.ucsb.edu/~rhessys, and in Tague and Band (2004).

RHESSys explicitly accounts for hydrologic connectivity through the flowpath system in the terrestrial and aquatic phase. The model operates at subdiurnal through decadal time scales allowing the specification of disturbance and land cover change events. The model can therefore be used to simulate long term canopy growth and aggradation, hydrologic recovery from disturbance (e.g. fire, thinning, harvest), or the impact of development with transient impacts on hydrology and drainage water biogeochemistry. A key component of the ecohydrological model is the incorporation of direct and indirect human activity of the ecosystem at the patch level as determined by our proposed parcel-level research (**2.5a**)*.* This includes impacts of land cover change in rural through suburban catchments, with representation of altered vegetation, climate, road networks, impervious area, sanitary infrastructure and direct human activity such as irrigation and fertilization (Law 2003, Law et al. 2004).

The explicit spatial hierarchy of the model allows a straightforward approach to “telescope” the simulation from detailed models of small catchment dynamics to regional watersheds (**Figure 2.20**). Aggregation allows simulating dynamics at progressively coarser resolutions such as parcels to differentiate socioecological heterogeneity or MODIS pixels to compare, calibrate or assimilate estimates of surface carbon stores and fluxes (e.g. LAI, NPP). At the finest scales, the model is designed with a grain capable of resolving the scale of our terrestrial sampling plan at the hillslope scale, as well as terrestrial/aquatic linkage at the 1st to 2nd order stream scale (**2.5b**).

Nutrient Spiraling. The RHESSys model provides the mechanism to move water and nutrients to the stream edge, while the nutrient spiraling model routes and processes the water and nutrients through the aquatic ecosystem. There are currently two models for the Little Tennessee River. Webster (2007) published a model that synthesizes our LTER-funded research of the stream gradient from the small headwater streams at Coweeta downstream to the Needmore USGS gage. This model provides a mechanistic understanding of organic processes along the river that is useful in characterizing changes in metabolic processes along the river continuum (**Figure 2.21**). As part of the LINX2 study, Mulholland et al. (n.d.) developed a simulation model of nitrate loading, transport, and biotic uptake within stream networks. This spatially explicit model routes nitrate and water from the landscape through a stream network while biological uptake removes nitrate from the water column in each stream reach based on an observed relationship between uptake velocity and nitrate concentration. When applied to the Little Tennessee River network upstream of Franklin, NC, the model demonstrated the importance of both small- and regional-sized rivers in nitrate removal (Helton 2006). According to model results, the river network removed 28% of nitrate entering the stream from the catchment with 40% occurring in 1st and 2nd order streams and 60% occurring in 3rd and 4th order streams.

Biodiversity Forecasting of Trees: Although functional-type simulations and niche models predict substantial changes in biodiversity for our region (Iverson et al. 1999, Bachelet et al. 2001), we do not expect large-scale immigrations or extinctions in southern Appalachia during the next six-year funding cycle. We will therefore use demographic analyses to derive sensitivities to climate variation among species and among sites and use these fitted relationships to explore potential impacts of change scenarios. These goals are directly linked to hypotheses for system level sensitivities and vulnerabilities expected from the interaction of land use and climate described above (**2.5a** to **2.5d**). The data assimilation/prediction framework involves a well-developed hierarchical Bayes model (**Figure 2.22**), Scalable Landscape Inference and Prediction (SLIP), developed in collaboration with computer scientists at Duke University (Govindarajan et al. 2004, Clark et al. 2007a, Govindarajan et al. 2007). Inference comes from demographic relationships to climate fitted to over a decade of observations from the Piedmont and southern Appalachia, in a range of soil and hydrologic settings. Scenarios for SLIP modeling include land cover change and climate forecasts for the region derived from the analyses of data described above (**2.5a** to **2.5d**); parameterized models of demographic responses to variation obtained in the coarse of the research described in Subsection **2.5c**; a forward simulation to move from inference to prediction; and regional climate models (e.g., Mearns et al. 2003).

SLIP carries forward uncertainty from the inference stage and from our understanding of future conditions to provide predictive distributions of demographic rates and of species assemblages that include all of the ways in which such schedules interact (**Figure 2.23**). SLIP is unique in allowing for dispersal based on observations, because standard models of spatial interactions require more computer memory and processor time than is presently available from existing hardware. SLIP solves this problem through application of data structures, algorithms, and graphics hardware to speed computation (Govindarajan et al. 2004, 2007). By simulating whole stands across landscapes, SLIP generates predictive distributions of species abundance that can be directly linked to data. These predictive distributions for scenarios of change include how climate (e.g., temperature and soil moisture) and land cover transition are mediated by competition for light. With the proposed field data and model development we will determine sensitivities of biodiversity to climate and land cover scenarios, sensitivities to variables that affect life history characteristics, and processes (e.g., habitat influences on dispersal, recruitment, growth rate) that could offset potential vulnerabilities.

The land cover change scenarios will derive from analyses in Subsection **2.5d**. Several recent studies using analytical or simulation models have examined how the creation and destruction of habitat can affect the persistence of regional populations (Keymer et al. 2000, Johst et al. 2002, DeWoody et al. 2005, Wilcox et al. 2006). The population response to both land use and climate change has not been widely investigated despite the recognition that these factors may interact in unanticipated ways (Ewers and Didham 2006). To complement SLIP studies of trees, which include spatially explicit scenarios of alternative landscape patterns and climate, we will simulate potential distributions of selected native and invasive species. Parameter estimates will come from field studies described in Subsection **2.5c**. We will give particular attention to the loss of species in cove hardwood communities, which are among the most vulnerable to exurban development (Turner et al. 2003a).

Model Linkage. The models will be used to develop and explain the dynamics of the focal ecosystem services of *provisioning* water quantity, *regulating* water quality, and *supporting* biodiversity. Linkage of the hillslope ecohydrologic model components with population and biodiversity components from SLIP will be done at the patch level through soil moisture interactions with growth, aboveground biomass, and LAI calculations, but communicated to the full hillslope by the impact of lateral water and nutrient transport. We will produce specific rooting zone soil moisture parameters (e.g., minimum summer soil moisture) as well as maximum annual strata LAI (Clark et al. 2007a). This recognizes soil water stress as a primary limitation on canopy growth and a key variable for species selection and LAI as the primary variable for light interception. These models will then simulate forest canopy structural properties (e.g., size class distributions, species composition) to update the canopy description used in RHESSys.

This coupling will allow us to explore feedbacks between short and long-term hydroclimate dynamics with forest canopy structure and composition. Explicit representation of riparian and floodplain effects as critical interfaces can be easily developed from high resolution terrain data within the RHESSys framework. The patch-scale biodiversity models interact with stream spiraling indirectly through ecohydrologic components, and directly through riparian canopy dynamics. We will implement detailed simulations of catchments along the development gradient (Subsection **2.5b**) to investigate the impacts of climate, ecological community structure, and development on the processes and connectivity governing the production of freshwater quantity and quality.

Current Ecosystem Services. Socio-ecological links at the parcel, patch, or reach level will be incorporated by specifying both land cover and infrastructure and direct additions or abstractions of water, carbon, fertilizer or wastewater (Tague and Band 2004, Band et al. 2005). Statistical expectations and variance of stormwater nutrient additions from commercial and industrial parcel-level activities will be assigned from the National Stormwater Quality Database (NSQD, Maestre and Pitt 2005) while residential parcel-level activities will be derived from our survey results (Subsection **2.5a**). Connectivity effects of development will be investigated by incorporating a full representation of land cover, road networks, and drainage infrastructure within our intensively studied small catchments and altering impervious/pervious spatial pattern and engineered flowpaths. We will use soil moisture and riparian groundwater dynamics as key diagnostic patterns to link simulations with empirical sampling (Subsection **2.5b**). Simulations will extend over 4 orders of magnitude in drainage area, using our distributed monitoring of terrestrial and aquatic variables (**2.5b**) to test increasingly larger scale model performance.

Historic Ecosystem Services. We will test and extend our models and understanding of the linkage between freshwater and biodiversity ecosystem services as a function of watershed socio-ecological conditions by incorporating distinct land cover and human populations within the historic era. We will force the linked models with decadal land use and population changes from historical reconstruction as developed in Subsection **2.5d** over the last century to generate watershed stream flow, nutrient loading, and export at monthly and annual levels. Stream discharge records are available from the USGS and USFS gages since the 1940s along with meteorological information. This work will develop transient simulations of the evolution of current conditions over the past several decades covering significant changes in land cover and human occupancy. Small catchment simulations of carbon, water and nutrients from the past 70 years of record in Coweeta catchments have been carried out, following transient recovery from clear cuts, and long term development of canopy and soil patterns. We will extend the set of small catchment simulations to larger catchments using the archival information.

Forecasting Future Ecosystem Services. Climate change scenarios are being developed by the North American Regional Climate Change Assessment Program (http://www.narccap.org) that nest mesoscale climate models within a set of coupled ocean-atmosphere GCM under specific emission scenarios. We will use these and other transient simulations of climate through mid-century along with development scenarios to estimate the future vulnerability of ecosystem services. Alternative development scenarios incorporating different approaches for managing development would address water extraction from surface water and groundwater, developed with state, county and community stakeholders. Watershed runoff and nitrogen export products for these simulations, we well as ecological community structure will also be at the monthly and annual levels to evaluate changes in expected distribution functions. These forecast simulations will build from historic and current ecosystem service simulations using land use, population and climate scenarios to evaluate vulnerability of our key ecosystem services.

2.6. Summary. We expect landscapes in southern Appalachia to change profoundly in the next five decades as the socioeconomic factors driving the dramatic exurbanization of the past three decades persist, and important climatic factors continue to change. While southern Appalachia remains a mountainous rural refuge in the Southeast, the influence of Atlanta only 120 miles southwest of the Coweeta Hydrologic Laboratory via four-lane highway is impossible to ignore. The Coweeta LTER is built on the strong tradition laid down by the Coweeta Hydrologic Laboratory of process-based hydrological and ecosystem research and the impact of human disturbances on those processes. Our proposed research for the 2008-2014 funding cycle integrates past strengths with the need to examine contemporary realities such as exurbanization, second-home development, climate change, and altered biotic communities. This presents real conceptual and practical challenges for which we have developed observational, experimental, and synthesis initiatives that incorporate both new and proven empirical and modeling approaches to integrate complex socio-ecological information for examining ecosystem services and land use decisions in scientifically and socially relevant ways.

We will focus on mountainous forest catchments and valley landscapes within watersheds ranging across four orders of magnitude using a process-based approach designed to resolve cross-scale interactions among gradients in moisture, microclimate, settlement intensity, and regulatory environment. Our explicit examination of parcel-level decision making tied to scaled integration of longitudinal variation in physical and biotic systems by co-locating study sites is both a critical and unique aspect of our proposed research. The success of our rests on the composition of research teams (**Tables 2.3**, **2.5**, **3.1**), the management of the project (**Section 3**), and the accomplishments and approach to information management (**Section 4**) that ensure that different groups of collaborating investigators can develop a comprehensive knowledge of local-to-regional systems. While there is a strong tradition of focusing only on the human impact to natural systems, our research gives equal attention to the feedback from natural to social systems in order to understand future decisions and change. We are confident that the Coweeta LTER has the potential to lead the ecological community in socio-ecological research, and expect our results will be of considerable interest to policy makers, planners, and regulators in southern Appalachia and the Piedmont Megapolitan Region.

The success of the proposed research depends on a diverse group of PhD scientists as appropriate for a project augmented to examine regional issues. Taking advantage of the retirement of several senior Coweeta LTER researchers during the current funding cycle, 14 new researchers were recruited of which five are social scientists; four additional researchers work at the interface between the social and the physical sciences. While the Coweeta LTER project has always had strong expertise in landscape ecology we now also have strong regional geographic expertise to ensure scaled integration of local empirical results. Finally, the conceptual advances achieved through cross-site collaboration over the last several years with social scientists at other LTER sites has translated into the co-teaching of a class across the LTER Network in integrative socio-ecological methods as well as other advances in outreach (**Section 5**). We are pushing the Coweeta tradition of integrating human disturbance effects on hydrology and ecosystem processes to their explanatory limits as expected by the best practices of science. It is the true collaborative relation between ecological, physical, and social scientists within the historical context and contemporary framework of Coweeta LTER research that will synergistically advance our understanding of the consequences to the southern Appalachian socio-ecological system of the interaction between changing climate and land use.

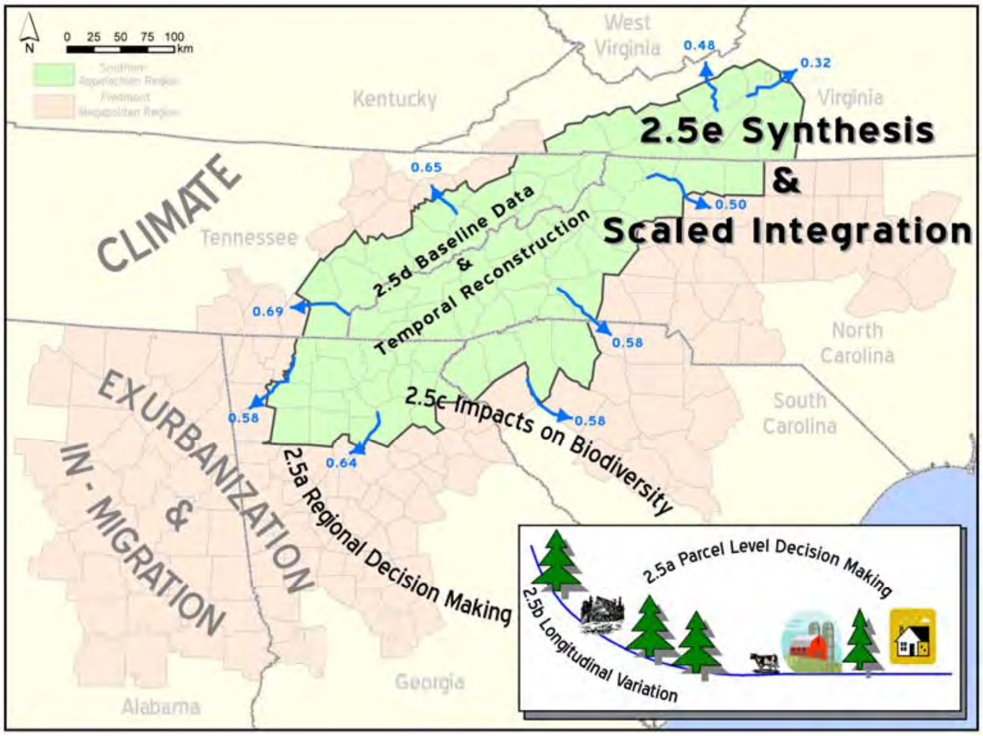

Figure 2.1. Conceptual and operational overview of the proposed Coweeta LTER project. Water outflow units are in GL/km^2/yr based on USGS real-time streamflow records, 30+ years in length (http://waterdata.usgs.gov/).

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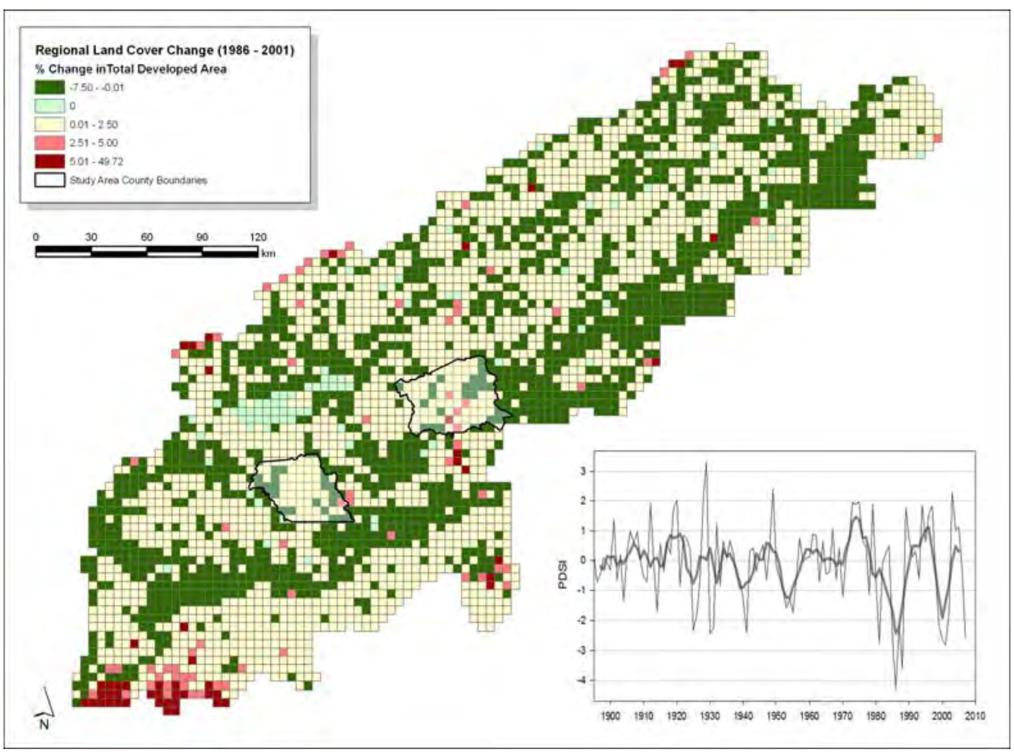


Figure 2.2. Change in percent impermeable surface, 1986 to 2001, per 20 km^2 grid cell (based on Coweeta LTER land cover classification http://coweeta.ecology.uga.edu/ecology/gis/landcover.html). Graph shows mean Palmer Drought Severity Index (PDSI), 1895 to 2007, for western North Carolina.

Table 2.1. USGS gages in the Little Tennessee and French Broad watersheds within each level of the research scale.

watershed drainage area > ~10^3 km^2	**watershed drainage area > ~10^2 km^2**	**watershed drainage area > ~10^1 km^2**	**watershed drainage area > ~10^0 km^2**	**record length**
French Broad at Asheville				1895 to present
	Swannanoa at Biltmore			1925 to present
		Swannanoa at Swannanoa		1925 to present
			Bee Creek	198x to present
Little Tenn. at Needmore				1944 to present
	Cartoogechaye Creek			1961 to present
	Little Tenn. at Prentiss			1941 to present
		Cullasaja below Highlands		2001 to present
		Coweeta 8 and 9 watersheds		1934 to present
			Coweeta catchments	~1934 to present

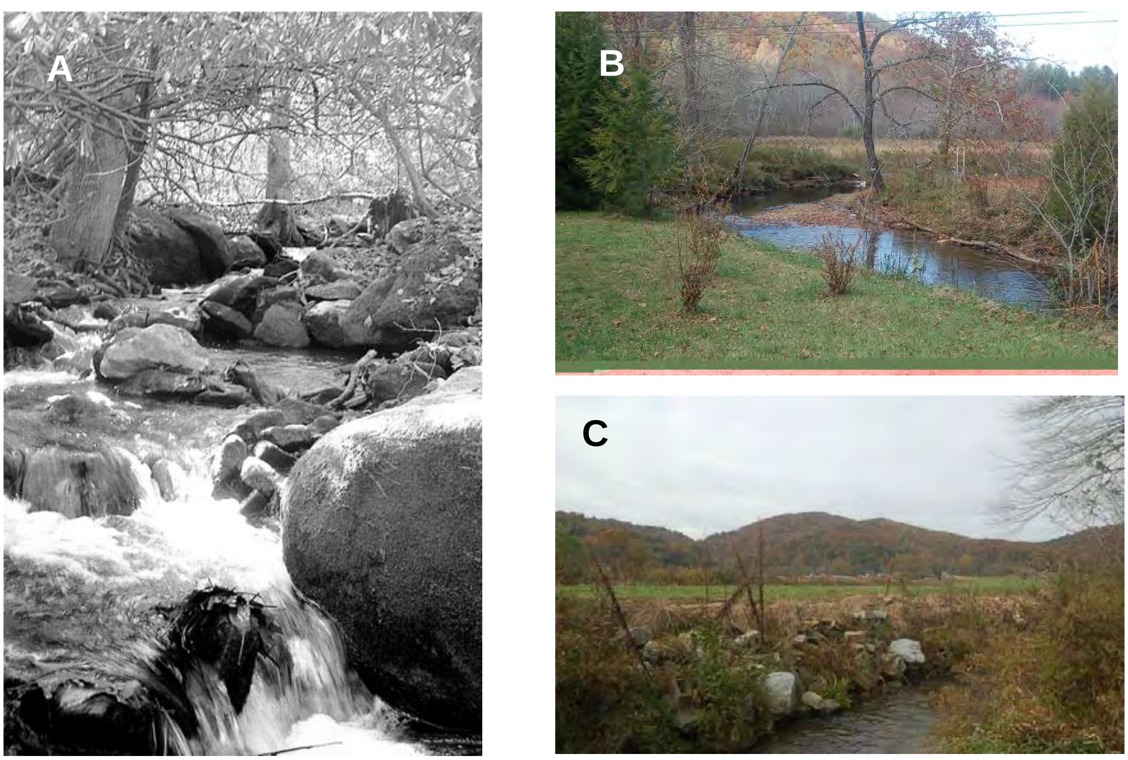


Figure 2.3. Ball Creek (**A**), undeveloped mountainous catchment at Coweeta Hydrologic Laboratory (photo by John Kominosky); agricultural land use (**B**) and stream bank alterations (**C**) along Coweeta Creek (photos by Rhett Jackson).

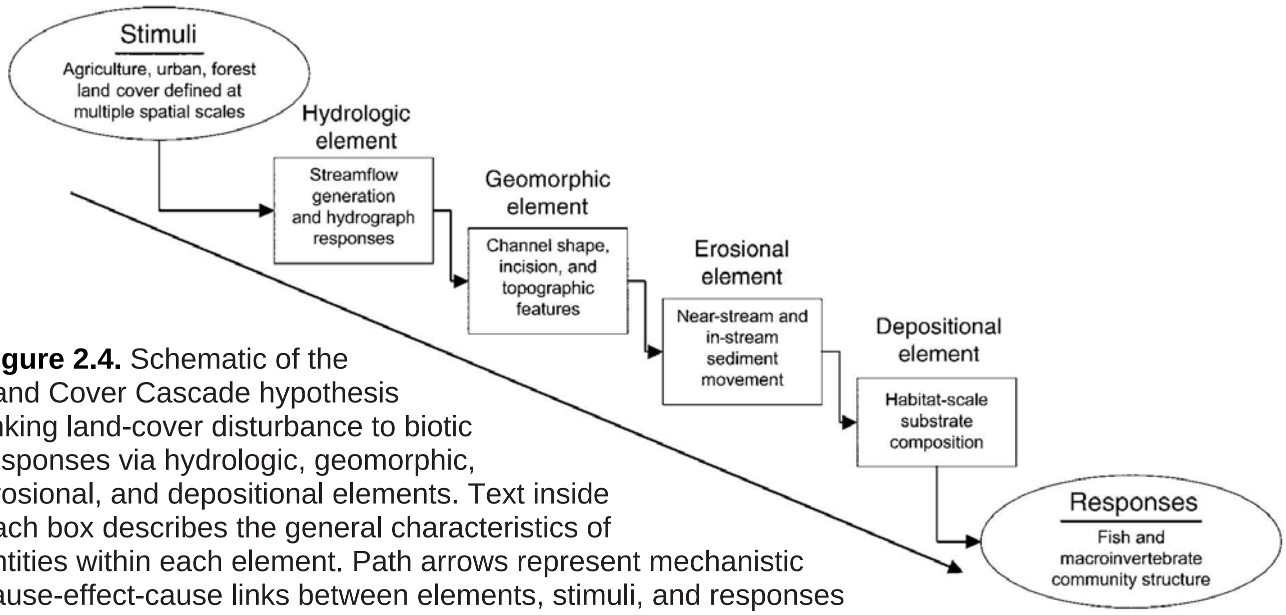


Figure 2.4. Schematic of the Land Cover Cascade hypothesis linking land-cover disturbance to biotic responses via hydrologic, geomorphic, erosional, and depositional elements. Text inside each box describes the general characteristics of entities within each element. Path arrows represent mechanistic cause-effect-cause links between elements, stimuli, and responses (Burcher et al. 2007).

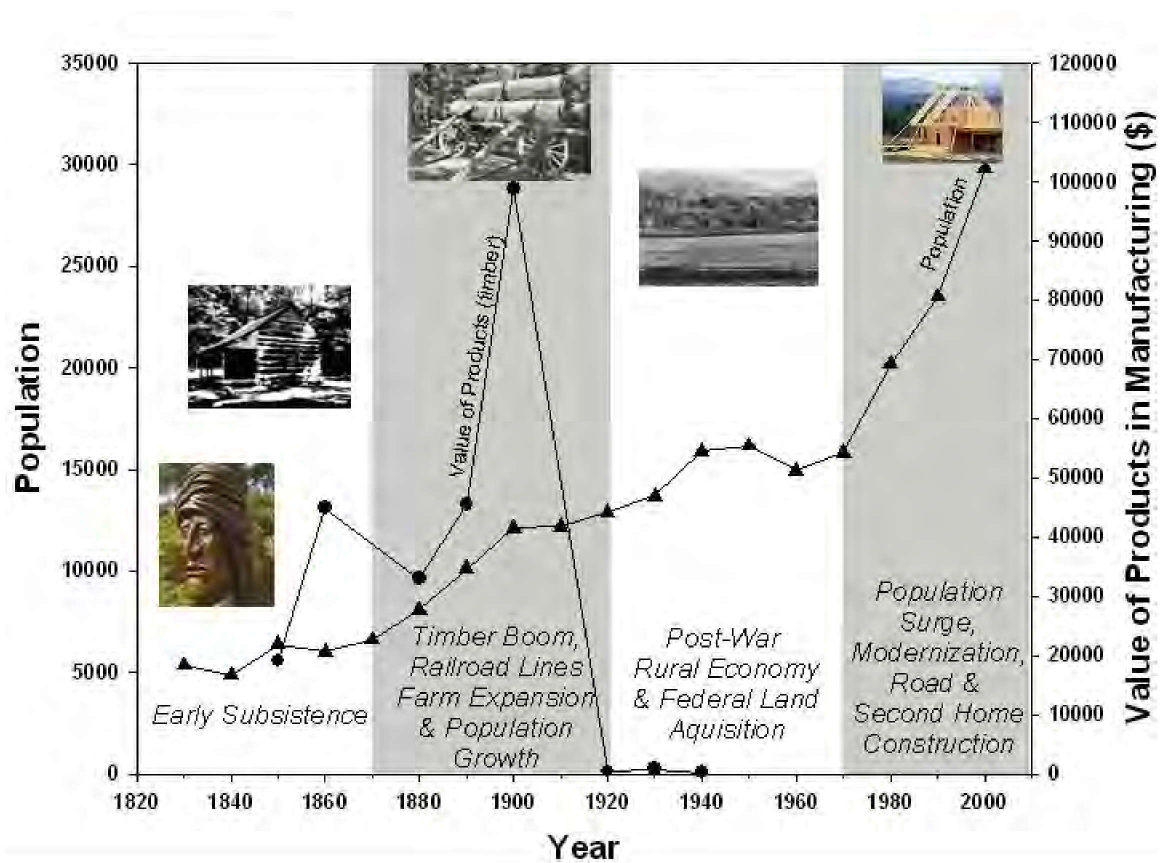


Figure 2.5. Historical timeline of human population and economic development in western North Carolina (Macon County).

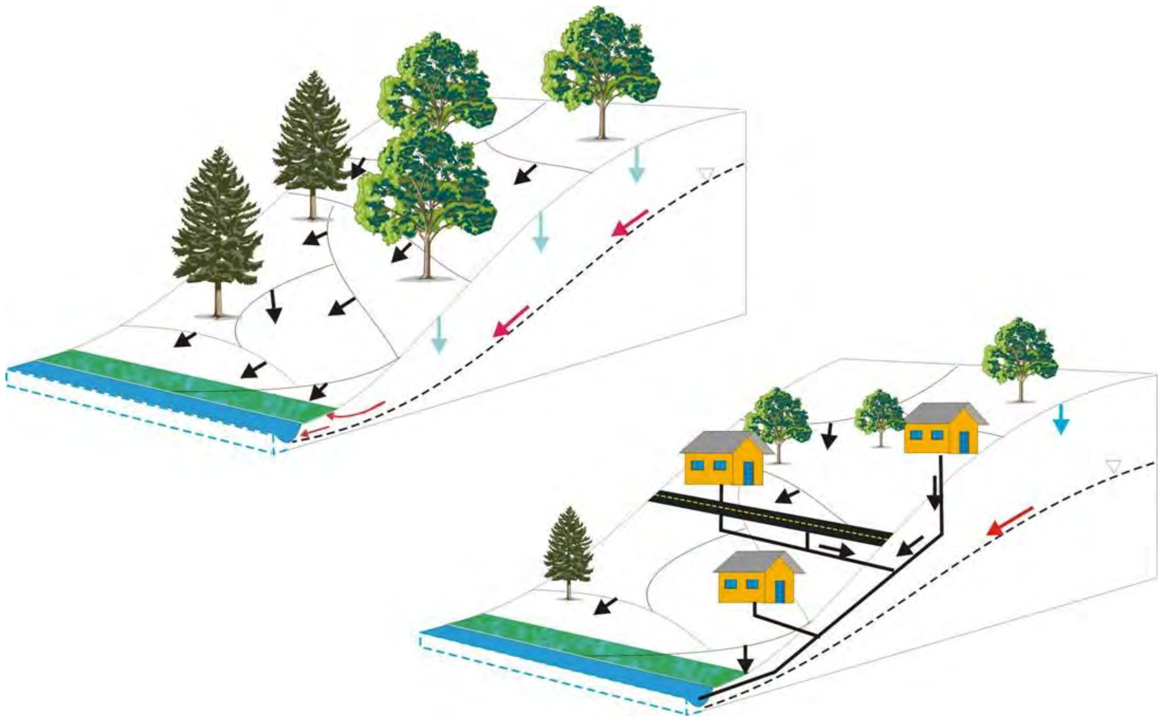


Figure 2.6. Hillslope ecohydrologic system showing a network of ecosystem patches connected through natural and engineered flowpaths. Note the riparian patches (base of hill) that are maintained by recharge from above (Tague et al. 2005)

Provisioning Services:
- *Fresh water quantity*
- *Fiber and fuel*
- *Genetic resources*

Regulating Services:
- *Water regulation*
- *Erosion regulation*
- *Water quality and waste treatment*
- *Natural hazard regulation*
- *Climate regulation / carbon storage*

Cultural Services:
- *Aesthetic values*
- *Cultural knowledge*
- *Recreation and ecotourism*

Supporting Services:
- *Soil formation and retention*
- *Nutrient cycling*
- *Water cycling*
- *Preserving biodiversity / habitat*

Figure 2.7. “Classic” (photo) southern Appalachian development consisting of forested headwaters with a mix of agriculture and suburban land use in the valley, and the beginnings of “modern” development on the far right. Ecosystem services (table) identified as significant in southern Appalachia.

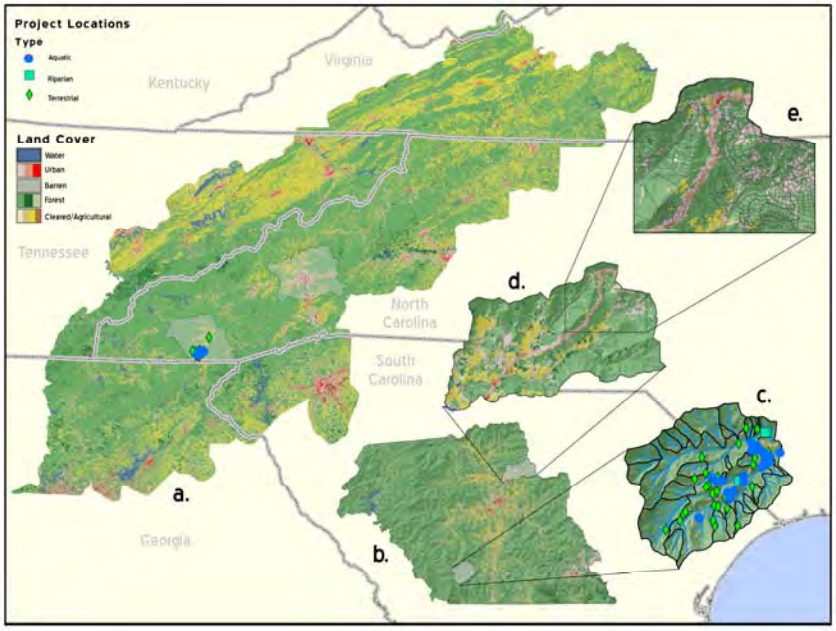


Figure 2.8. Land cover change across multiple spatial scales in the Coweeta study area: a) southern Appalachian region (73 counties); b) individual counties (e.g., Macon); c) experimental watersheds (Coweeta Hydrologic Laboratory); d) urban areas and communities (e.g., U.S. highway 441 corridor); and, e) land ownership parcels (e.g., Deer Run/Wautaga Vista area).

Table 2.2. Sample of available land use data sets organized into 3 spatial scales.

1) Watershed level, ~1,500 ha in size (Macon County, NC)
Land cover: digitized from high resolution aerial photographs as lattice of points equivalent to 25m cells and classified simultaneously to ensure logical temporal consistency into 7 classes. Dates of photos for Skeenah Creek: 1942, 1954, 1963, 1967, 1976, 1984, 1988, 1993, 1998, 2003, 2006.
Building point locations: digitized from 1907 (USGS topo), 1929 (soil survey), and dates of land cover photos
Road locations: digitized from 1907, 1929, and dates of land cover photos
2) County level, 136,000 ha (Macon County, NC)
Land cover: 1904 forest/non-forest classification, 1 acre vector land cover classification for 1954 and 2003 into 14 classes, and 1 ha resolution generalized land cover for 1954, 1993, and 2003 classified into 7 classes
Building point locations: digitized from 1907, 1929, 1954, 1993, and 2003 maps and photos
Road locations: pre-imagery years: 1865, 1886, 1892, 1907, 1929, 1936; imagery interpreted years - 1954, 2003; NCDOT years: 1993, 1998, and 2005
3) Region level, "Mountains of North Carolina" FIA unit (21 counties)
TM/ETM derived land use from 1986, 1991, 1996, and 2001; MSS forest/non-forest classification from mid 1970s; decadal population data since 1850, and forecasted to 2030 from census bureau; census block group housing unit estimates since 1950; agricultural census area estimates for each decade from 1850-1950, and ~5 year periods from 1954-2002; 1930s census at Minor Civil Division level rather than county aggregate; county forest area estimates from USFS reports and FIA: 1911, 1938, 1955, 1964, 1974, 1984, 1990, 2002; roads from 1994 (SAMAB) and 2006 (NCDOT), highways from 1924.
Ancillary data: Terrain Features (elevation, aspect, slope, shape index, curvature); Infrastructure Features (distance from roads, distance from highways, distance from towns, distance from markets, building density, road density, public/private ownership); Soil/water Features (distance from streams, distance from rivers, soil water availability, soil drainage class).

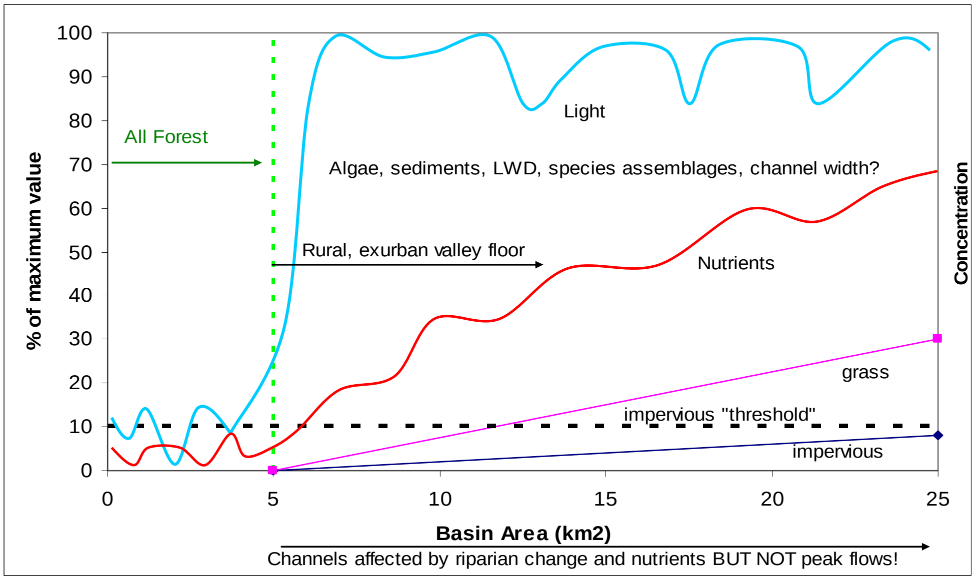


Figure 2.9. Examining riparian forest removal and nutrient additions across basins of different area in southern Appalachia provides the opportunity to separate stressors from the hydrologic changes associated with exurbanization.

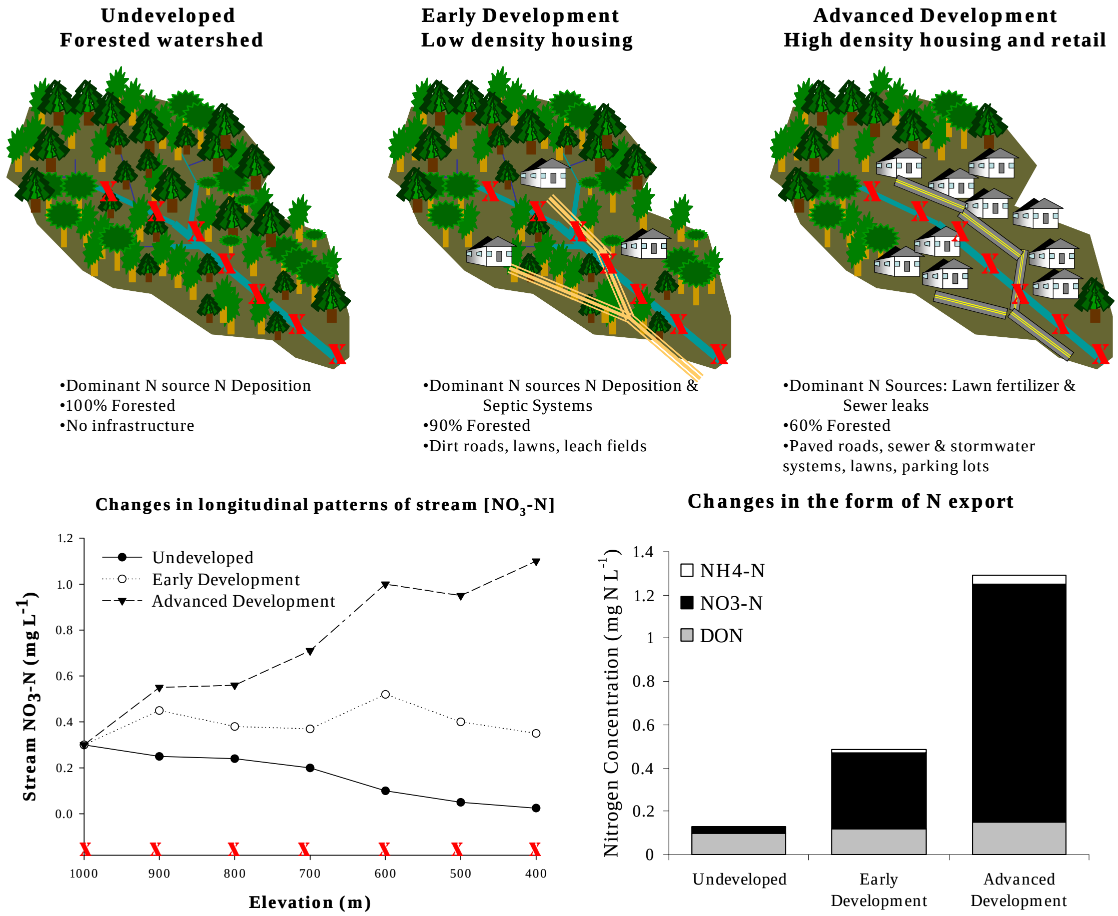


Figure 2.10. Down-gradient sampling of reach flow and chemistry characterizing a geomorphic sequence within different development patterns.

Table 2.3. Metrics and an approaches to the proposed riparian, hillslope and stream research described in Subsection **2.5b.**[1]

Type	Class	Variables	#Sites	Frequency	Investigator
		Riparian & Stream Subsystems			
synoptic	geologic / hydrologic	channel width, slope, cross-sectional area, particle size distribution, discharge	50	1 time	Jackson, Leigh
synoptic	physical / chemical	DOC, TP, SRP, NO_3^-, NH_4^+, DON, TN, turbidity, DO, water temperature	50	2 times	Bernhardt, Valett, Webster
synoptic	biological	large wood, canopy cover	50	once	Jackson, Leigh
intensive	geologic / hydrologic	stage-discharge turbidity	12	continuous	Jackson, Leigh
intensive	physical / chemical	POM, DOC, TP, SRP, NO_3^-, NH_4^+, DON, TN, TSS, DO, water temperature	12	continuous or bi-weekly composite	Valett, Bernhardt, Webster, Knoepp, Ford
intensive	biological	riparian litterfall	12	1 year	Benfield, Webster
intensive	biological	N uptake	12	4/year for 1 year	Valett, Bernhardt, Webster
intensive	biological	amphibians	9	once	Maerz
intensive	biological	algal standing crop (chl)	9	twice/year, one year	Pringle
		Hillslope Subsystem			
synoptic	hydrologic	Soil moisture patterns – portable TDR	6	bi-monthly	Band
intensive	hydrologic	automated TDR	6	hourly	Band, Knoepp
intensive	geologic/ hydrologic	riparian wells	6	hourly	Band, Valett, Bernhardt
intensive	soils	profile morphology – mineral and forest floor (O horizons)	12	1 time	Knoepp
intensive	soils	soil C and N, forest floor C and N	12	1 time	Knoepp
intensive	soils	soil solution and well chemistry - (NO_3, NH_4, PO_4, TP, SO_4, Ca, Mg, K, Na, DOC, DON)	12	1 month ea. Season	Knoepp
intensive	biological	hillslope to stream vegetation transects (trees, shrubs, herbs; native and invasive plants)	12	Overstory: 1 time; herbaceous: 3 times/year	Elliott

[1] This research is coordinated and the field activities are co-located with the research profiled in Table **2.5**.

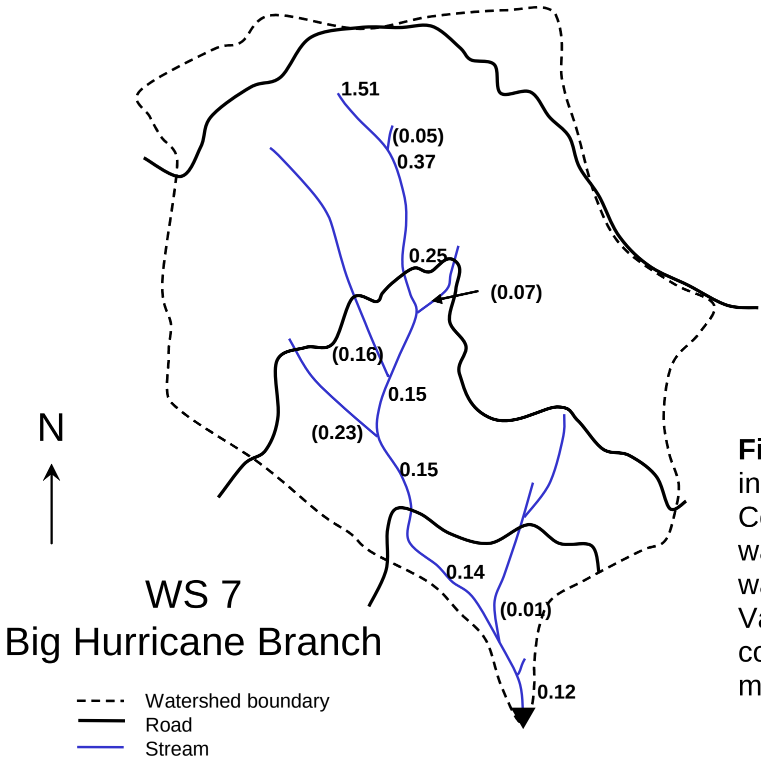


Figure 2.11. NO_3-N concentrations (mg/L) in Big Hurricane Branch, watershed 7, Coweeta Hydrologic Laboratory. This watershed was clearcut-logged in 1976; water samples were collected in 1999. Values in parentheses are tributary concentrations; other values are from mainstream samples (Webster unpubl.).

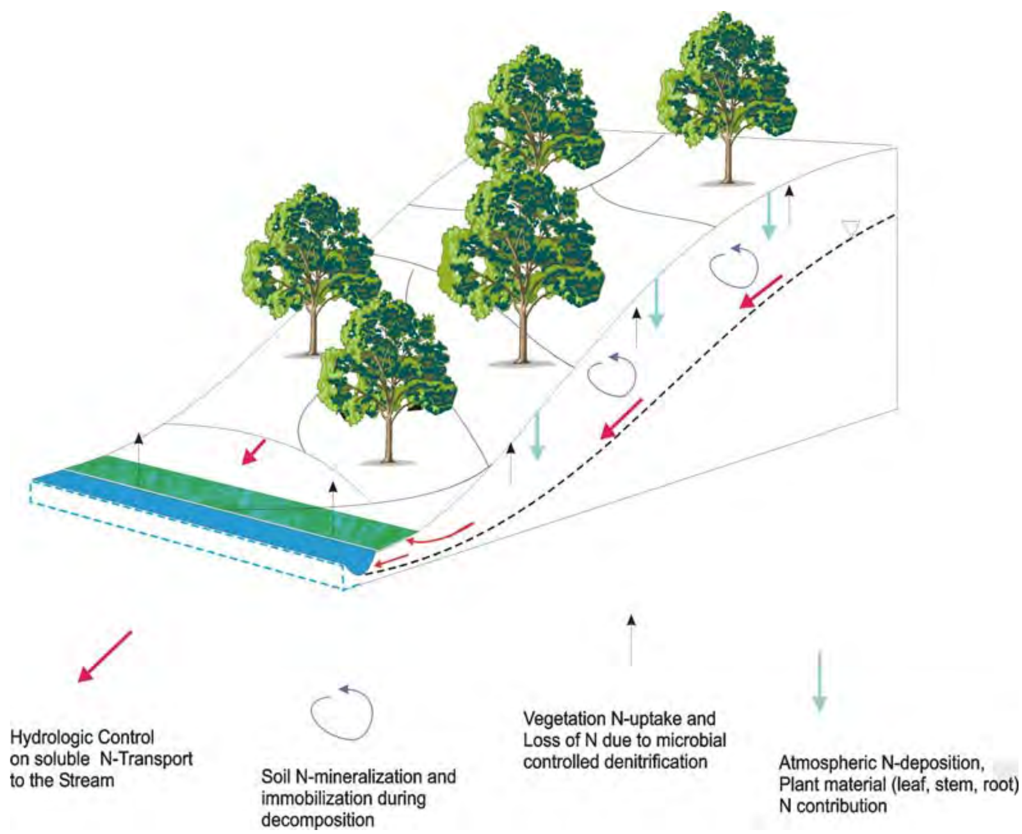


Figure 2.12. Ecosystem patches embedded within a hillslope hydrologic flowpath network, form characteristic spatial patterns and dynamics of soil moisture and ecosystem processes, with residual drainage contributing to a stream reach. Roads, pipes, and curbs reroute the flowpath network, altering the distribution of unsaturated and saturated zone moisture and ecosystem processes (Tague et al. 2005).

Table 2.4. Predicted consequences of climate and land-use change for biodiversity at local and regional scales.

LOCAL		REGIONAL
climate change toward increased aridity		
terrestrial habitats	dry sites: loss of species that are close to moisture/drought tolerance threshold.	upslope migration of species; loss of some high elevation species.
	wet sites: reduced in area around margins.	species from lower elevations and lower latitudes favored by longer growing seasons.
	increase in soil temperature rates of C & N cycling.	altered regional nutrient budgets.
stream habitats	habitat abundances reduced by low base flows.	headwater streams will contract and intermittent flows will become more so.
	sediment load, DOC, and nutrient export increased by high discharge events in spring and winter.	shifts in distribution and abundance of fishes caused by headwater contraction, low base flow, and rising stream temperatures.
exurbanization and increased land use intensity		
greater abundance of disturbed soils and loss of riparian vegetation.		increased sediment and nutrient loading in streams with negative effects on stream biota.
flashy stream flows caused by expansion of hard surfaces.		greater variance in stream flows.
species turnover due to disturbance and arrival of invasive species.		accelerated spread of invasive species.
local extinctions and reduced migration among suitable sites for forest species with limited dispersal resulting from reduction in forest patch size and increase in edge.		shifts in relative abundance of species due to habitat fragmentation. Region-wide distributions become more patchy.
impacts of pesticides, control of invasives on non-target species.		differential manage. regimes for exurban and rural landscapes.
interactions between climate and land use change - local and regional responses		
increased invasion potential by exotics in developed areas; drought stress will make natives less able to resist exotic invasion.		
invasive species will accelerate soil N and C cycling if exotics produce litter with higher N concentrations.		
homogenization of biological diversity in terrestrial and aquatic systems.		
greater drought impacts with increased demand on water resources; more humans produce greater demand on a variable supply.		

Table 2.5. Response variables and approaches for proposed research described in Subsection **2.5c**.[1]

RESPONSE VARIABLE(S)	APPROACH	INVESTIGATOR
Q.1: Climate change and exurban development impacts on taxa		
climate impacts on canopy tree growth and survivorship	annual or semi-annual censuses of naturally-recruited individuals	Clark
climate impacts on tree growth	annual tree ring samples of trees	Mohan
climate impacts on tree fecundity	semi-annual censuses of tree seed production using traps	Clark, Mohan
climate impacts on germination, abundance, demography and phenology	3X yearly censuses of naturally-recruited individuals and experimentally-planted individuals	Clark, Turner, Fraterrigo
climate and exurban impacts on invasive understory herb abundance and distribution	broadscale sampling across exurban and topographic; germination studies, 2008-2010	Turner, Fraterrigo, Pearson, Elliott
climate impacts on native forest herbs phenology, growth, survival, reproduction	experimental plantings across elevational and topographic gradients, 2010-2014	Clark, Turner, Pearson
exurban and climate impacts on salamanders	sampling across exurban and climate gradients, 2009-2011	Maerz, Pearson
Q.2: Nonrandom species gains/losses and ecosystem processes		
changing tree recruitment and demographics effects on forest composition	3X yearly censuses of naturally-recruited individuals and experimentally-planted individuals to parameterize growth models	Clark
changing tree abundance effects on stream salamanders	added leaf packs; samples of in-stream leaf packs, 2009-2011	Pringle, Maerz
declines in riparian salamander abundance on in stream nutrient capture and export	manipulate presence of salamander species impacted by exurban development or climate change.	Maerz
changing tree recruitment and demographics effects on forest productivity	3X yearly censuses of naturally-recruited individuals and experimentally-planted individuals to parameterize growth models	Mohan
changing tree species abundance impacts on litter decomposition and nutrient release / retention	transplants of litters from dominant species across elevation and topographic gradients	Bradford
Microstegium vimineum impacts on nitrogen cycling and partitioning between soils and plants	^{15}N pulse-chase experiments in *Microstegium vimineum* invaded and non-invaded forests across exurban and elevational gradients, 2010-2012	Fraterrigo, Bradford
disease effects on nitrogen cycling, soil respiration rates and litter decomposition	simulated disease outbreaks (e.g., tree girdling) using replicated, experimental plots, 2009-2014	Vose, Bradford, Fraterrigo
climate and changing species abundance effects on tree and forest water use	sapflow of individuals and stands in Coweeta Basin for girdled and control trees, 2009-2014	Ford, Vose

[1] This research is coordinated and the field activities are co-located with the research profiled in Table **2.3**.

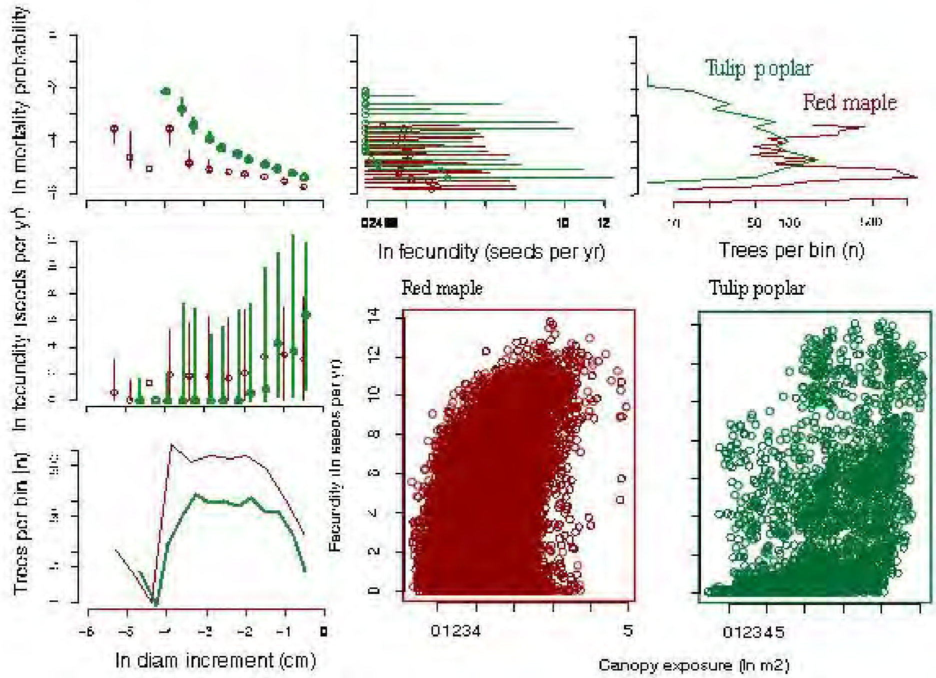
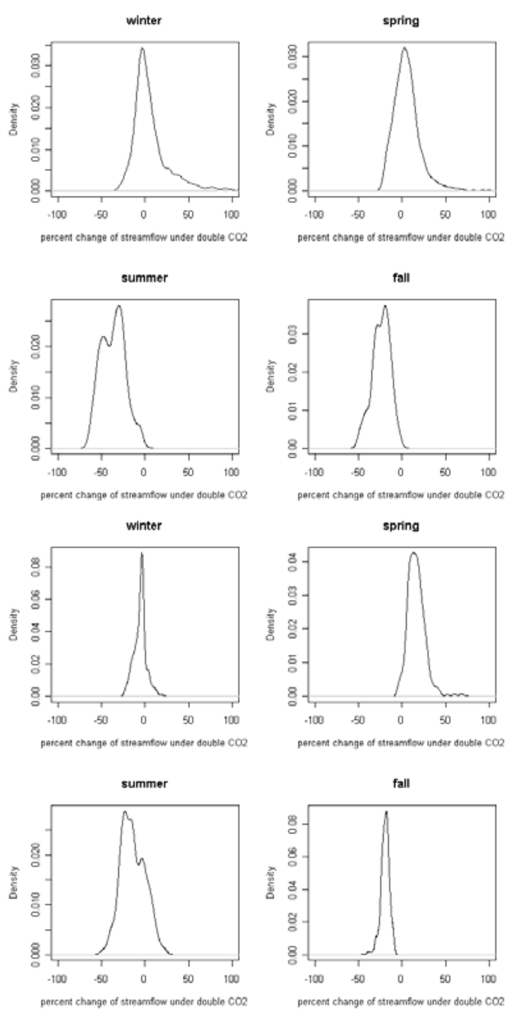


Figure 2.13. Interactions among red maple and tulip poplar life history schedules (Clark et al. 2007a).



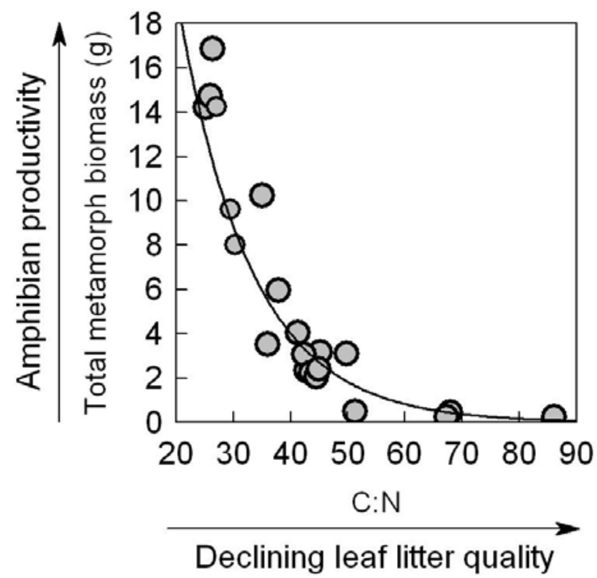


Figure 2.15. Relationship between leaf litter quality and amphibian metamorph biomass production from experimental communities (from Maerz and Blossey, unpubl.).

Figure 2.14. Predicted percent change of streamflow over time under a doubling CO_2 scenario at different seasons at low (upper four) and high (lower four) elevations (Clark unpubl.).

Table 2.6. Long-term Coweeta LTER environmental monitoring network.

(a) Coweeta Hydrologic Laboratory				
Data Description	**Record Length**	**Loca-tions**	**Elevational Range (m)**	**Data Source**
air temperature	1934 to present	12	695 to 1389	LTER/USFS
air relative humidity	1936 to present	12	610 to 1417	LTER/USFS
solar radiation	1965 to present	2	610 to 695	USFS
intercepted PAR	2001 to present	2	823 to 1402	LTER
vapor pressure	1983 to present	6	610 to 1417	USFS
barometric pressure	1934 to present	6	610 to 1417	USFS
wind speed and direction	1936 to present	6	610 to 1417	USFS
precipitation	1934 to present	10	695 to 1417	USFS
atmospheric chemistry	1972 to present	9	695 to 1417	USFS
stream flow	1934 to present	16	702 to 1021	USFS
stream chemistry	1972 to present	16	702 to 1021	USFS
soil moisture	1992 to present	9	788 to 1389	LTER
soil temperature	1978 to present	11	695 to 1417	LTER/USFS
soil solution chemistry	1991 to present	5	695 to 1389	USFS

LTER = Long-Term Ecological Research, USFS = United States Forest Service,
PAR = photosynthetically active radiation

(b) LTER regionalization study area				
Data Description	**Record Length**	**Loca-tions**	**Elevational Range (m)**	**Data Source**
air temperature	1931 to 2004	123	6 to 1902	NCDC/NOAA
monthly wind movement	1931 to 2004	123	6 to 1902	NCDC/NOAA
evaporation pan water	1931 to 2004	123	6 to 1902	NCDC/NOAA
precipitation	1931 to 2004	123	6 to 1902	NCDC/NOAA
stream flow (see below)	1897 to present	5	256 to 749	USGS
Prentiss	1944 to present	1	612	USGS
Logan	1998 to present	1	256	USGS
Bryson	1897 to present	1	523	USGS
Needmore	1998 to present	1	537	USGS
Cataloochee	1934 to present	1	749	USGS

NCDC = National Climatic Data Center, NOAA = National Oceanic and Atmospheric Administration,
USGS = United States Geologic Surve

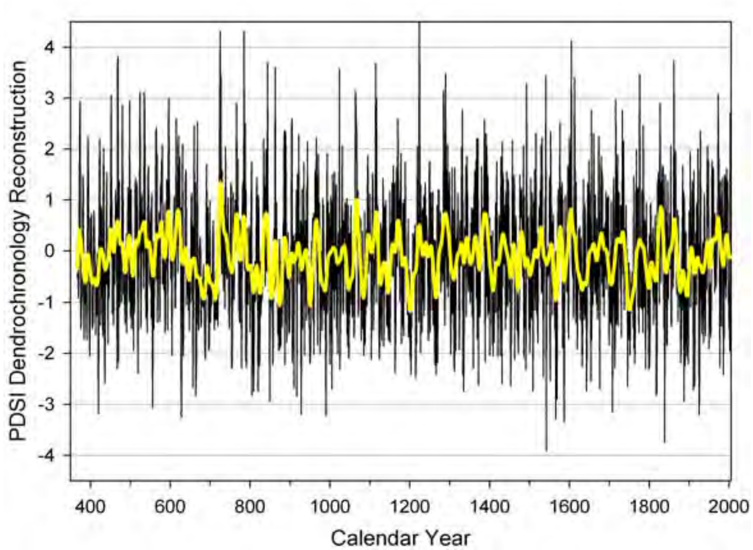
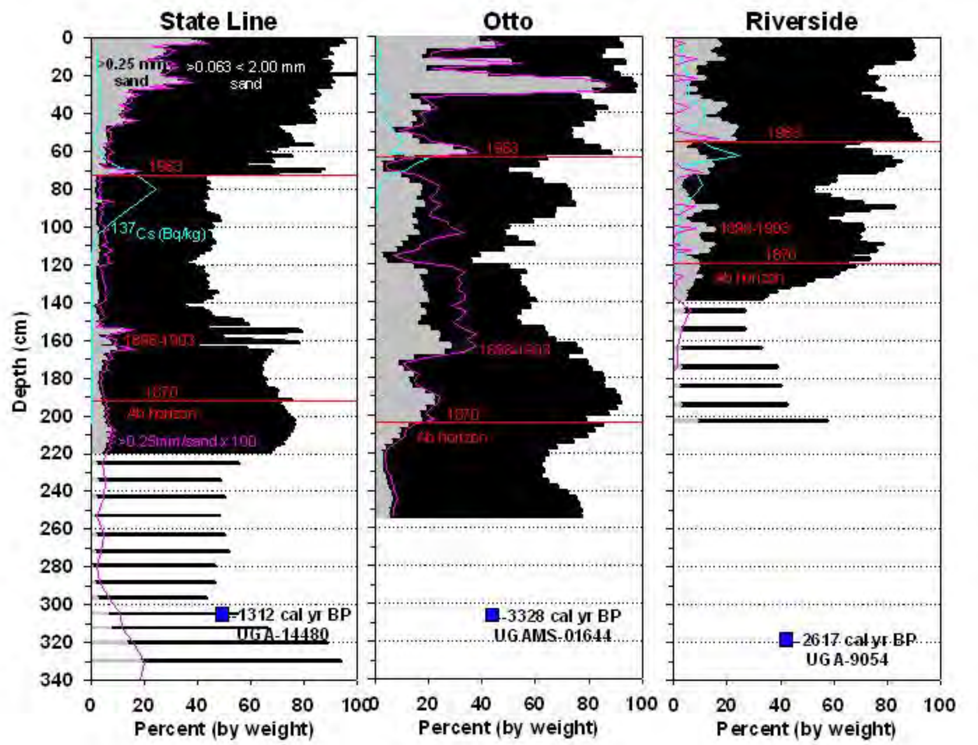


Figure 2.16. Composite long-term paleo-record of variations in surface moisture, Palmer Drought Severity Index (PDSI), in the southern Blue Ridge from dendrochronology records (NCDC grid cell 238 centered at 35 degrees north and 82.5 degrees west; Cook, E.R., 2000). The yellow line is a 20-year low-pass filter. The maximum and minimum values (black lines) indicate that A.D. 1000-1500 had no severe droughts (<PDSI of -3), whereas preceding time (A.D. 400-1000) and later times (A.D. 1500-1950) had several severe droughts.



Study Site	Time Range of pre 1870 Record	Sedimentation Rate (mm/year)			
		pre 1870	1870-1920	1920-1970	1970-2005
State Line	612 BC to AD 1870	1.0	11.6	14.5	17.3
Otto	1323 BC to AD 1870	0.3	13.4	16.2	16.0
Riverside	693 BC to AD 1870	0.8	6.8	8.4	12.9
AVERAGE		0.7	10.6	13.0	15.4

Figure 2.17. Cesium-137 and sand-fraction stratigraphy (percent sand fractions by weight)at three locations within the Upper Little Tennessee River Basin (Leigh 2007).

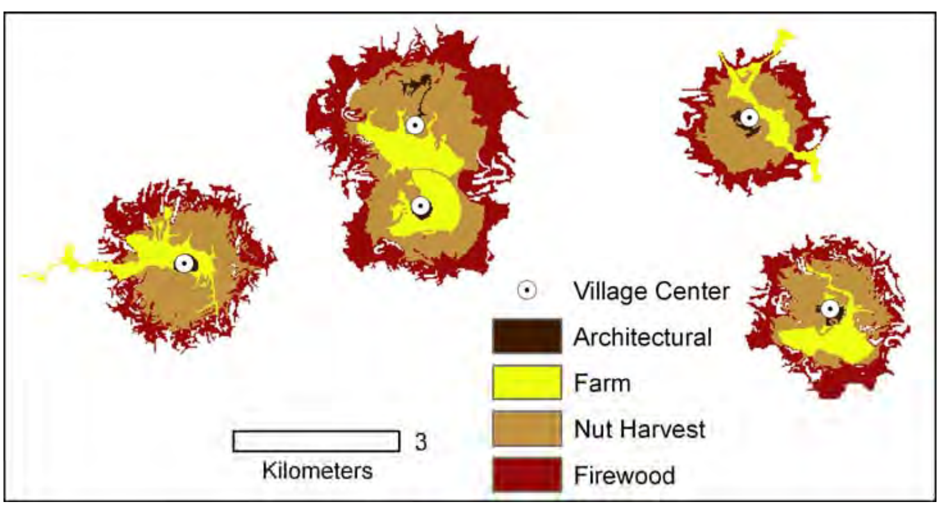


Figure 2.18. Land required for architecture, agriculture, firewood, and mast harvest by a group of Cherokee villages in 1721. This allocation is under the "best" assumptions for per capita with architectural and agricultural requirements assigned first in order and exclusive of other uses; firewood and mast harvest could be coincident on the remaining land (Bolstad & Gragson 2007).

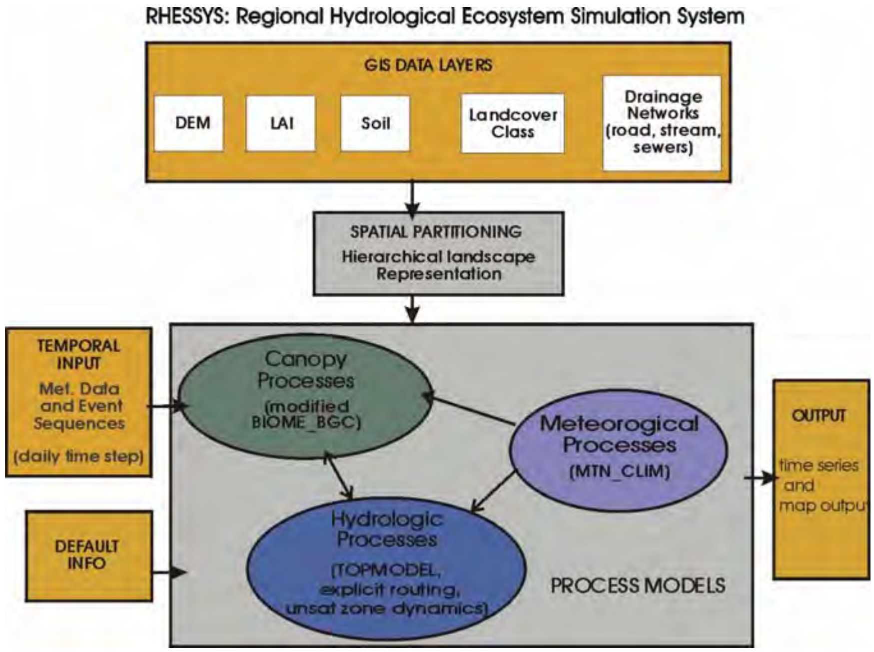


Figure 2.19. RHESSys interface between GIS representation of the landscape with a hierarchical watershed representation and system dynamics. Output and input are directly linked into the GIS, allowing visualization and animation of system dynamics. A Python based scripting capability facilitates wrapping and coupling of the model with other applications.

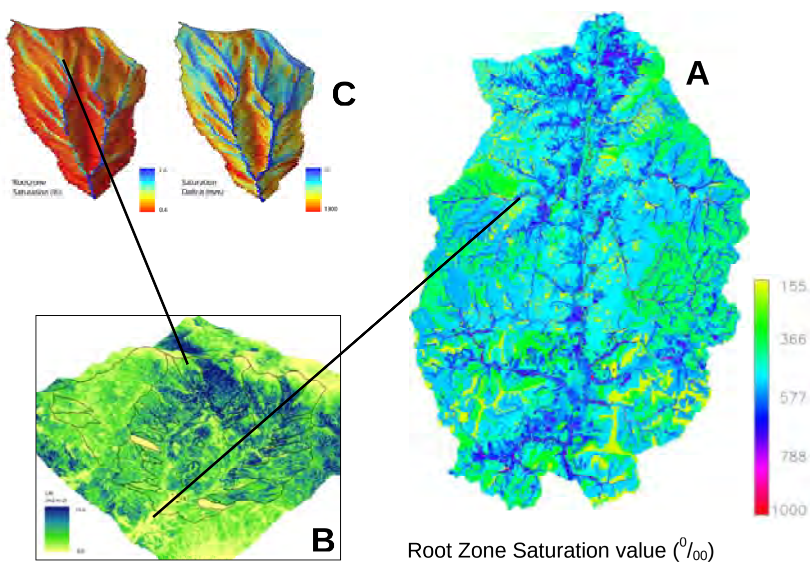


Figure 2.20. Spatial telescoping of watershed process and storage dynamics between a) the 363 km^2 Little Tennessee watershed (above Prentiss), b) the Coweeta watershed (20 km^2), and c) Coweeta Watershed #27 (< 1 km^2). The simulations range over 3 orders of magnitude of area, and include varying numbers and resolutions of the hierarchy of basin, hillslopes and patches in developed and undeveloped landscapes as shown in figures 2.6. and 2.12.

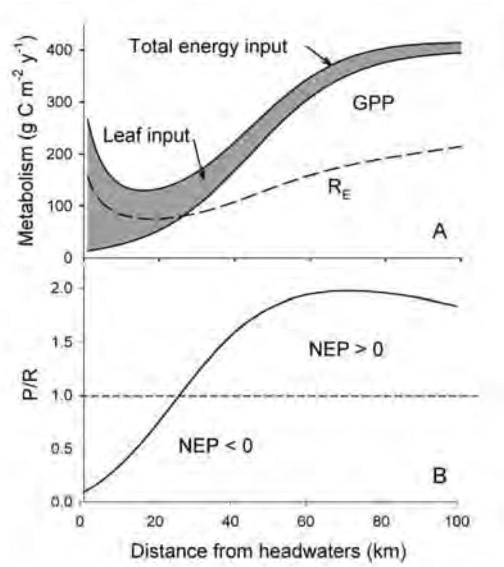


Figure 2.21. A) Simulated metabolism in the Little Tennessee River based on total energy input, gross primary production (GPP), leaf input, and ecosystem respiration (R_E). B) Ratio of production (P) to respiration (R) corresponding to the simulated metabolism results (Webster 2007).

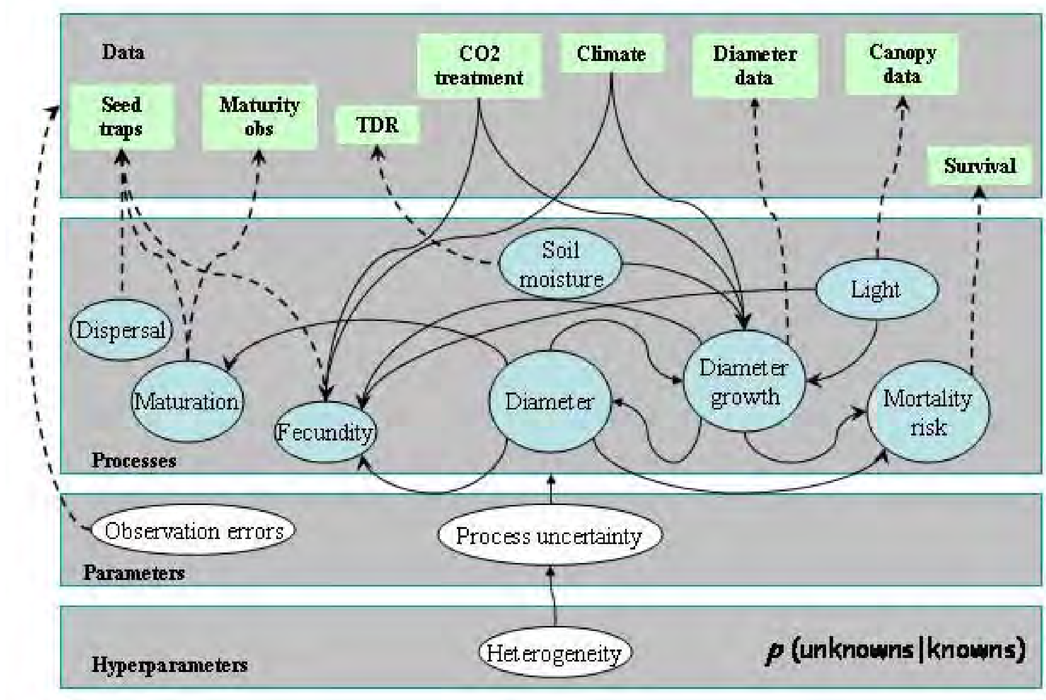
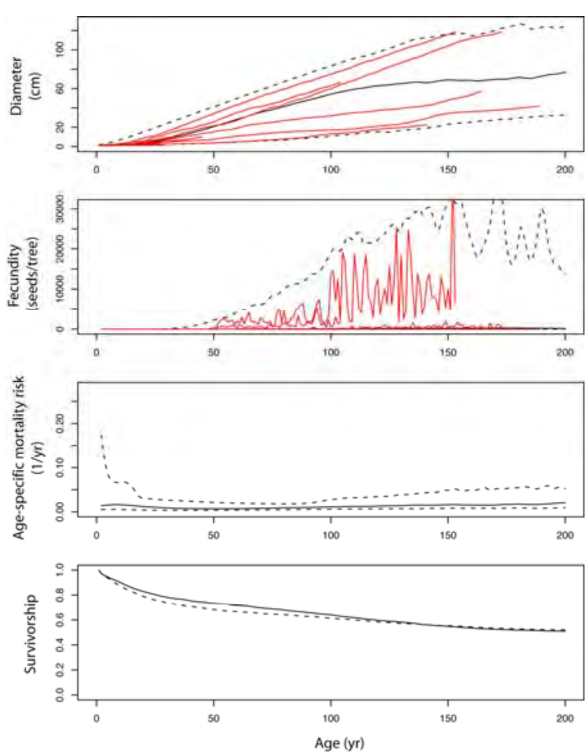


Figure 2.22. Hierarchical Bayes model denoting linkages between data, processes, parameters, and hyperparameters (Clark et al. 2007b).



$p(\theta|\mathbf{X},\mathbf{y},M)$--and in the scenario $p(\mathbf{X}^*)$,

$$p(\mathbf{y}^*|\mathbf{X},\mathbf{y},\{\mathbf{X}^*\}) = \int\int p(\mathbf{y}^*|\mathbf{X}^*,M,\theta)\,p(\theta|\mathbf{X},\mathbf{y},M)\,p(\mathbf{X}^*)\,d\theta\, d\mathbf{X}^*$$

Figure 2.23. Predictive distributions of life history schedules for *Liriodendron tulipifera* based on equation 1 above. Solid lines are predictive means, dashed lines are 90% predictive intervals. Upper two panels display 30 example predictions in red for diameter and fecundity (based on Clark et al. 2007b).

SECTION 3. PROJECT MANAGEMENT

3.1. Composition and Governance. The organization of the CWT LTER consists of a Lead Principal Investigator (T. Gragson, LPI), the Science Advisory Committee (SAC), Project Principal Investigators (PPI), and Affiliated Investigators. This organization has proven effective over time in governing the overall direction of the project, determining resource allocation and acquisition, managing day-to-day operations, and building relations with other LTER sites, federal agencies, and other entities. T. Gragson, who first served as LPI with the 2002 renewal, will again serve in this capacity during 2008-2014. He has final responsibility to NSF for the overall design and implementation of the research program and to the University of Georgia (UGA) for project management and administration. J. Vose is the USDA-FS Project Leader at the Coweeta Hydrologic Laboratory (a USDA Forest Service Experimental Forest with a staff of 5 scientists and 12 professional, technical, and administrative support personnel) and lead Forest Service scientist on the Coweeta LTER. Gragson and Vose consult frequently to align and leverage LTER and Forest Service research activities and coordinate use of shared-use facilities.

Governance of the CWT LTER is vested in the 8-person SAC. Members are selected to represent the disciplinary and institutional breadth of the program, their proven scientific expertise, and their ability to make decisions in the best interest of the project. The committee includes: Lawrence Band (U of North Carolina), Paul Bolstad (U of Minnesota), Jim Clark (Duke U), Ted Gragson (U of Georgia), Brian Kloeppel (U of Georgia), Catherine Pringle (U of Georgia), Jim Vose (USDA Forest Service), and Jack Webster (Virginia Tech U). The SAC focuses on strategic planning and project direction, provides oversight on the design, implementation and resource allocation in support of the research program, and makes decisions about project administration and staffing.

Project Principal Investigators constitute a Committee-of-the-Whole, and are all PhD-level scientists with a university or a federal agency appointment and a major commitment to CWT research. They typically receive some level of direct funding from the project, and are expected to participate regularly in project research, meetings and decision-making. They also generally work directly with graduate and undergraduate students. Training students has always been a priority for the CWT LTER, so involving them directly in project research at all levels is extremely important. The roster of PhD-level scientists includes 27 PPI, of which 9 are early career (assistant professor or research scientist); of the total, 10 are women and of these 6 are early career (Table 3.1). The large turnover of senior investigators through retirement during the present funding cycle presented an ideal opportunity to reconsider how to maintain the strength of the research project through recruitments to meet specific project needs, address recommendations from the mid-term review, and take advantage of opportunities as they emerged.

Affiliate Investigators (AI) play a critical role in meeting these recruitment objectives. There are no defined AI on the renewal, although several of the early career scientists listed in Table 3.1 filled that role in the 2002-2008 funding cycle. We strongly encourage, even actively recruit, new researchers for the purpose of filling a specific research need or to collaborate with a PPI. These individuals have an interest in CWT research, may be independently funded to conduct research at one or more CWT research locations, or even receive nominal or in-kind support from CWT to conduct research that complements the project direction. These individuals are encouraged to participate in CWT activities to the level they are able and willing, but without the expectation they will do so fully. The objective is to have individuals who could become PPI as opportunities present themselves, either through retirement or departure within the project or as new funding becomes available. In all cases, appointment of new investigators as PPI is determined by consensus of the SAC with input from all PPI.

3.2. Staff and Facilities. Brian Kloeppel, Site Director and Schoolyard Coordinator, assists Ted Gragson with program administration and organization, serving as an on-site UGA representative at the Coweeta Hydrologic Laboratory and supervising technicians and field personnel. These include: Jim Deal, Analytical Lab Manager (employed since January 1979); Carol Harper, Analytical Lab Technician (employed since February 1994); Greg Zausen, Field Technician (employed since March 2006); as well as temporary and summer workers. Significant improvements were made to Coweeta Hydrologic Laboratory facilities during the 2002-2008 research cycle with Forest Service, UGA, and NSF funding in direct support of CWT LTER activities. The Coweeta Analytical Laboratory (4,000 ft^2) was completely renovated and expanded to process approximately 1500 water, plant, and soil samples per month; the

Coweeta Residence (5600 ft^2) can now house 20 visitors in a modern and fully ADA compliant facility; and the Coweeta Conference Center (7,000 ft^2) includes an 80-person conference room, a central meeting/reception area, eight offices, and a library. On-site facilities are owned and maintained by the USDA Forest service with shared use by LTER investigators facilitated by a Memorandum of Understanding between the US Forest Service and the University of Georgia (see Supplementary Documents).

3.3. Budgeting & Accountability. PPI are regularly evaluated by the SAC for the number and impact of publications, need for their particular expertise, participation in program planning, cooperation with information management practices, graduate student participation, cross-site activities, and ability to attract complementary funding. Each investigator submits a progress report every year that is used in preparing the NSF annual project report. Every two years, the investigators associated most directly with a research initiative must submit a progress report that details findings and datasets compiled, and presents a mini-proposal describing their research plan and resource needs for the next two years. Funding is allocated in support of initiatives, which have assigned co-lead investigators to achieve the appropriate mix of experience and discipline to guide the activities of the group of researchers directly associated with an initiative. Integration across initiatives is the practical outcome of individual researchers participating in activities that cut-across initiatives, participating in biannual meetings, and the flow of information ensured by our approach to information management.

The active participants in each initiative receive a nominal base budget to cover their direct expenses; decisions on how to allocate resources to the initiative are made by the group, with final oversight by the LPI. A separate budget allocation covers long-term measurements, information management, building and equipment maintenance costs, and contingencies such as equipment replacement or unanticipated opportunities. Day-to-day project management is the responsibility of the LPI who is assisted by a 50% time staff person. While the number of scientists participating in the CWT LTER is large, Coweeta is a regional project and this requires a greater disciplinary breadth than would be expected at a research station. Our organization ensures the proper balance between institutional memory, productivity, technical/disciplinary approach, and scientific vitality. Our philosophy is that LTER base funding and infrastructure provides a stable research platform from which individuals are expected to leverage additional resources.

The cost of supporting graduate students has increased dramatically over the last several years, but we have a commitment from the University of Georgia that any UGA graduate student who is supported as a research assistant at 1/3rd time or greater will receive a full tuition waiver for each semester he/she is enrolled.

3.4. Communication. Online forms are used for reserving equipment and facilities, and initiating research projects. We are currently developing a web calendar to log research plans, coordinate activities, and determine progress on research initiatives. We will expand our use of internet conferencing to increase the ability of investigators and staff at multiple sites to participate in meetings. SAC members have monthly video-conference meetings during the academic year, meet as a group during biannual project meetings or as necessary throughout the year. They are also in regular contact via telephone and email.

Interaction among PPI, AI, technicians, graduate and undergraduate students, and other collaborators is maintained by the distribution of programmatic information and biannual meetings. The January meeting is limited to PPIs and is used to plan and coordinate research activities for the calendar year using breakout groups arranged by research initiatives. The June meeting brings everyone together, typically 75-90 participants, to present and discuss research results to date. The agendas, abstracts, and results from both meetings are posted to the Coweeta website (http://coweeta.ecology.uga.edu). We convene a committee of three to four scientists to serve as external project advisors and invite them to the June meeting in years 2, 4, and 6. These individuals are charged with reviewing our progress and to provide us with scientific and organizational guidance.

Table 3.1. Name, institutional affiliation, disciplinary approach and initiative involvement of Coweeta LTER investigators (the name of individuals who will be new to the project are italicized).

Name	Affiliation	Discipline	Initiative*
Larry Band [1]	U North Carolina	Ecohydrologic modeling	B, E
Fred Benfield	VA Tech	Stream processes	B
Emily Bernhardt [2]	Duke	Stream processes	B
Paul Bolstad [1]	U Minnesota	Forest processes	A, B, D
Marc Bradford [2]	U Georgia	Ecosystem processes	B, C
Jim Clark [1]	Duke	Biotic modeling	C, E
Carolyn Dehring [2]	U Georgia	Land economics	A, B
Craig Depken	U North Carolina	Econometrics	A
Katherine Elliott	USFS Coweeta	Plant community ecology	B, D
Chelcy Ford [2]	USFS Coweeta	Ecophysiology	B, C, D
Jennifer Fraterrigo [2]	U Illinois	Landscape ecology	C
Ted Gragson [1]	U Georgia	Historical ecology	A, D
Jeff Hepinstall [2]	U Georgia	Landscape ecology	A
Nik Heynen	U Georgia	Political ecology	A, B
Rhett Jackson	U Georgia	Surface hydrology	B
Brian Kloeppel [1]	U Georgia	Forest processes	D
Jennifer Knoepp	USFS Coweeta	Soil processes	B
David Leigh	U Georgia	Geomorphology	B, D
John Maerz [2]	U Georgia	Ecosystem processes	B, C
Jackie Mohan [2]	U Georgia	Forest succession	C
Rebecca Moore [2]	U Georgia	Non-market valuation	A, B
Scott Pearson	Mars Hill College	Landscape ecology	C
Cathy Pringle [1]	U Georgia	Stream processes	B, C
Monica Turner	U Wisconsin	Landscape ecology	C
Maury Valett	VA Tech	Stream processes	B
Jim Vose [1]	USFS Coweeta	Forest processes	B, C
Jack Webster [1]	VA Tech	Stream process	B, E

* A = Parcel-Level to Regional Decision Making
B = Longitudinal Variation in Hillslope, Riparian, and Stream Ecology
C = Impacts of Climate and Land Use Change on Biodiversity
D = Baseline Data and Temporal Reconstruction
E = Synthesis & Scaled Integration

[1] Member of the Coweeta Science Advisory Committee

[2] Junior Project Principal Investigator (i.e., assistant professor or equivalent)

SECTION 4. INFORMATION MANAGEMENT

4.1. IM Approach at CWT. The core responsibility of the CWT Information Management (CWTIM) is to provide a comprehensive repository of scientific information from research and monitoring activities in southern Appalachia, available on-demand. Early in the current (2002-2008) funding cycle, we developed a scalable, dependable architecture to house data and provide users a single portal for discovery and access to all archived Coweeta LTER information (http://coweeta.ecology.uga.edu). CWTIM goals include:

- Developing an integrated information system to manage, archive and distribute all the products derived from scientific research in southern Appalachia by the Coweeta LTER and partners.
- Establishing web sites to provide secure, convenient access to all relevant information for southern Appalachia in support of the scientific activities of Coweeta LTER investigators, members of the LTER Network, and the larger scientific community.
- Supporting LTER Network Information System protocols and standards to facilitate network-level science, cross-site comparisons, and large-scale synthetic research.

4.2. CWT Information System. CWTIM is housed in the Department of Anthropology at the University of Georgia. This ensures full access to the UGA network and computing infrastructure needed to serve geographically dispersed project participants who access information through public and private websites. CWTIM maintains one remote access point with a networked cluster of computers at the Coweeta Hydrologic Laboratory (Otto, NC) with T-1 connectivity to the UGA campus. Information is served through a scalable, dynamically generated website built on MYSQL and PHP. Our global search functionality allows a user to search on a term (e.g., “quercus”) and have direct access to relevant data, publications, and samples interconnected by threaded links. We comprehensively support the EML 5.0 metadata standard and participate fully in all LTER NIS modules (e.g., All-site Bibliography). The Coweeta LTER Information Manager, Barrie Collins, was elected in 2007 to the IM Executive Committee in recognition of CWTIM network leadership.

4.2a. *IT Resources*. Computing resources at UGA for processing and serving data are centered on four Dell workstations and two servers built on Xeon class processors and a large format (48x36 in) color inkjet printer in a network configuration. All servers and workstations are backed up weekly and stored offsite; backups are full-scale replications of each computer including operating system, installed software, and data. Connectivity to the campus backbone is provided by the University of Georgia. Computing resources maintained at the Coweeta Hydrologic Laboratory consist of 17 Pentium-class computers and printers. The LTER project covers all network hardware and maintenance expenses, and the monthly charges for T-1 connectivity back to the UGA campus.

4.2b. *Data Acquisition*. As a regional site, the Coweeta LTER relies on data from a wide variety of sources. Data from investigators are submitted according to project schedules. Instrumental data from stations maintained by CWT (e.g., climate stations) are uploaded monthly; instrumental data from stations maintained by other agencies including USFS, USGS, and NOAA are uploaded quarterly. Some data is available at no cost other than personnel time; other data, like the satellite imagery we use to develop our incremental regional land cover classification, must be purchased (http://coweeta.ecology.uga.edu/ecology/gis/landcover.html).

4.2c. *Data Access & Distribution Policy*. Data summaries for new data sets are posted to the data catalogue on receipt; the data is added once Quality Assurance and Control procedures (QA/QC) are completed. Long-term monitoring data and data from individual investigators are available immediately to Coweeta LTER participants. In compliance with LTER Network data policy (i.e., Type 1 and Type 2 data), data are available to the public with 2 years (http://coweeta.ecology.uga.edu/webdocs/3/static/datapolicies.html).

4.2d. *Data Processing & Quality Control*. CWTIM uses a team-based approach to standardize raw data processing, data set development, and quality-assurance for all web-served products. Priorities and products are determined in coordination with the LPI while execution and supervision of day-to-day activities are the responsibility of the Information Manager, Barrie Collins. Individual investigators prepare their own data and metadata files and then submit to CWTIM for content verification, formatting and posting. Primary responsibility for data quality rests with the investigator. Recent improvements now make it possible to audit the archive and track investigator adherence to Project Site Use and Data Policies.

The standard development cycle for common-use datasets (e.g., regional land cover classification) begins with a scoping exercise to determine the steps and time frame for execution. An empirical proof-of-concept follows to ensure the design is fully functional and meets user expectations. The project is then divided into operational phases that are implemented by different members of the IM team and cross-validated by other team members before moving to the next phase. Archived information is made available in common formats (e.g., **.dbf**, **.shp**, **.xls**, **.csv**) and linked to a comprehensive meta-description. Data processing and server maintenance guidelines are published at: http://coweeta.ecology.uga.edu/process/php_improcess/process_home.php while other guidelines are published at: http://coweeta.ecology.uga.edu/ecology/publications_catalog.html

4.3. Information Archive. Selected accomplishments during the current funding cycle are proof of the advantages of the CWTIM architecture and management:

<u>Coweeta Data Catalog</u> - the point-of-access to research projects and associated information (i.e., data, coordinates, publications, etc.) in a database-driven, searchable format (http://coweeta.ecology.uga.edu/ecology/ecology_data.html). Information conforms to the EML 5.0 standard and is presented in human- and machine-readable formats for harvesting by the LTERNET Metacat Server.

<u>COGENT</u> – the Coweeta Geographic Network serves as the point-of-access for spatial resources serving data at the scale of the experimental watershed and the entire study region (http://coweeta.ecology.uga.edu/ecology/cogent.html).

<u>Publications Catalog</u> – a comprehensive bibliography of Coweeta LTER and USFS publications since 1928 in a database-driven, searchable format. Over 1,600 citations are linked to nearly as many PDFs of the publications including most theses and dissertations since 2001 (http://coweeta.ecology.uga.edu/ecology/publications_catalog.html).

<u>The EcoTrends Project Socioeconomic Catalog</u> – developed in collaboration with LTER-LNO, USDA-FS, USDA-ARS, CAP-LTER and BES-LTER. CWTIM collected human population and economic data from 1790 to 2000 and designed the architecture for the database. The database includes 29 variables describing decadal changes in population and economic structure for 738 counties for the 21 continental LTER sites plus LUQ (http://coweeta.ecology.uga.edu/trends/catalog_trends_base2.php).

<u>USGS Hydrologic Near-Real-Time Data</u> – developed in collaboration with GCE-LTER. CWTIM harvests daily USGS hydrologic data (daily max, min and mean discharge; and daily max, min, and mean gage height) from five stream gages near the Coweeta Hydrologic Laboratory for

posting to our website using the GCE Data Toolbox based on MATLAB (http://coweeta.ecology.uga.edu/ecology/hydrologic_data/hydrologic_data.html).

4.4. Web Usage. The Coweeta LTER web architecture was brought online in April 2003 and by the end of that calendar year we had served 52,000 pages and 13 gigabytes of information; 46% of served pages were from the dynamically-driven portions of our website, where data and publications are housed. In the first complete year of operation (May 2003 to May 2004), we served 168,995 pages to 39,315 unique users who downloaded 33 gigabytes of data; 36% were **.pdf** files (publications) and 26% were **.php** files (data/pub catalogs). In the most recent year of operation (January 2007 to December 2007), we served 857,462 pages. From August 17, 2006 to December 31, 2007, 154,284 unique hosts accessed the Coweeta LTER website, and downloaded 336 gigabytes of data; 77% were **.pdf** and 7% were **.php** files, indicating the increase in viewership as directly related to dramatically increased public access to Coweeta publications (**.pdf**) and data (**.php**) (http://coweeta.ecology.uga.edu/web_statistics/statistics.html).

4.5. New Directions. Maintaining and enhancing the centralized component of CWTIM at UGA, which provides data authorship, storage, management, and preservation of our extensive information holdings, will be the foundation to our continued success in information management. During the renewal, we want to improve the scalability and dependability of the architecture to provide for large, regional-scale collaborative projects within and across the boundaries of the Coweeta LTER project in the following ways:

4.5a. *Geospatial Data Archiving.* Our proposed research will use parcel-level data, which places a burden on data storage and discovery resources that are beyond those previously encountered with ecological data. For example, a parcel-level study in Buncombe County, NC that is currently being conducted by Coweeta researchers uses 1,000,000 records with a 2.6 GB storage footprint representing slightly more than 3% of current Coweeta storage capacity. We will continue to develop our GIS server to ensure ease-of-use in determining machine-readable spatial relationships such as intersection, containment, and adjacency. At the same time, we will begin explicitly encoding the scalar concepts in database schema so that we can organize and serve data at the watershed, county, regional, and macroregional scale.

4.5b. *Data Ingestion & Discovery*. Process-oriented studies of a regional socio-ecological systems not only place heavy burdens on data storage needs, but also increase the required procedural complexity for ingesting new data and maximizing user discovery. We will continue to explore ways to improve the processing of data streams and ensure QA/QC standards are efficiently satisfied. The true value of ingesting data is the ability to provide diverse and dispersed users the means to discover not only what exists in the archive but the ability to use locally managed tools to analytically examine relationships within the data. We will build on tools such as "Global Search", the value of archiving information in multiple, common information archiving formats, and comprehensive meta-descriptions in ways that emphasize **usability** and facilitate user discovery and access to all archived Coweeta LTER information.

4.5c. *Data Storage to Aid Integration*. Coweeta LTER researchers are geographically dispersed and the project is best served by a mixed data management model of centralized and distributed tools. We will explore development of a client/server application that allows users to "check out" data sets, add value by performing additional analysis and research, then "check-in" the data set and compare it against existing holdings discarding duplicate information, and add new metadata. Such an application will build on our recently-completed ability to audit the archive and link investigators to the diverse types of information they have generated.

SECTION 5. EDUCATION AND OUTREACH

5.1. Introduction. The Coweeta LTER Program has a long history of providing formal and informal education and outreach to local, national, and international communities. Most outreach is conducted by US Forest Service scientists and the full-time USFS Technology Transfer Specialist, Randy Fowler, with selective involvement by Coweeta LTER staff and researchers. Randy Fowler develops workshops for regional land and resource management professionals; coordinates guided scientific tours for visiting students, scientists and land managers; and organizes and schedules the Coweeta seminar series. On-site UGA staff and selected UGA researchers direct the Coweeta Schoolyard program while nearly all Coweeta LTER researchers participate in the training of undergraduate, graduate, and post-doctoral scientists. Each type of activity is described in more detail below.

5.2. Resource Management Workshops. Workshops disseminate contemporary and time-tested Forest Service and Coweeta LTER research results to scientists, managers, and policy makers by: 1) providing rigorously tested scientific information using the latest technology; 2) creating an effective environment for knowledge transfer using the Coweeta Hydrologic Laboratory facilities and land base; 3) increasing collaboration between researchers, land managers, and cooperators; and 4) gathering information to ensure research remains relevant and responds to manager needs. Recent topics have included the use of prescribed fire; road and stream sediment; and, riparian management.

5.3. Guided Scientific Tours. Each year, an average of 65 groups and 1200 individuals visit the Coweeta Hydrologic Laboratory to participate in guided tours. About 70% of the visitors are university students, scientists, and land managers. Guided tours provide: 1) a succinct and clear synopsis of the project's study questions and conclusions; 2) direct access to the scientists and staff conducting research; 3) insights into the design and implementation of studies in the complex southern Appalachian terrain; and 4) an appreciation for the value of the knowledge gained from long-term ecological research. The needs of an additional 300 drop-in visitors are met each year by Coweeta staff (http://coweeta.ecology.uga.edu/ecology/education/summary.html).

5.4. Coweeta Seminar Series. The seminar series provides researchers and resource managers the opportunity to interact and increase their awareness and knowledge of current southern Appalachian issues. Monthly seminars are open to all interested attendees and do not require a reservation. Topics have included ruffed grouse population dynamics in southern Appalachia; modeling water yield response to deforestation / reforestation at watershed and regional scales; soil and soil invertebrates; and the use of alternative materials to control erosion.

5.5. Schoolyard Program. Our Schoolyard Program provides instruction, field research, data summary, and analysis experiences built around Coweeta LTER research to students and instructors from our partner institutions: Macon Middle School in Franklin, NC, Rabun Gap Nacoochee School (a local private high school) in Rabun Gap, GA, and Southwestern Community College in Sylva, NC. All Schoolyard programs are built around Coweeta LTER research. Program goals include: A) providing direct learning experiences about long term ecological studies to middle school, high school, community college students, and their instructors; B) promoting student-scientist interactions that foster understanding of careers in science; C) collecting and sharing data that are relevant to core LTER research areas; and, D) providing opportunities for students to learn about local ecosystem structure and function. From 2002 to 2008, 23 teachers and researchers, and 277 students across all grade levels participated in the program (http://coweeta.ecology.uga.edu/ecology/education/schoolyardmain.html).

5.6. Scientist Training. The Coweeta LTER Program has a long tradition of training undergraduate, graduate, and post-doctoral scientists in contexts that range from volunteer through full-time staff positions. The support for these individuals consists of both direct and in-kind support from the Coweeta LTER as well funding from diverse state, federal and other sources.

We support three programmatic undergraduate training activities. The first is the NSF Research Experience for Undergraduate (REU) Program. This program provides an undergraduate student with a stipend for a summer research project on a topic of their choice. Since 2002, eight Coweeta-sponsored REU have examined topics such as ecosystem effects of the hemlock wooly adelgid; nutrient content and bulk density of coarse woody debris; dendroecological reconstruction of disturbance history of the Coweeta Basin; and, modeling regional socioeconomic trends using the EcoTrends database. The second program is a cooperative mentoring partnership with the Carolina Environmental Program (CEP) based at the Highlands Biological Station (HBS). Each fall semester undergraduate students in residence at HBS explore a topic and assist with field and laboratory research in order to produce a written report of their findings for presentation to scientists, staff, students and public at Coweeta and HBS. The third is an undergraduate internship program funded by the US Forest Service that hires four to six interns each year to work with Forest Service scientists on field and laboratory projects.

We also provide numerous conventional approaches to scientist training. These include research assistantships for graduate and undergraduate students who are either assisting Coweeta LTER researchers, or working towards a degree. Since 2002, Coweeta LTER affiliated researchers have worked directly in one or both capacities with 83 graduate students and 60 undergraduates students. These students have produced in that time 27 PhD dissertations, 21 MSc theses, and two BSc theses. Coweeta LTER researchers have also worked with eight post-doctoral researchers since 2002.

Finally, there are courses and other educational materials that derive in part or in whole from the experiences of Coweeta LTER researchers. Three are particularly significant. The first two are textbooks that are used extensively in courses around the country: Bolstad, Paul. 2006. *GIS Fundamentals: A First Text on Geographic Information Systems*. 2nd Edition. St. Paul, MN: Eider Press. And, Clark, James S. 2007. *Statistical Computation for Environmental Sciences in R: Lab Manual for Models for Ecological Data*. Princeton: Princeton University Press. The third is a graduate seminar on socioecological methods. This seminar is being hosted by Coweeta and co-taught by Ted Gragson (CWT), Laura Ogden (FCE) and Morgan Grove (BES). Twelve additional guest presenters representing a total of seven LTER sites. The course is taught over the Internet and video-conferencing technology is being used to reach over 40 participants from across the LTER network and including sites in Mexico, Argentina and England. All content is archived and publicly accessible (http://coweeta.ecology.uga.edu/ecology/web_learning/intro.html).

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