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PROJECT SUMMARY

Andrews LTER 1 and 2 programs consisted of long-term field experiments and observation programs on disturbance regimes, vegetation succession, trophic interactions, forest/stream interactions, and controls on primary production, decomposition, and nutrient cycling. These studies will be continued in LTER 3 (1991-1996). In addition, synthesis efforts, initiated in LTER 1 and 2, will be expanded greatly. Long-term records of climate, stream flow and chemistry, tree growth and mortality, along with Andrews-wide data on fire history and geomorphic disturbance regime, will be used to develop and verify models of stand- and landscape-level response of the forest/stream ecosystem to natural disturbance (wildfire), land use (conversion of natural to intensively managed forest), and climate warming. This work, some of it underway, is made possible by collaboration with other LTER sites (e.g. VCR, CPR, NWT) and Federal agencies (USGS-Denver, EPA-Corvallis). Emphasis will also continue on data management, LTER network and intersite activities, and dissemination of research results to the public. Andrews LTER research is highly relevant to major issues concerning natural resource management in the Pacific Northwest and in other regions of rapid land-use change.

Results from Prior NSF Support of H. J. Andrews Experimental Forest LTER Program

The Andrews LTER Program, funded by NSF awards DEB 8012162 and BSR 8514325, completes its first decade with many accomplishments, as indicated by the products, applications, and growth and development of the research site and programs. Andrews LTER is the hub of a much larger research program totaling approximately $1.7 million per year coming from National Science Foundation, Oregon State University (OSU), US Forest Service (USFS) PNW Station, and other sources. The Andrews Ecosystem Group comprises over 50 scientists from ten departments in three colleges of OSU, USFS Research Station, Willamette National Forest, and EPA-Corvallis Laboratory. The philosophy of management of the research site, including our active facilitation of access to sites and to data, has attracted extensive use by researchers and students from many institutions (over 100 research projects annually for the last decade).

Major research results of the Andrews LTER program in the 1980's include:

* characterization of, and inventory criteria for, natural forests of the Pacific Northwest, particularly old-growth Douglas-fir forests.

* studies of previously neglected roles of coarse woody debris in forest and stream ecosystems.

* analysis of CO_2 flux to the atmosphere resulting from forest cutting in the Pacific Northwest. Results suggest that the amount released may have been significant by global standards and that fluxes resulting from forest cutting worldwide may have been underestimated (Harmon *et al.* in press).

* studies showing that landform strongly influences stream productivity and fish distributions.

* analyses suggesting that projected climate changes would affect ecosystems in the Pacific Northwest mainly by altering disturbance patterns--increased wildfire and decreased flooding.

* studies showing that logging disturbance affects mainly stand architecture and not species composition.

Andrews LTER 1 and 2 have consisted of seven component studies, plus a program of long-term measurements, and synthesis and modeling. Substantial effort has been directed in these components toward each of the five core areas mandated for LTER by NSF. In this section, we describe the components under titles used in LTER 1 and 2 (some projects have been renumbered in the LTER 3 proposal).

In LTER 1 and 2, studies of vegetation succession and higher trophic levels involved a large program of periodic remeasurement of permanent vegetation plots in natural and managed stands (15- to 1000-yr old) distributed over the Pacific Northwest. Analyses have focused on changes in tree mortality rates (Franklin *et al.* 1987), plant population dynamics (Franklin and DeBell 1988), and biodiversity through early (40 yr) succession. Diversity of understory species in early succession did not vary greatly from pre-disturbance levels, although structure of the forest was greatly altered by clearcutting (Halpern 1988, 1989; Schoonmaker and McKee 1988). Work on higher trophic levels has focused on arthropods; over 3600

species have been identified from the Andrews Forest making the site's arthropod fauna one of the best known in the world (Parsons *et al.* in press). The distribution of soil arthropods with successional stage and environment has been examined over a range of sites spanning the environmental field of the Andrews.

Disturbance studies have mapped the history of wildfires, river channel changes, several types of landslides, tree death gaps, and logging over the Andrews Forest. Wildfire has been more frequent and of lower severity for the last 1800 yr. than previously believed (Teensma 1987; Morrison and Swanson 1989). This finding implies that structural components of old-growth forests (large live and dead trees, downed woody debris) may have persisted in the past for many centuries and even millennia on a site. We have also examined how the spatial pattern of geomorphic disturbance is controlled by the balance of forces that tend to create disturbance (*e.g.*, stream power) relative to those that tend to resist it (*e.g.*, landform constraints) (Swanson *et al.* in press).

Two long-term experiments consider controls on primary production. The Young Stand experiment, installed in 1981, is designed to investigate the influence of forest structure (thinning and pruning manipulations) and topo-edaphic (nutrient manipulations) factors on productivity of 20- to 25-yr-old Douglas-fir stands. We have confirmed our hypothesis that N availability strongly affects net primary production at this site, but we have been surprised to find that levels of total soil P and exchangeable Ca significantly influence N cycling rates. The second experiment examines the effects of the N-fixing shrub, snowbrush (*Ceanothus velutinus*), on growth of Douglas-fir and on soil chemical and physical properties. Soil nutrient status was measured before and after logging and burning. Although snowbrush seeded in prolifically, growth has been much slower than expected. A vegetation survey this summer will determine how we proceed with this experiment.

The Log and Snag Decomposition component of LTER has established a series of long-term experiments on the role of coarse woody debris (CWD) in terrestrial and stream systems. A major step in LTER research on CWD was publication of a review monograph (Harmon *et al.* 1986). A 200-yr field study of 570 logs of four species (50-cm diameter and 6-m length) has been installed. Data on decay of these logs has shown that growth and fragmentation of fungal sporocarps is an unexpectedly important mechanism of nutrient export from logs. The rates of weight loss and relative importance of different decay processes vary among the four species studied and between terrestrial and aquatic systems. With separate NSF funding, we have measured rates of consumption by invertebrates, N fixation, water flow, nutrient leaching, fragmentation, respiration, and changes in carbon fractions for two years.

The Forest-Stream Interactions component of Andrews LTER covers linkages among geomorphology, riparian vegetation, and stream ecosystems (Swanson *et al.* 1982a, 1990; Gregory *et al.* in press). Research in this component spans the full range from reach-level research on local controls of streamside vegetation on aquatic ecosystems to landscape-level studies placing stream systems in the hydrologic and geomorphic context of the full drainage network. Studies include long-term experiments (effects of CWD levels on fish and channel stability), modeling (*e.g.*, input of CWD to streams--Van Sickle and Gregory submitted), and long-term observation programs (*e.g.*, integrated measurements of changes in structure and composition of streamside forest, stream morphology, CWD configuration and movement, and aquatic ecology). We found that unconstrained valley floor areas (areas where channels have room to shift laterally) are zones of high aquatic productivity and standing crops of fish, because high light levels result in high levels of primary and secondary production and improved foraging efficiency by fish (Wilzbach *et al.* 1986). We have examined vegetation and stream

recovery at two sites severely disturbed by debris flows in 1986 (Lamberti *et al.* submitted). Aquatic primary and secondary production and fish populations recovered surprisingly quickly, apparently because more light reached the stream.

Andrews researchers have moved increasingly into the area of causes and consequences of global climate change. For example, preliminary analysis suggests that a dominant effect of climate change in the Pacific Northwest would be alteration of the disturbance regime. Wildfire is expected to increase in the Andrews drainage basin in response to warming, while flooding will likely decrease as a result of reduction in area of the flood-producing transient-snow zone (Franklin *et al.* in press).

Concepts from Andrews ecosystem studies have heuristic value for interpretation and formulation of hypotheses and field experiments. Our experiences with clearcut/burn experiments and the eruptions of Mount St. Helens have led to the "biological legacy" concept that many biologically derived predisturbance elements of the ecosystem, such as structures (*e.g.*, snags and down logs), biota (*e.g.*, propagules of plants, soil microfauna, and mycorrhizal fungi), and distinctive soil chemical patterns, carry over into the post-disturbance system and guide its rate and pathway of recovery. The "bootstrapping" concept (Perry *et al.* 1989a,b) recognizes the tight, system-stabilizing links between above- and below-ground systems. Aboveground plant parts pump resources below ground to support rhizosphere communities; prolonged interruption of these linkages can destabilize ecosystems and reduce their productivity.

Andrews LTER is also heavily involved in intersite work. S. Stafford leads the LTER Data Management Committee and M. Harmon directs the 21-site litter decomposition study. Andrews researchers have published five papers describing LTER to the scientific community and five other papers on intersite research, and have organized or participated in numerous symposia and workshops. Companion studies to our LTER experiments have been set up in China, Costa Rica, and Zambia.

Andrews LTER makes a strong commitment to data management and use of a data bank. Ten full-time OSU and USFS professionals provide statistical consulting, data bank management, data analysis, and hardware/software support. This investment has paid off by promoting collaborative research efforts, such as modeling of forest stand dynamics (LTER intersite with VCR and CPER plus EPA) and modeling surface water hydrology (US Geological Survey). The educational role of the Andrews Forest has grown over the past decade. Tours are arranged for undergraduate and graduate students, a program for Research Experiences for Undergraduates was initiated in 1989 (renewal submitted), and a growing number of graduate students now work with Andrews faculty,

Results of Andrews research have been disseminated in a variety of ways: presentations at scientific meetings; refereed papers and other publications including two books in print and three more in preparation; field trips and workshops for land management groups including the Oregon State Board of Forestry; TV reports and newspaper articles; and presentations to lay audiences and special interest groups including Congresspersons and staff.

LTER research results have been applied widely in forestry and stream management. Federal forest management has changed fundamentally as a result of ecosystem research, much of it initiated at the Andrews Forest. For example, better understanding of the roles of coarse woody debris in natural terrestrial and aquatic systems (Harmon *et al.* 1986) has spurred efforts to retain this material in managed systems. Analysis of landscape patterns created by forest cutting has shown that the current system of dispersed cutting rapidly fragments a forest landscape, reducing the amount of interior forest habitat and making the remnant forest patches vulnerable to disturbances at stand edges. To avoid such

fragmentation, Franklin and Forman (1987) have proposed that cutting should be strongly aggregated, a suggestion that has prompted wholesale reevaluation of forestry practices in the Pacific Northwest.

Facilities at the Andrews Forest were upgraded significantly during the 1980s with grants from the Biological Research Resources Program at NSF and matching funds from USFS and OSU. Administrative offices were moved from the USFS District Office to the present Headquarters site on the Forest, which now provides ca. 3000 sq. ft. of lab/office space and 5000 sq. ft. of living space. Two construction projects, funded by USFS, are planned for 1990 that will provide a dormitory (cap. 10) and a classroom with space for 50.

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Table 1. Organization of LTER 3 in relation to the six components described in the LTER 1 and LTER 2 proposals.

LTER 3 Topical Areas/Studies		LTER 1 & 2 Components
I.	Disturbance Regime	Component 1
II.	Vegetation Succession	Component 1
III.	Trophic Interactions	Component 1
IV.	Controls on Long-Term Productivity	Components 3,4,6
V.	Decomposition	Component 5
VI.	Forest-Stream Interactions	Component 2

1.0. PROPOSED RESEARCH

1.1. INTRODUCTION

As the Andrews and other Cohort 1 LTER programs enter a second decade, we face the difficult challenge of sustaining existing long-term studies while undertaking synthesis and new research on emerging regional- and global-scale issues. Fortunately, these issues are natural extensions of our past research. Our overall theme remains:

Develop concepts and tools needed to predict effects of natural disturbance and forest management on ecosystem structure, function, and species composition.

In its first decade, Andrews LTER developed six long-term field studies of ecosystem and landscape patterns and key processes (Table 1). We continue all of these long-term field studies in LTER 3, although we have renumbered some to better meet organizational needs. In addition, we plan a major expansion of synthesis efforts with special emphasis on understanding and predicting potential landscape-level effects of climate and land-use change.

Below, in section 1.2, we describe the long-term field experiments established during LTER 1 and 2 and continued in LTER 3 (1991-1996). Descriptions are brief because the experiments were presented fully in LTER 1 (1981-1985) and LTER 2 (1986-1990) proposals. Next we describe proposed modeling and synthesis studies aimed at understanding effects of disturbance, management, and climate change on Pacific Northwest (PNW) ecosystems (section 1.3). These synthesis studies build on data and concepts developed during LTER 1 and 2 and related studies. Because funds are limited, no major new experimental components are proposed. However, some new small-scale field studies will be needed to provide information for synthesis work; these are described in conjunction with the existing experimental studies (1.2).

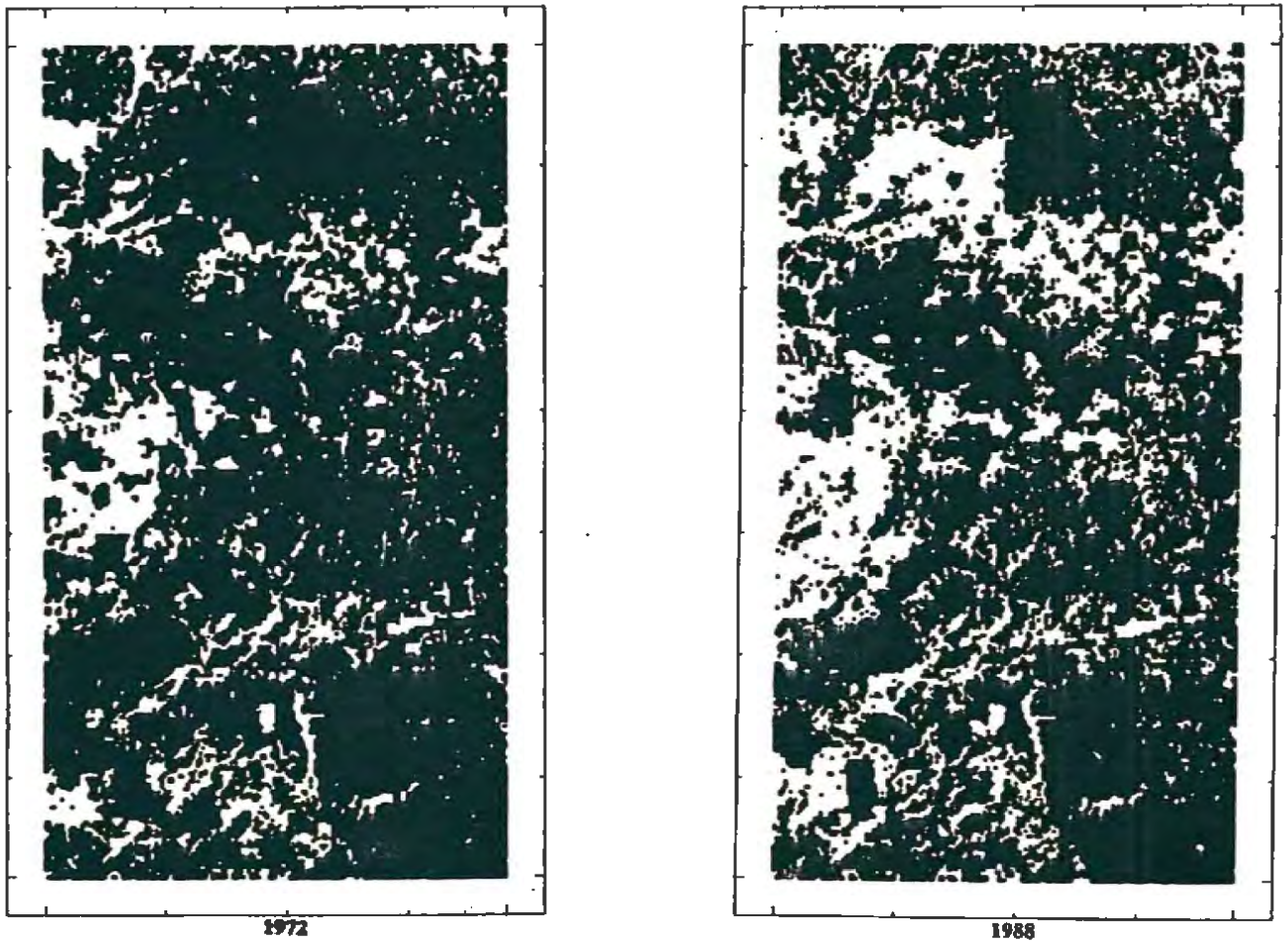


Figure 1. Landsat images showing areas of non-forest (mainly forest sites cut in the previous 25 years--shown in white) and forest (natural and older managed forest) across an area of 2584 km^2 (68 x 38 km) in the central Cascade Mountains of Oregon. The H.J. Andrews Experimental Forest is located in lower center. The large area cut between 1972 and 1988 in the upper portion is private land located west of the Middle Santiam Wilderness Area on the Willamette National Forest. Images prepared by G.A. Bradshaw, Environmental Remote Sensing Applications Laboratory, Oregon State University.

Under "synthesis", we include both conceptual and quantitative modeling designed to increase our understanding of process and pattern across a hierarchy of temporal and spatial scales (O'Neill *et al.* 1986). We focus on stand/stream reach and landscape levels because these are appropriate scales for long-term studies by an individual research site. Andrews researchers are participating also in studies at finer scales (process studies) and coarser scales (such as changes in regional carbon stores--*e.g.*, Harmon *et al.* in press), but such studies are for the most part beyond the scope of this proposal.

Synthesis will focus on the question:

How do natural disturbance, land use, and climate change, acting individually and jointly, affect key ecosystem variables at stand and landscape scales?

We approach this question by applying data and process models resulting from LTER and related field studies to alternative scenarios of stand and landscape change.

Increased emphasis on synthesis is timely for several reasons. Land-use practices (including extensive logging of old-growth forest) are altering the PNW landscape at an unprecedented rate (Fig. 1). Simultaneously, evidence accumulates that changes in global climate may have dramatic impacts on the region's ecosystems (Neilson *et al.* 1989, Franklin *et al.* in pressa). What are the consequences for biological diversity, ecosystem sustainability, CO_2 fluxes, hydrology, and other important system attributes? As an LTER site, we feel obligated to address these issues, a position supported by recommendations from NSF (*e.g.*, during site review in July 1989), from our National Advisory Committee, and from the LTER Coordinating Committee (*e.g.*, LTER workshop on global climate change held in Denver, Dec. 1989).

The Andrews LTER group is uniquely positioned to tackle these difficult questions. We have the personnel, geographically extensive and long-term data sets, process-oriented field experiments, field site, and conceptual understanding essential for the task. The

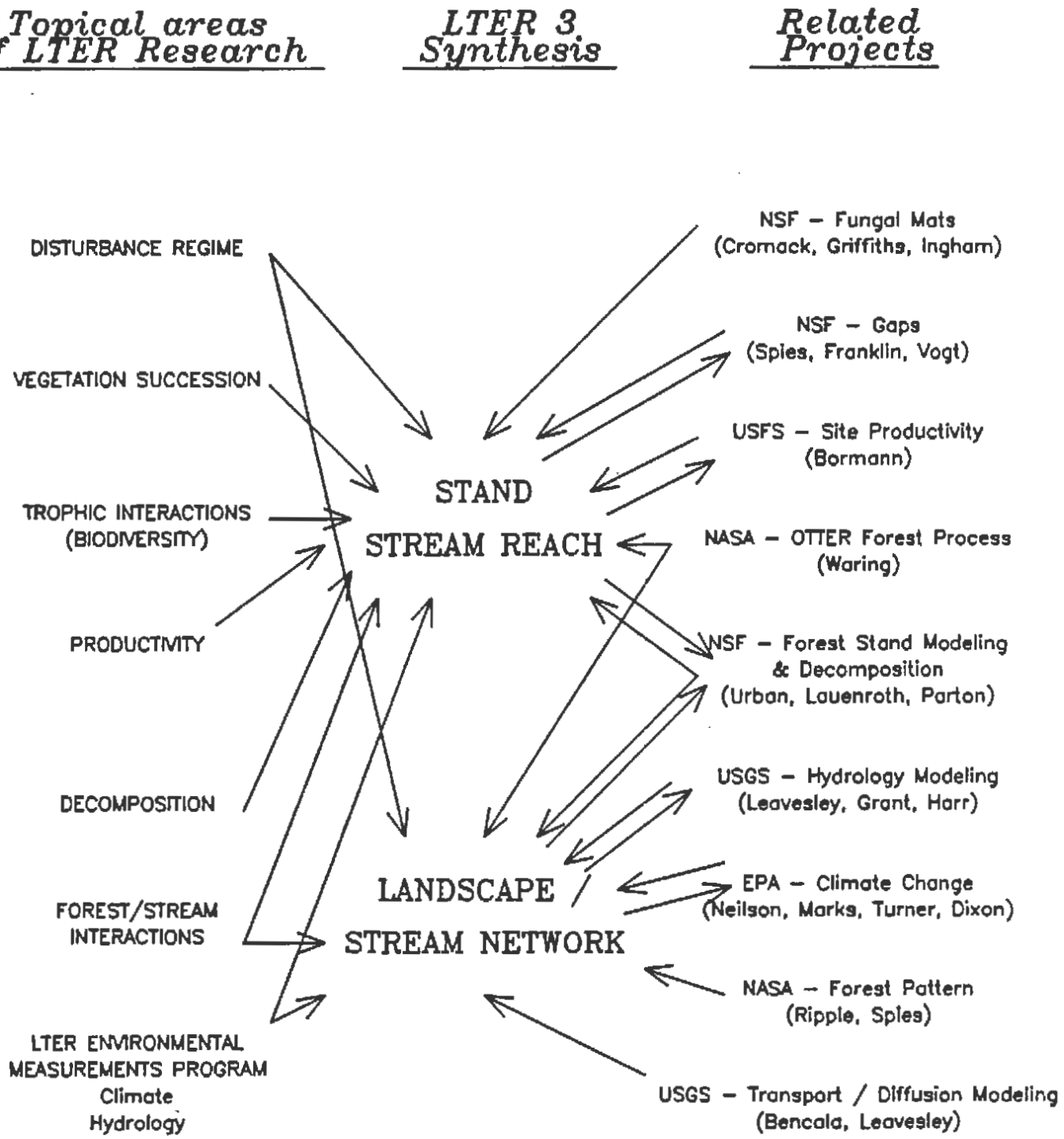


Figure 2. Interrelations between LTER 3 topical areas and associated non-LTER research projects at stand/stream-reach and landscape scales.

Andrews Experimental Forest comprises a 6400-ha drainage basin that includes the largest contiguous area of low- and mid-elevation old-growth forest remaining in the PNW, as well as extensive areas of younger forest (Appendix F). Additionally, Lookout Creek, the fifth-order stream draining the Andrews Forest, offers excellent opportunities for studies of forest-stream interactions.

Cooperation among LTER-related institutions and research projects is excellent. The Andrews LTER site provides a focal point for research by 50+ scientists at Oregon State University (OSU), US Forest Service (USFS) Pacific Northwest Station and Willamette National Forest, EPA/Corvallis, USGS, and other institutions and agencies (2.9, Appendix B). Andrews LTER, particularly the proposed stand- and landscape-level synthesis and modeling activities, is the hub for interaction among numerous research projects (Fig. 2). A strong spirit of cooperation, essential to interdisciplinary work, has developed in the 20 years of collaborative work at the Andrews Forest. This has resulted in a research program that is broad in scope yet focused on a specific geographic region, as reflected in this proposal.

1.2. CURRENT TOPICAL AREAS OF LTER RESEARCH

LTER 1 and 2 research at the Andrews Forest was organized into six components constituting separate experiments or programs of field observations. We continue these original components in LTER 3 (Table 1), although we have renumbered several topical areas. This section describes past and proposed work by topical area. Our long-term monitoring program is addressed specifically in section 2.1. Proposed synthesis and modeling are described in section 1.3.

Table 2. Information on disturbance regimes of the Andrews Forest.

Disturbance	Information Source and Period	References
wildfire	archival documentation 1850-1970 stand reconstruction 1100-present	Burke 1979 Teensma 1987 Morrison and Swanson 1989
tree death	field sample 1900-present	Spies et al. in press
river channel change	photo/field mapping 1950-present	Swanson et al. in press; Grant and Swanson in prep.
landslides	photo/field inventory 1950-present	Swanson and Dyrness 1975
debris flows	photo/field inventory 1950-present	Swanson unpublished
logging records	photo/Andrews records 1950-present	unpublished

1.2.1. Disturbance regime

Work in this topical area has characterized the pattern and frequency of both natural and management-related disturbance (Table 2). These studies directly address one of the 5 core areas identified by NSF for LTER (2.1). Ecosystem response to disturbance is considered in sections 1.2.1 for vegetation and 1.2.6 for streams.

Until relatively recently, the pristine Pacific Northwest landscapes were shaped largely by natural disturbances (*e.g.*, wildfire, flooding, landslides, windstorms, and insects). Since World War II, however, logging and other management activities have radically changed the disturbance regime. Moreover, we may be entering a period of rapid climatic change which could markedly alter disturbance processes and patterns. The potential simultaneous convergence of land-use and climate change presents major challenges for predicting ecosystem behavior under possible future disturbance regimes.

Past research indicates that topography, geology, and soil characteristics exert substantial control over the spatial and temporal pattern of natural disturbance processes (Swanson et. al. 1988, 1990, in press). Consequently, the disturbance regime of our area must be described in a topographically specific fashion. Disturbance regimes differ among landscape segments, with important effects on overall landscape vegetation dynamics. For example, frequently disturbed patches may provide refugia for early seral species during periods of generally low disturbance.

In LTER 3, we plan to analyze further the local disturbance regime. Data on disturbance patterns will be compiled in GIS to compare quantitatively natural and management-driven disturbance patterns and frequencies, and their interaction (such as blowdown at edges of logged areas and subsequent salvage logging--Franklin and Forman 1987). A major windstorm in January 1990 has given us a fresh opportunity to analyze blowdown patterns in relation to stand type, edge location, and topography. We will

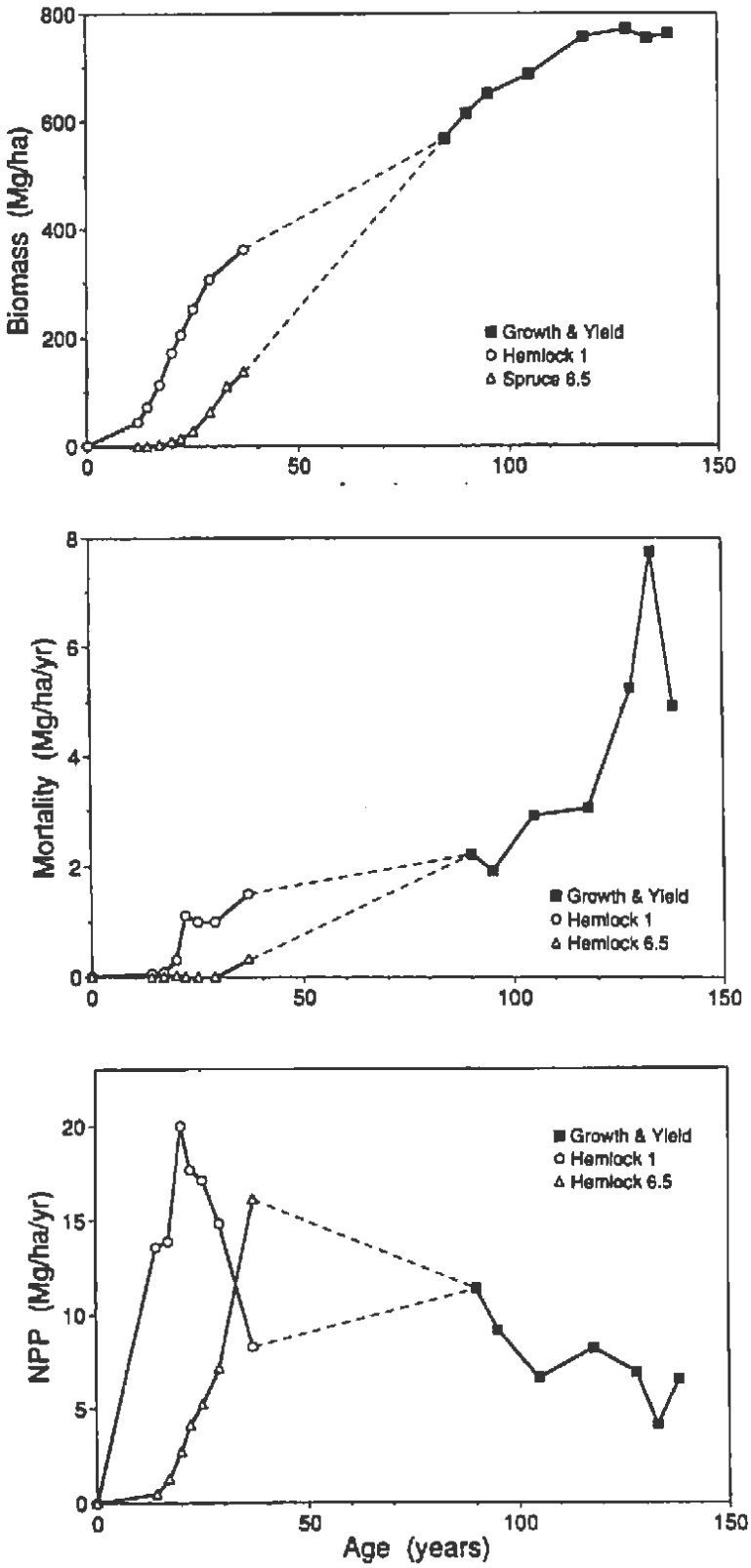


Figure 3. Change in bole biomass, mortality and NPP (boles only) after disturbance in a *Picea-Tsuga* forest, based on permanent plots in two series of stands (12-40 years and 85-140 years old). Data from Harcombe *et al.* (submitted).

continue monitoring patterns of future disturbance by flood, wind, and fire in order to strengthen our ability to predict disturbance regimes in relation to topography and stand structure.

1.2.2. Plant community succession

Knowledge of the processes driving succession in terrestrial plant communities is fundamental to an understanding of ecosystem pattern and dynamics. Research within this topic directly addresses three of the 5 core areas identified by NSF for LTER, and is highly relevant to the other two (2.1). Data gathered as part of this topical area are needed also for implementation and verification of stand-level models, such as ZELIG (Smith and Urban 1988), which are basic to much of our synthesis efforts.

Significant progress has been made in summarizing results during LTER 2 in the areas of plant succession (Halpern 1988, 1989; Schoonmaker and McKee 1988), tree population dynamics (Harcombe 1986), mortality (Franklin *et al.* 1987, Franklin and DeBell 1988), and net primary production (NPP) and biomass accumulation (Fig. 3). Permanent plots have been established at Andrews Forest and elsewhere (Table 3) in three important seral stages: early seral communities (<30 years), mature forest (100-150 years), and old-growth forest (>250 years). Measurements on these plots include changes in species composition, stand age structure, and key ecosystem processes (Table 4). Pre-disturbance conditions were measured in the early seral stands. LTER funding has allowed us to resurrect numerous other plots across the region, many very old and long abandoned, and to add them to this continuing measurements program.

Vegetation studies also concern the scale of gaps and stand edges, where discontinuities in stand structure affect microclimate, and thereby animal and understory plant populations. Chen Jiquan (PhD student with Franklin) is measuring microclimate along transects from forests to clearcut areas on the Andrews Forest. This work is revealing much greater edge effects (exceeding 200 m distance from the edge) than we

Table 3. Permanent vegetation succession plots maintained by LTER and U.S. Forest Service.

Plot type	Number	Size	Duration of record	Sampling interval
LTER				
Circular				
Trees	162	0.1 ha	1981-present	6 yr
Shrub, herb	162	62.5 m^2	1981-present	6 yr
Reference stands				
Andrews	34	0.25-6.1 ha	1971-present	6 yr
other regional	91	0.25-4.5 ha	1976-present	5-8 yr
Watershed				
# 1 & 3				
Trees	194	250 m^2	1980-present	3-4 yr
Understory	194	20 m^2	1962-present	1962-73 annually since '73 2-3 yr
# 10				
Trees	36	150 m^2	1973-present	2-3 yr
Understory	36	16 m^2	1973-present	2-3 yr
Streamside	40	5-7 m^2	1977-present	3-4 yr
Riparian				
Debris torrent	200+	1 m2	1986-present	2 yr
Biomass	3	0.6 ha	1982-present	6 yr
PNW plots				
Noble fir	15	0.1 ha	1976-present	5-8 yr
Growth/yield	36	0.2-0.4 ha	1910-present	5-50+ yr
Mount St. Helens				
Upland	120	250 m^2	1980-present	1980-86 annually since '86 3 yr
Mud flow	130	250 m^2	1980-present	1980-86 annually
Debris flow	100	250 m^2		since '86 3 yr
Riparian				
Streamside	45	line intercept	1980-present	1980-86 annually
Lakeside	26	30 x 0.1 m^2		since '86 3 yr

expected. Effects of edges on vegetation and birds is being analyzed with non-LTER funding. Above-below ground interactions are being studied in experimentaly created canopy gaps, funded largely throught the NSF Gaps grant (Vogt, Spies, Franklin).

The permanent plot system has provided a database with which we are examining regional effects of climate change on vegetation patterns (Franklin *et al.* in press) and CO_2 fluxes (Harmon *et al.* in press). The latter study is especially intriguing in that it suggests that conversion of natural forests in the PNW region to intensive management may have added large amounts of CO_2 to the atmosphere. The study indicates that intensively-managed young forests contain ca. 40% as much C as do old-growth forests. Therefore, cutting old-growth in the PNW region may have released 10-20 x 10^{15} g C over the last century, which is equivalent to 3-6% of the currently estimated CO_2 release from all sources worldwide during the 100-yr period. The magnitude of the calculated release for the PNW region alone suggests that releases due to forest cutting worldwide may have been underestimated in past assessments.

Data needed for this regional assessment were available for only a subset of the permanent plots. We will improve the accuracy of this assessment in LTER 3 by measuring forest floor and soil C in additional plots. Better information on patterns of litterfall through succession is also needed, because during the early stages of succession detrital production is much lower than losses to the atmosphere from decomposition. Six permanent plots in mature and old-growth stands are currently being used for core studies of fine litterfall (ongoing since 1976), however, these stands are too old to indicate when detrital production becomes equivilent to losses from decomposition. Because litter production and quality can be much different in early seral stages, but are not currently being measured, we will install litter traps in the Young-stand and Long-term Site Productivity (LTSP) Studies (1.2.4). Overall, this information will considerably improve assessment of the regional contribution to the global CO_2 flux.

Table 4. Variables measured in vegetation successional studies.

Measurements	Sampling intervals (yr)
Composition	3-4
Biomass	3-4
Growth of trees	3-6
Mortality of trees	1
Leaf area	3-6
Litterfall	12
Seedfall	2
Standing crop of woody debris	6
Inputs of coarse woody debris	1-5
Soil chemsitry	6

Remote sensing will be used to supply data needed to parameterize and validate models across a range of Andrews sites (1.3). Albedo and foliar N, measured directly, if possible, or else indexed through measures of leaf chlorophyll content (Card *et al.* 1988, Wessman *et al.* 1988, Waring *et al.* in prep.), will be remote sensed at least twice during a year, summer and winter (hopefully with snow present), and field verified. The remote sensing will involve two high-altitude U-2 overflights of the entire Andrews Forest with a high-resolution (AVRISS) spectrometer (400-2500 nm at 10-nm intervals) to be provided by the OSU NASA-funded OTTER project (Dick Waring, Rich McCreight). The USFS/NASA Forest Structure project (Tom Spies, Warren Cohen) will provide additional remotely sensed data on vegetative cover for the Andrews.

1.2.3. Trophic interactions

An understanding of trophic relationships is necessary to any synthesis of ecosystem pattern and process. Because of the importance of arthropods in our systems, the majority of LTER resources in this topical area have been and will continue to be directed toward better understanding the distribution, dynamics, and ecological roles of invertebrate decomposers and herbivores. This research directly bears on the LTER core area addressing spatial and temporal distribution of populations in different trophic levels (2.1).

1.2.3.1 *Decomposers.*

Past work on decomposers focused on arthropods associated with logs and forest floor. A study of arthropods colonizing freshly cut logs was initiated in conjunction with LTER Decomposition Studies (see 1.2.5.) and a related NSF grant (BSR-8516590). The direct role of beetles in removing mass (Zhong and Schowalter 1989) and nutrients (Griffiths *et al.* submitted) was extremely small in comparison to their role in introducing other decomposers (Carpenter *et al.* 1988, Moldenke *et al.* in press). Our work on litter

and soil organisms indicates that successional stage of vegetation was the strongest correlate with arthropod community structure, followed by season of sampling and moisture regime (as indicated by habitat type) (Moldenke *et al.* in prep.).

In LTER 3, we will examine the role of plant successional stage in determining the successional dynamics of litter arthropod communities. Successional changes in arthropod communities may be controlled by predation, by changes in the physical environment (light, temperature, and moisture), or directly by the plants in their role as a food source. We will target future sampling to develop hypotheses about these interactions, and to help identify key species in each functional group. We will also initiate a number of small-scale experiments to examine the role of arthropods in fine litter decomposition (see 1.2.5). Arthropods can have a significant impact on decomposition and nutrient recycling, especially certain common mesofauna such as millipedes (Fogel and Cromack 1977, Persson 1989, Swift *et al.* 1979). We therefore propose to measure litter decomposition with and without large arthropods by varying litterbag mesh size. Finally, we will continue to sample insects that channelize wood as logs proceed from a beetle- to a termite-dominated community (in association with log decomposition studies, 1.2.5).

1.2.3.2 *Herbivory.*

The role of canopy arthropods as herbivores will be studied during LTER 3 because of their capacity to regulate ecosystem production. Herbivory has generally been assumed to be negligible along the west slope of the Cascade Mountains. However, recent work has shown that even low-to-moderate herbivory substantially affects plant productivity and nutrient cycling (Schowalter *et al.* 1986, Schowalter and Crossley 1987, Schowalter 1989).

Climate change could have large impacts on rates of herbivory. Drier forests east of the Cascade Mountains have a much higher rate of arthropod herbivory than those on the west side (Perry and Pitman 1983). Climatic differences could cause this difference

indirectly through effects on predation or plant production of defensive chemicals. Direct climatic effects are also likely but could be complex; drought for example, reduces disease in insect populations, but high temperatures can be lethal.

Effects of herbivory on plants will also be examined during LTER 3. For example, Schowalter (1989) showed that, although less than 1% of old-growth Douglas-fir and western hemlock foliage was consumed, 14% of the buds were destroyed. Such bud consumption could reduce productivity far more than would consumption of an equal mass of foliage. This work also suggests that both reduced predation rates and low vegetation diversity may promote herbivory. In young Douglas-fir at Watershed 10 on the Andrews Forest, defoliation up to 20% had no effect on diameter growth, but did significantly increase turnover (litterfall and throughfall) of foliar N, K, and Ca over the course of the growing season (Schowalter *et al.* submitted).

In LTER 3, we will study annual and successional variation in herbivory by resampling the stands sampled by Schowalter (1989) along with the 20- to 30-year-old stands of the Young Stand Productivity experiment (1.2.4) and additional stands 100 to 200 years old. The effects of predation and vegetation diversity on herbivory will be evaluated in 10- to 15-year-old regenerating stands which are patchy mixtures of many plant species. The effect of non-host plants on hindering discovery and exploitation of host plants will be tested by selective removal of shrub and tree species from plots. Such studies will improve our understanding of the role of herbivory in regulating primary production, and position us well to better evaluate possible ecosystem response to disturbance and climate change.

1.2.4. Controls on long-term productivity

Research in this topical area is directed at gaining a mechanistic understanding of the factors controlling long-term patterns of primary production, a key ecosystem process. It includes three experimental studies that directly bear on all 5 core areas identified by NSF for LTER (2.1): 1) Young Stand Productivity, 2) Effects of Snowbrush on Soils, and 3)

Long-Term Site Productivity (LTSP). Listed as separate components in LTER 1 and 2, these studies are grouped together in LTER 3 because of their common focus on primary production and nutrient cycling.

1.2.4.1. *Young stand productivity*

Installed in 1981, this experiment is designed to investigate the influence of forest structure and topo-edaphic factors on productivity of 20- to 30-year-old Douglas-fir stands. These stands are intended, in part, as validation sites for our stand-level models of effects of nutrient availability on tree growth and competition (1.3.1).

Experimental treatments include thinning, pruning, and multi-nutrient fertilization, each replicated in four stands. As a means of identifying controls over belowground productivity, we have also installed root traps. These are containers open to root ingrowth and filled with sand plus exchange resin (to provide ion-exchange capacity). By pre-loading the resin with nutrient ions, a fertilization treatment is imposed.

We have confirmed our hypothesis that available N is the most important direct control over NPP at the stand level. Other nutrients, however, appear to play an important role in the N cycle and in the ability of trees to take up N. For instance, N mineralization rates (anaerobic) correlate positively with concentration of exchangeable base-metal cations (especially Ca) and foliar N concentration correlates more closely with total soil P and exchangeable Ca than with measures of soil N availability. These findings are consistent with those of Schulze *et al.* (1989) in an acid-stressed German forest, but were unexpected here because our volcanic soils are rich in P and base cations and because precipitation is not very acidic. In contrast to nutrients, neither aspect nor soil rock content correlates well with NPP across this site, suggesting that water availability may explain relatively little spatial variability in NPP at this site.

1.2.4.2. *Effects of snowbrush on Douglas-fir growth*

This experiment examines the effects of snowbrush (*Ceanothus velutinus*), an early successional N-fixing shrub, on the growth of Douglas-fir and on soil chemical and physical properties. The basic hypothesis is that high density of snowbrush will suppress growth of Douglas-fir in the first 10-20 years, but that thereafter Douglas-fir will grow better in the presence of snowbrush because N fixation by snowbrush will lead to long-term increases in soil N availability. The study has attracted the attention of forest managers who have long debated whether the presence of N-fixers (*Ceanothus* and *Alnus* spp.) early in succession increases or decreases conifer growth over the long-term. The study also provides interesting possibilities for comparison with studies of ecosystem effects of invasion by N fixers elsewhere (*e.g.*, Vitousek *et al.* 1987, Vitousek and Walker, in press).

The study design consists of 4 replicates of 4 treatments (different snowbrush densities) at a site logged and burned in 1983 and planted in 1984. Treatments went as planned, but snowbrush has been growing much more slowly than expected. As a result, the current height and cover of snowbrush bear little relation to the intended treatments. A vegetation survey in 1990 will determine whether there are areas of dense snowbrush large enough to allow us to rearrange the treatment plots and to proceed with the study. Snowbrush density will no longer be randomized, as in the original experimental design, but we do have extensive pre-treatment soils data, which will allow us to determine whether snowbrush has preferentially occupied more or less fertile sites. If the snowbrush experiment cannot be carried forth as originally intended, the site will be used instead for small-scale manipulations for the nearby Long-Term Site Productivity study described next.

Table 5. Experimental manipulations, subplot treatments, and measurements planned for the long-term site productivity experiment during LTER 3.

Manipulations[1]	Subplot Treatments	Measurements
standard	vegetation-free	total C and N (Leco, Kjeldahl)
semi-clean	planted to conifers	microbial C and N (fumigtation-extraction)
clean	planted to conifers, removal of understory species	belowground food-web structure (Ingham et al. 1989)
semi-clean + broadcast burn	planted to conifers, surface litter removed	anaerobic mineralizable-N (Binkley and Hart 1989)
	planted to conifers, trenched to prevent root turnover	*in situ* rates of gross and net mineralization, nitrification (Davidson et al. in press a, submitted.
		N-fixation (C_2H_2 reduction)
		size distribution and stability of soil aggregates (Elliott 1986. Strickland et al. 1988, Tisdall and Oades 1982)
		water storage (pressure plate, oven-dry wt.)
		nutrient leaching (Ion exchange resins; if add. funding avail., zero-tension lysimeters)
		extractable cations, NOx, CH_4, CO_2 emissions (soil cover technique; Ryden and Dawson 1982, Steudler et al. 1989, Edwards 1982, Ewel et al. 1987)
		field soil transfers as a bioassay of biological activity (Amaranthus and Perry 1987)
		net primary production (allometric, equations), mortality, litterfall

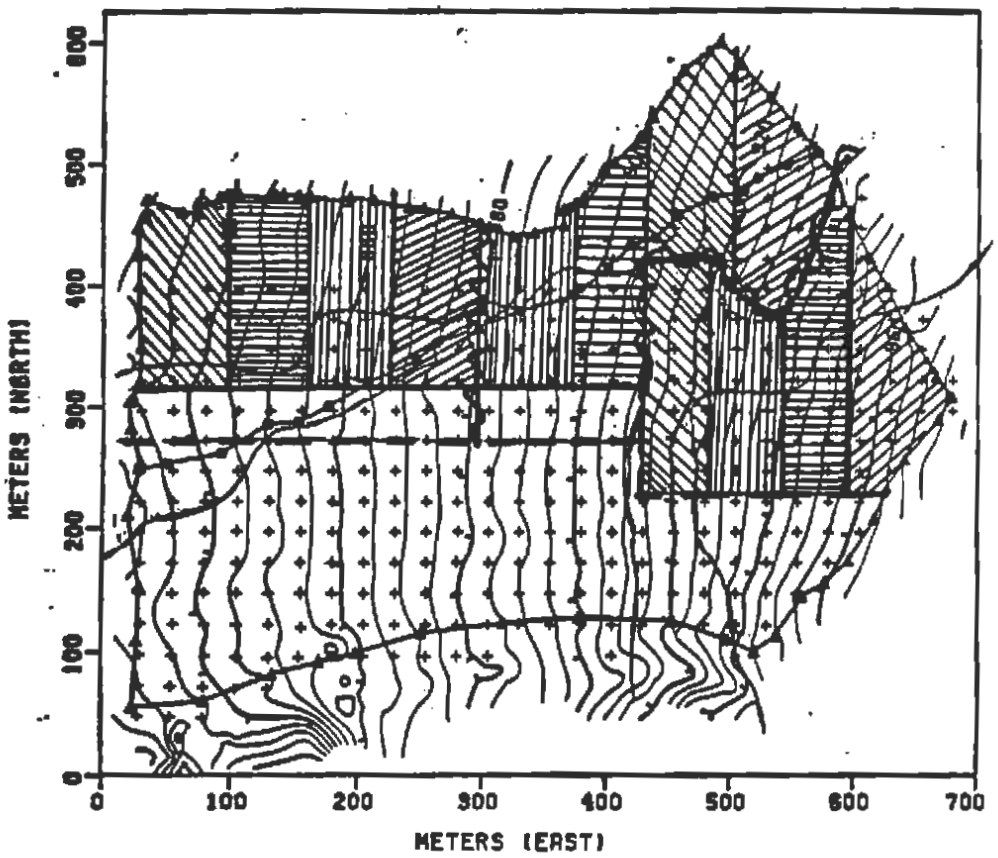
[1] standard = clearcut harvest with standard utilization levels of wood products removed with logging slash is left unburned but scattered evenly over the site; semi-clean = stem-only clearcut harvest with all residue >20 cm dia. and >2 m length removed; clean = whole-tree harvest with all residue >5 cm diameter and >30 cm length removed.

1.2.4.3. *Long-term site productivity (LTSP)*

PNW researchers generally agree that soil N and OM stores are important to long-term productivity (*e.g.*, Perry *et al.* 1989a), and concerns have been voiced over the past 20 years that forest management practices in the region remove excessive amounts of C and N. This experiment is the first designed to test this hypothesis over the long term. Plots will be logged, and subjected to different levels of burning and slash and litter removal (Table 5).

This experiment will also provide insights into general mechanisms that help stabilize systems against natural disturbances, such as wildfire and insects, and against climate change. We believe that the spatial and temporal pattern of system recovery after catastrophic disturbance is determined by biological legacies from the pre-disturbance stand. Such legacies may be structural (*e.g.*, decayed logs in the soil, or soil aggregate structure created by the previous stand), biological (*e.g.*, propagules of higher plants, mycorrhizal fungi, and other soil microflora), or chemical (*e.g.*, local accumulations of C, N or allelochemicals in the soil). Our LTSP experiment therefore involves selective manipulation of several of these legacy elements in order to determine the pattern and magnitude of their effect on primary production, nutrient cycling, and other system behavior.

The importance of legacies in ecosystem recovery spins out of two pieces of work by members of our group and others: recovery in areas damaged during the 1980 eruption of Mt. St. Helens, and the mechanisms underlying poor recovery on high-elevation clearcuts in southwest Oregon and northern California. In both cases, system recovery is greatly influenced by biotic factors that persist in the soil after destruction of the forest (*e.g.*, mycorrhizal fungi, vegetative propagules, buried logs and seeds, large soil aggregates). Our initial studies indicate that site degradation in high-elevation clearcuts is related to disappearance of legacies (especially mycorrhizal fungi and large soil aggregates) in the absence of perennial plants. These observations sparked our interest in the importance of



CUT BOUNDARY

BLOCK BOUNDARY

MINIMUM SLASH REMOVAL

STANDARD YUM

STANDARD YUM AND BURN

MAXIMUM SLASH REMOVAL

Figure 4. Arrangement of Long-Term Site Productivity plots. Yum refers to "yarding unmerchantable material", the "semi-clean" manipulation in Table 5. "+" indicates location of sample point on coarse grid.

positive feedback between plants and various aspects of soil biology, chemistry, and structure in regulating ecosystem stability (so-called "bootstrapping", see Perry *et al.* 1989b).

We hypothesize that systems rapidly degrade when the positive feedback links between soils and plants are disrupted. Vegetation-free plots within the LTSP will be used to test this hypothesis, and to determine the time scale over which legacies such as mycorrhizal fungi and soil structure can persist in the absence of their energy source (plants). This work relates closely to that of others on nonequilibrium and positive feedback in ecosystems (Gutierrez and Fey 1980, DeAngelis *et al.* 1986, Pastor and Post 1988). We believe it will yield general insights into the nature of ecosystem stability that have important implications for a variety of disturbances, including ecosystem response to climate change. To test the generality of these concepts, we are installing similar studies in moist tropical forest at La Selva (Costa Rica) and dry tropical forest in Zambia.

During LTER 2, we established a 25 x 25 m grid over the entire 15-ha LTSP study area and sampled soil for total N at each grid point (Fig. 4). Results show that soil N is quite uniform across the site at this scale, so blocking will be unnecessary. We have also installed several fine-scale soil sampling transects (1- or 2-m spacing). On two of these, we sampled total soil C and N, anaerobically mineralizable N, microbial biomass C and N, and soil invertebrates. On the remainder, we sampled only total N. These fine-scale transects revealed patterns at two scales for total C, total N, and microbial biomass: 1 m and 20 m, the latter corresponding roughly to the width of an old-growth tree crown. We have thoroughly mapped trees and logs in the vicinity of these transects and are currently using multivariate techniques to identify the source of both the 1- and 20-m patterns. This analysis will then be used to guide the layout of subplot treatments and to design future sampling strategies.

Experimental manipulations in LTSP include clearcutting with and without slash burning and with different levels of OM removal (Table 5). Several subplot treatments will

Table 6. Continuing and proposed (new) decomposition experiments for LTER 3.

Substrate type	Experimental methods	Duration (yrs)	Variables measured
Logs	Long-term time series	200	mass, N content, decomposer colonization, fragmentation respiration
Logs	Stream/land comparison	20	mass, N content, decomposer colonization, fragmentation
Snags	Snag fragmentation	20	fragmentation
Branches	Size effect	12	mass, N content
Branches	Clearcut (new)	10	mass, N content
Leaves	Intersite (new)	10	mass, N content, C fractions
Leaves	Succession effect (new)	10	mass, N content
Leaves	Invertebrate effect (new)	2	mass, N content, arthropods

be nested within these large site-preparation plots in order to remove or alter various legacy elements and thus determine their effect on system behavior.

The LTSP study is being designed in collaboration with the USFS PNW Station LTSP project under the direction of Bernard Bormann, and will serve as a template for a series of such studies to be installed throughout the PNW region.

1.2.5. Decomposition processes

Research on decomposition and release of nutrients from detritus bears strongly on three of the LTER core areas: controls of primary productivity, nutrient cycling, and OM accumulation (2.1). During LTER 1 and 2, we focused primarily on coarse woody debris (CWD), but in LTER 3 more emphasis will be placed on decomposition of fine litter, roots, and branch wood (Table 6). A major task in LTER 1 and 2 was the installation of long-term decomposition studies of fine and coarse woody debris (Carpenter *et al.* 1988). The thrust of these experiments is to determine effects of substrate quality, piece diameter, and environment on the pattern and rate of decomposition and nutrient release. In the largest and longest experiment, more than 500 logs (ca. 50 cm in diameter and 5.5 m in length) of four species were placed in old-growth forests (Harmon submitted). Mass and N content have been sampled annually since 1985, revealing unexpectedly rapid decay rates for Pacific silver fir (*Abies amabilis*) (Fig. 5).

This experiment has offered an exceptional opportunity for detailed study of the decay process. In conjunction with an NSF grant (BSR-8516590), rates of consumption by invertebrates, N fixation, water infiltration, leaching, fragmentation, respiration, and changes in carbon fractions (*i.e.*, cellulose and lignin) were measured for two years. These studies revealed that logs are net sources of N for the forest floor in their early stages of decomposition (Griffiths *et al.* submitted). The primary mechanism of export is the production and subsequent fragmentation of fungal fruiting bodies. Logs thus differ strikingly from fine litter, in which leaching controls N export and fungi serve primarily to

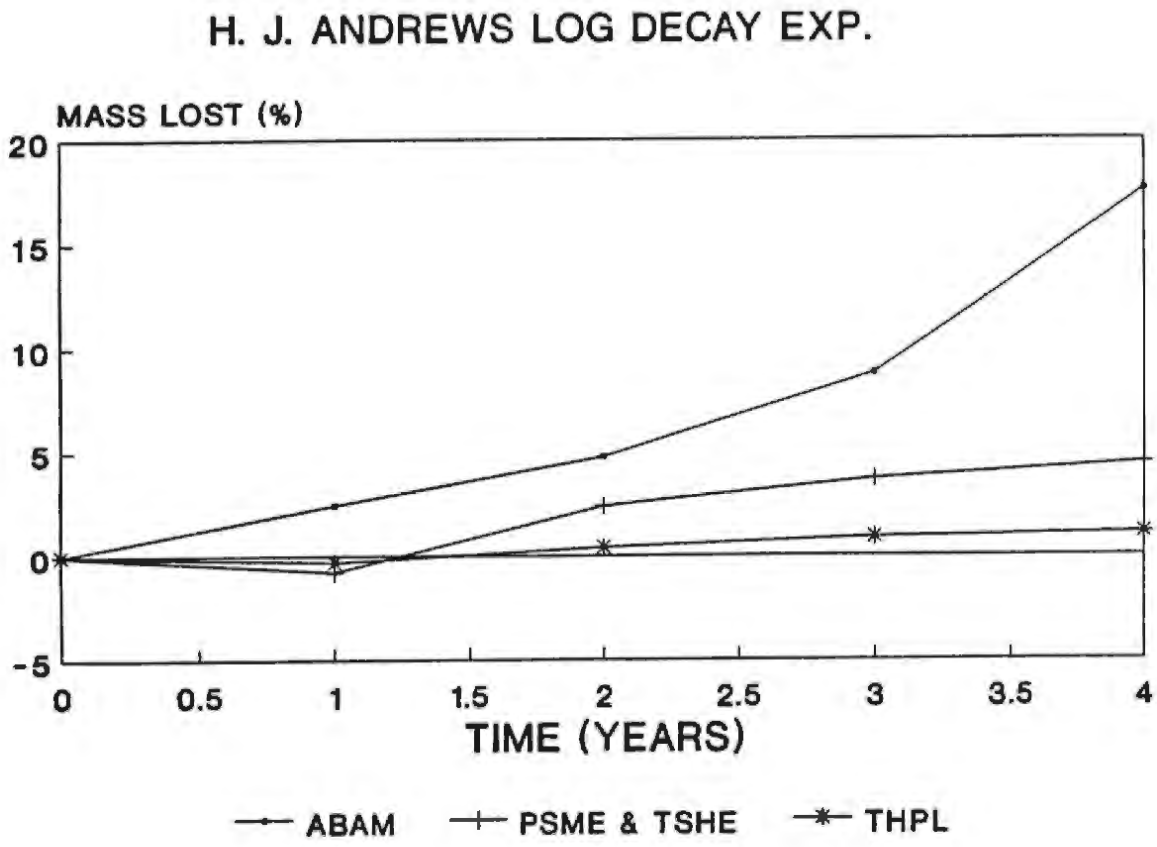


Figure 5. Cumulative mass loss from logs in long-term decomposition experiments. ABAM = *Abies amabalis*, PSME = *Pseudotsuga menziesii*, TSHE = *Tsuga heterophylla*, THPL = *Thuja plicata*. Note the increasing rate of decomposition for *Abies*.

immobilize N (Vitousek and Matson 1985, Hart and Firestone submitted). We found also that excess moisture severely limits log respiration (Fig. 6). Log and fine litter respiration are asynchronous at Andrews; log respiration peaks at the end of summer drought (Carpenter *et al.* 1988) when fine litter respiration is at a minimum (Phillips 1975). Such information on the role of water in decomposition processes is important in modeling effects of climate change on nutrient availability and CO_2 release.

In other studies begun in LTER 1 and 2, we have examined decomposition of branch wood, compared log decomposition between land and stream environments (1.2.6), and measured snag fragmentation rates (Table 6). Mass and N content in 1-, 2-, 4-, and 8-cm diameter branchwood have been measured annually since 1985 for the same four species used in the log experiment. As expected, smaller woody material decomposes faster than larger material, although pieces >10 cm decay at fairly similar rates. Snag fragmentation has been measured at Andrews and at Cascade Head Experimental Forest, a wetter coastal environment; rates for a given species are similar at both sites suggesting that environment has little effect on this process.

In LTER 3, we will continue to measure decomposition rates and N dynamics of branchwood, logs, and snags. New decomposition studies, to be established at the LTSP and Young-stand study sites, will allow us to examine long-term effects of stand age, canopy structure, and nutrient availability on decay and nutrient immobilization/mineralization rates in fine litter, branch wood, and roots. These studies are intended mainly to provide data to parameterize and validate models of release of CO_2 and nutrients from detritus other than CWD (1.3.1.4). Invertebrate control of litter decomposition will be tested by varying litterbag mesh size in conjunction with the Trophic Interaction studies (1.2.3). We will measure fine litter and soil respiration intensively during one year to better resolve seasonal effects of temperature and moisture.

In order to separate effects of temperature and moisture on respiration rates, we will also set up a small-scale experiment in which we alter temperature and moisture

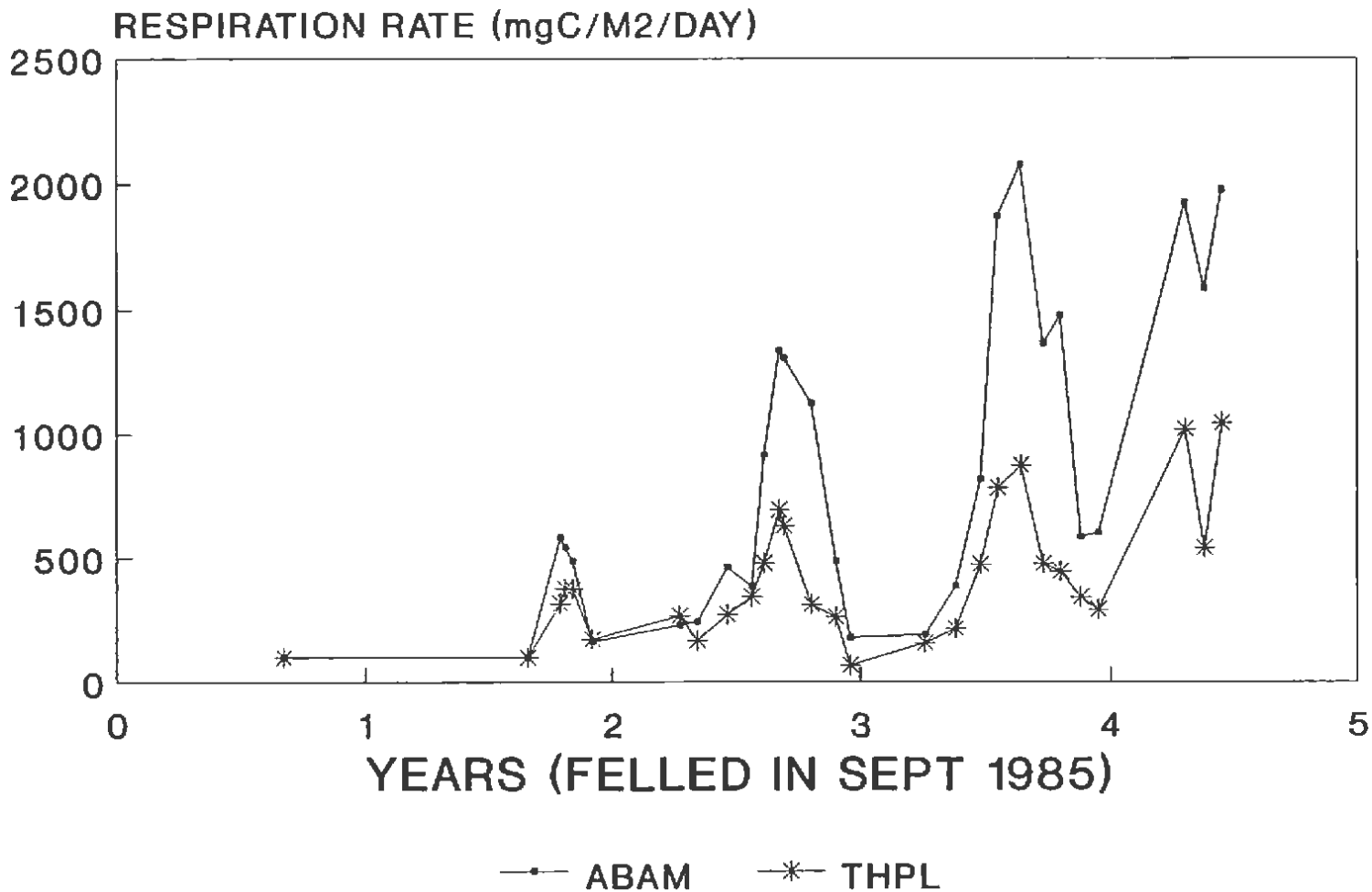


Figure 6. Seasonal respiration patterns for two species of logs in the long-term decomposition experiment. Respiration rates peak for both species in late summer/early fall after an extended drying period. Increasing magnitude of peaks in subsequent years reflects increasing colonization by decomposers. ABAM = *Abies amabalis*, THPL = *Thuja plicata*.

regimes in litter, CWD, and soil. This work will complement the long-term intersite litter decay experiment currently being installed at 21 sites in North and Central America (2.6).

1.2.6 Forest-stream interactions

The Andrews group's broad-based analysis of forest-stream interactions has grown steadily in intensity and breadth since the mid 1970's (Swanson *et al.* 1982a, Gregory *et al.* in press). LTER activities have been complemented by experimentation in natural and artificial streams (Lamberti *et al.* 1989), computer simulation, and field observations. These studies have been set within a hierarchical framework extending from the single particle (*e.g.*, boulder or piece of woody debris) to the full river network (Fig. 7). The major focus has been on influences of geomorphology and streamside vegetation on aquatic ecosystems, including distributions of aquatic organisms, rates of nutrient processing through a drainage network, and basin-wide distribution of major vertebrate predators (rainbow and cutthroat trout). Research in the forest-stream component bears strongly on all five core areas of LTER (2.1).

The forest-stream research component supports a diverse program of long-term measurements (Table 7) related to the aquatic studies and to other components: 1) long-term measurements to characterize and follow changes in channel morphology, riparian plant communities, and stream ecosystems in forest of different ages; 2) modeling and field experiments of CWD dynamics, including input (Van Sickle and Gregory submitted), decomposition (1.2.5), movement (Lienkaemper and Swanson 1987), and geomorphic consequences (Keller and Swanson 1979, Harmon *et al.* 1986); and 3) recovery of stream and riparian ecosystems after catastrophic disturbance by debris flows (Gecy and Wilson in press, Lamberti *et al.* submitted).

In LTER 3 we will continue studies of influences of valley floor geomorphology and vegetation patterns on aquatic systems. Long-term observations of forest-stream linkages have demonstrated that channel structure and riparian plant communities strongly

Table 7. Long-term measurements concerning forest-stream interactions. For description of experimental watersheds see Table 12.

Research Topic	Interval	LTER 2	LTER 3	Core Area[1/]
Stream Chemistry				
Proportional Sampling				
WS 10	Continuous	X	X	4
WS 2	Continuous	X	X	4
Mack Creek	Continuous	X	X	4
Storm Sampling				
WS 10	Annual	X	X	4
WS 2	Annual	X	X	4
Basin-Level Patterns in Surface Water Chemistry				
Lookout Ck Basin	5-yr		X	4
McKenzie R Tribs	5-yr		X	4
Fluvial Geomorphology				
Channel Cross-Sections				
WS 10	Annual	X	X	3, 4, 5
Mack Ck	Annual	X	X	3, 4, 5
Upper Lookout Ck	Annual	X	X	3, 4, 5
Lower Lookout Ck	Annual	X	X	3, 4, 5
Valley Landforms of the Lookout Creek Drainage				
Upper Lookout Ck	Annual		X	3, 4, 5
Mack Ck	Annual		X	3, 4, 5
McCrae Ck	Annual		X	3, 4, 5
Lower Lookout Ck	Annual		X	3, 4, 5
Woody Debris Dynamics				
Wood Mapping				
WS 10	5-yr	X	X	3
WS 2	5-yr	X	X	3
Mack Ck	Annual	X	X	3
Upper Lookout Ck	5-yr	X	X	3
Lower Lookout Ck	5-yr	X	X	3
Quartz Creek	Annual	X	X	3
Movement and Input				
Mack Creek	Annual	X	X	3
Quartz Creek	Annual	X	X	3
Log Decomposition				
Lookout Creek	Annual	X	X	3

influence aquatic processes and fish distributions. Study locations have been selected to include a wide range of geomorphic and vegetation types so that we can observe effects of major floods on channels and riparian zones with differing capacities for change. The probability of a major flood (>10-yr recurrence interval) within the timeframe of LTER 3 is reasonably high, and we are committed to examine the effects of such an event.

The Andrews group, along with others, have pioneered much work on CWD as an important linkage between terrestrial and aquatic systems (Bilby and Likens 1980, Swanson *et al.* 1982a, Harmon *et al.* 1986). Techniques for long-term monitoring of CWD dynamics include time-lapse photography, annual remapping of stream reaches, repeated measurements of permanent riparian vegetation plots, and annual resurvey of a 1000-m reach of third-order stream with every piece of CWD tagged (Van Sickle and Gregory submitted). LTER 2 studies of CWD also include installation of a large-scale experiment in which 170 logs (>5 m in length and >0.5 m in diameter) were placed in a 1.1 km reach of Quartz Creek South where CWD had been removed previously by floods and logging. One year after CWD introduction, fish populations were 22% higher, leaf retention was 2.7 times greater, and 99 new pieces of CWD (>1 m in length and >10 cm in diameter) had been retained.

Several large debris flows in LTER study sites in February 1986 have provided an excellent opportunity to examine effects of infrequent, but important, geomorphic disturbance processes in this region. Pre- and post-disturbance observations (Table 7) at Quartz Creek North and Watershed 10 revealed surprisingly rapid recovery of riparian plant communities, aquatic primary production, invertebrates, and fish relative to control reaches (Lamberti *et al.* submitted). In Quartz Creek North, both fry and adult trout were more than twice as abundant in the debris flow reach than in the upstream control. Over-winter trout survival continues to be ca. 50-75% greater in the control reach, but summer growth and production are much greater in the debris-flow reach. We attribute this response to greater aquatic primary production and subsequent production of aquatic

Table 7 (continued)

Research Topic	Interval	LTER 2	LTER 3	Core Area[1/]
Invertebrate Drift and Benthic Composition				
Mack Ck Old-Growth	Annual		X	2
Mack Ck Clearcut	Annual		X	2
Fish Population Dynamics				
Mack Ck Old-Growth	Annual	X	X	2
Mack Ck Clearcut	Annual	X	X	2
Lower Lookout Ck	Annual		X	2
Recovery After Catastrophic Disturbance				
Quartz Creek Debris Flow				
Geomorphology	Annual	X	X	2, 5
Stream Chemistry	Seasonal	X	X	2, 5
Vegetation	Annual	X	X	1, 2, 5
Algae	Seasonal	X	X	1, 2, 5
Detritus	Annual	X	X	2, 5
Invertebrates	Seasonal	X	X	2, 5
Trout	Seasonal	X	X	2, 5
Whole Stream Nutrient Enrichment				
Lower Lookout Creek	Seasonal		X	1, 2

[1/] Core Areas
1. Pattern and control of primary production
2. Spatial and temporal distribution of populations selected to represent trophic structure
3. Pattern and control of organic matter accumulation in surface layers and sediments
4. Pattern of inorganic inputs and movements of nutrients through soils, groundwater, and surface waters
5. Pattern and frequency of disturbance

insects and to enhanced foraging efficiency at higher light intensities. Vegetation recovery is dominated by resprouting at WS 10, whereas it is seedling-dominated at the more severely disturbed Quartz Creek North site (McKee 1988). Populations of certain aquatic and associated riparian organisms, especially aquatic insects, have recovered extremely rapidly, but overall community structure will apparently take much longer to return to its pre-disturbance state.

Fish populations in the clearcut (cut in 1964) and old-growth reaches of Mack Creek are reassessed annually. Trout populations in the clearcut originally were more than double those in the forest reach, but now are only 60% greater. This decline represents an apparent trophic response to the progressive canopy closure over the clearcut reach since 1964. In LTER 3, we will extend this network of long-term monitoring sites to include constrained and unconstrained (wide valley floor) reaches of lower Lookout Creek.

Basin-level patterns of water chemistry are important indicators of changes in upland vegetation or upstream aquatic processes resulting from natural disturbances, land use, and climate change (Triska *et al.* 1984, Webster and Swank 1985, Meyer *et al.* 1988). Current information on surface water chemistry is mainly restricted to small watersheds, ignoring basin-level patterns. Therefore, in LTER 3, we will conduct synoptic, basin-level surveys of stream-water chemistry. Sample sites will be selected to complement previous nutrient uptake studies and to represent contrasts in landform and vegetation that influence water chemistry.

Nutrient transfers in solution among hillslopes, channel, floodplain groundwater system, and vegetation are important elements of forest-stream interactions. Steve Wondzell (PhD student with Swanson) is examining these interactions at storm event and seasonal time scales in the Andrews. The timing of hydrologic fluctuations, geomorphic controls on surface and subsurface flow paths, and spatial patterns of key plant species (*e.g.*, N-fixing *Alnus*) strongly influence the magnitudes and patterns of nutrient fluxes in riparian zones.

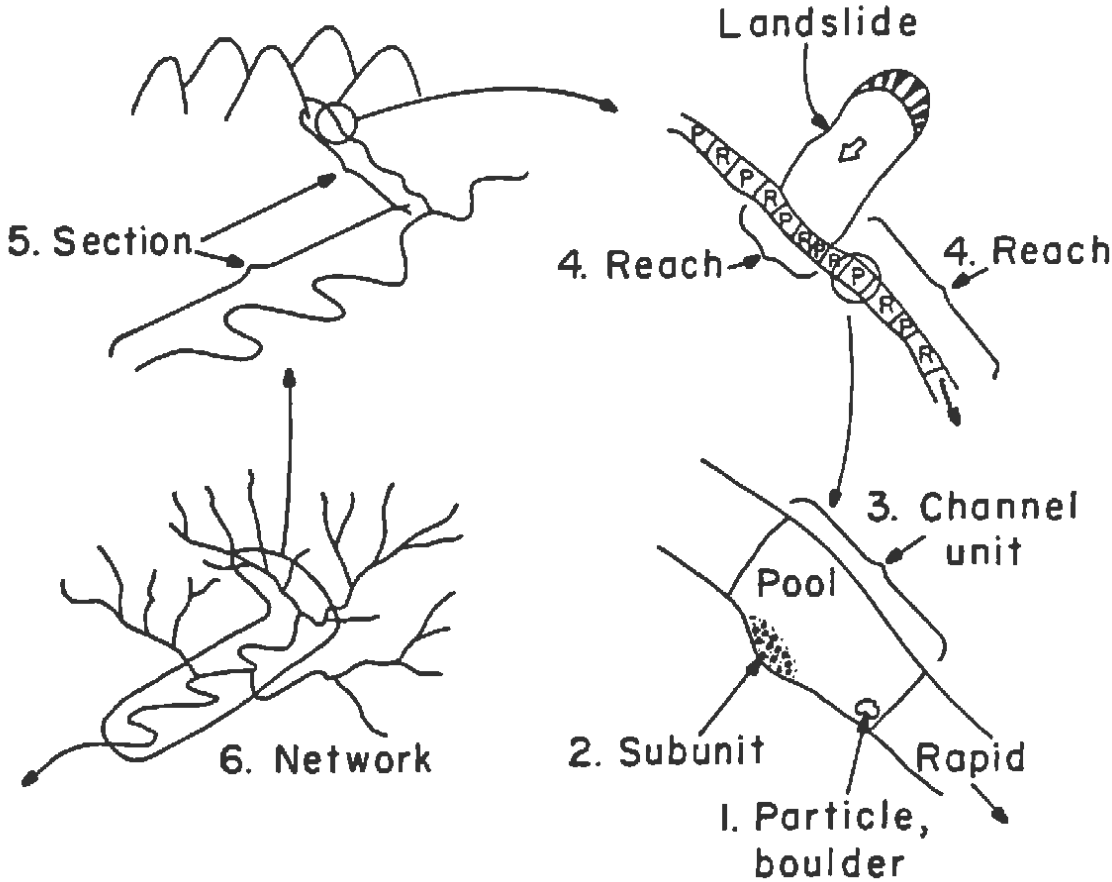


Figure 7. Hierarchical structure of river systems scaled from single particle to drainage network (Swanson *et al.* 1990). Scales are numbered from the single particle (1) to the full drainage network (6). At the channel-unit and reach scales (3), P = pool and R = riffle. The Section scale (5) shows mountain and lowland valley examples.

In LTER 3 we will continue long-term measurement programs (Table 7), incorporate additional study reaches within the basin, and increase efforts to integrate our understanding of geomorphic and vegetative controls of aquatic systems. We will continue to work toward incorporation of ecosystem perspectives into guidelines for land management (*e.g.*, Gregory and Ashkenas in press). Particular effort will be directed toward modeling lotic processes and population dynamics and in scaling up these models from stream reach to basin scale.

1.3. STAND AND LANDSCAPE SYNTHESIS

Synthesis will receive increased attention in LTER 3. Results and concepts from LTER 1 and 2 and other relevant work (Fig. 2) will be used to address the question:

> **How do natural disturbance (*i.e.*, wildfire, geomorphic processes), land use (*i.e.*, logging), and climate change (*i.e.*, warming, drying), acting individually or jointly, affect key ecosystem variables at stand and landscape scales?**

Models will necessarily play a major role in addressing such questions, particularly those involving long-term changes in productivity and landscape pattern. The models are not ends in themselves, but rather vehicles for synthesis. They serve to integrate the data collected and concepts developed in detailed process studies at the Andrews Forest and elsewhere. These results, in turn, provide crucial background with which to parameterize and validate models. Our databank development over the past 15 years is paying off handsomely as we enter this synthesis phase. Models also allow us to prioritize and design future research and to formulate mechanistic hypotheses about ecosystem response to disturbance. In several cases, we use models already in use across a range of sites worldwide. Adaptations to PNW conditions will be needed, but this process of modification is itself an important step in ecosystem analysis in that it highlights fundamental differences in ecosystem structure and function among sites.

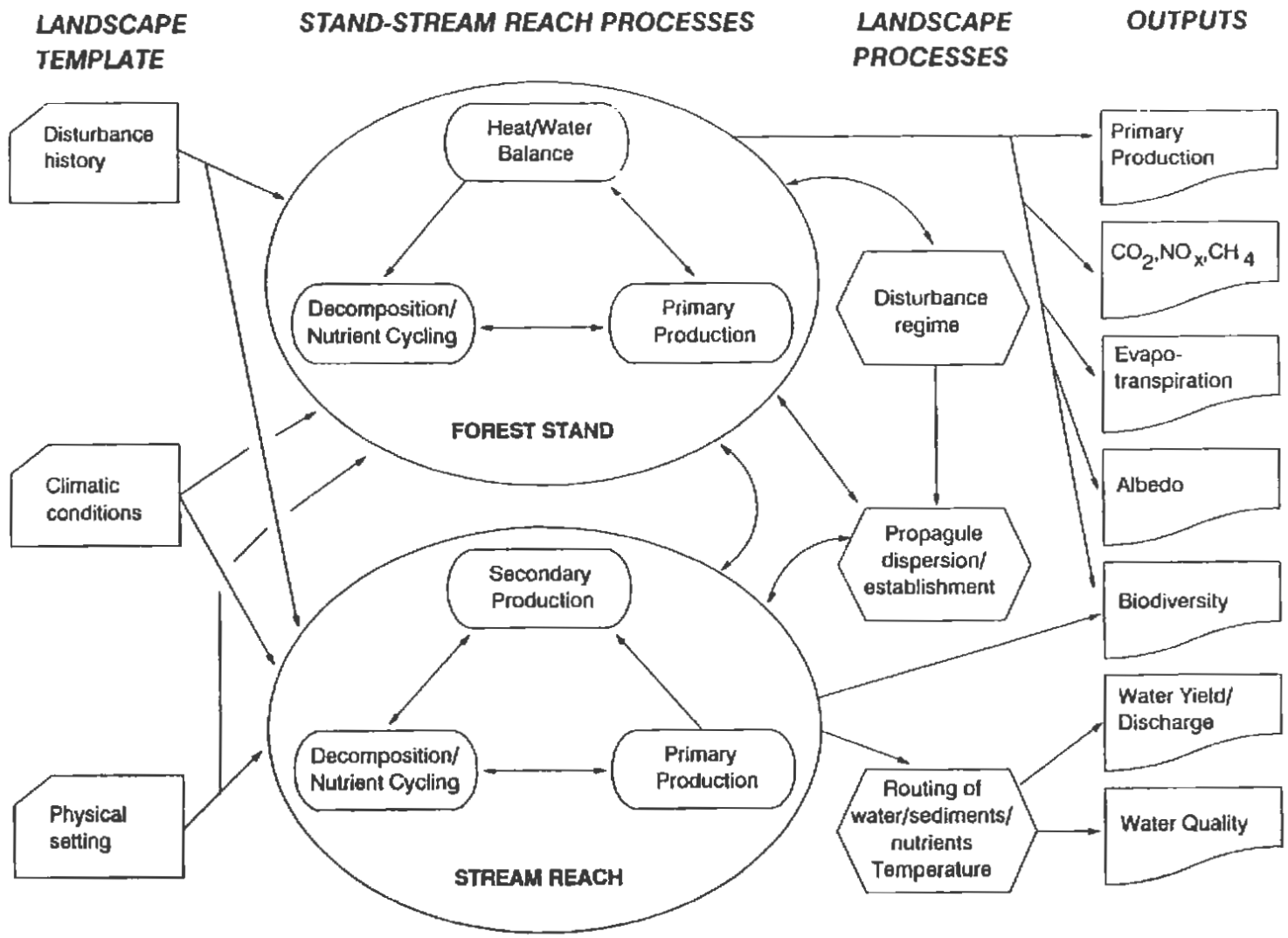


Figure 8. Linkages among stand and stream-reach processes.

Our synthesis approach, which includes modeling and GIS applications, recognizes the hierarchical relations among processes and output variables at a series of scales (Figs. 8, 9). The synthesis concentrates on stand and landscape scales, but draws heavily on process-oriented studies conducted as part of LTER and other projects. Thus we recognize that finer-level processes, such as foodweb interactions, strongly influence stand-level processes, such as nutrient cycling. Simultaneous modeling at these finer levels of resolution will help ensure that relationships in stand-level models are based upon mechanistic understanding and not fortuitous correlations.

Our approach to modeling differs fundamentally from that of the International Biological Program (IBP) modeling of the 1970's. In the IBP, it was assumed that a detailed mechanistic description of the entire system would eventually result in understanding at the stand and larger scales. Our approach in LTER 3 is less reductionist in that we are gathering data and formulating hypotheses at the landscape scale which serve to organize, prioritize, and constrain the modeling.

Specific modeling goals include the ability to forecast trends in: 1) primary production, biodiversity, water yield, and water quality (four variables that we hypothesize are sufficient together to indicate overall ecosystem health); 2) fluxes of radiatively important trace gases (RITGs) (particularly CO_2), surface albedo, and evapotranspiration (three variables that strongly influence global climate); and 3) leaf chlorophyll content (a variable along with albedo that can be sensed remotely, and which can therefore be verified at a landscape level). In addition, of course, we are interested in many other ecosystem variables including quantity and quality of C and N stores, soil aggregate structure, and composition of the soil microbial community.

Major linkages among processes, driving variables, and site physical conditions, and output variables are summarized in Fig. 8. Site physical conditions (*e.g.*, parent material, slope), disturbance history, and climate act as a template that constrains stand- and landscape-level response to disturbance. Landscape-level processes, such as nutrient

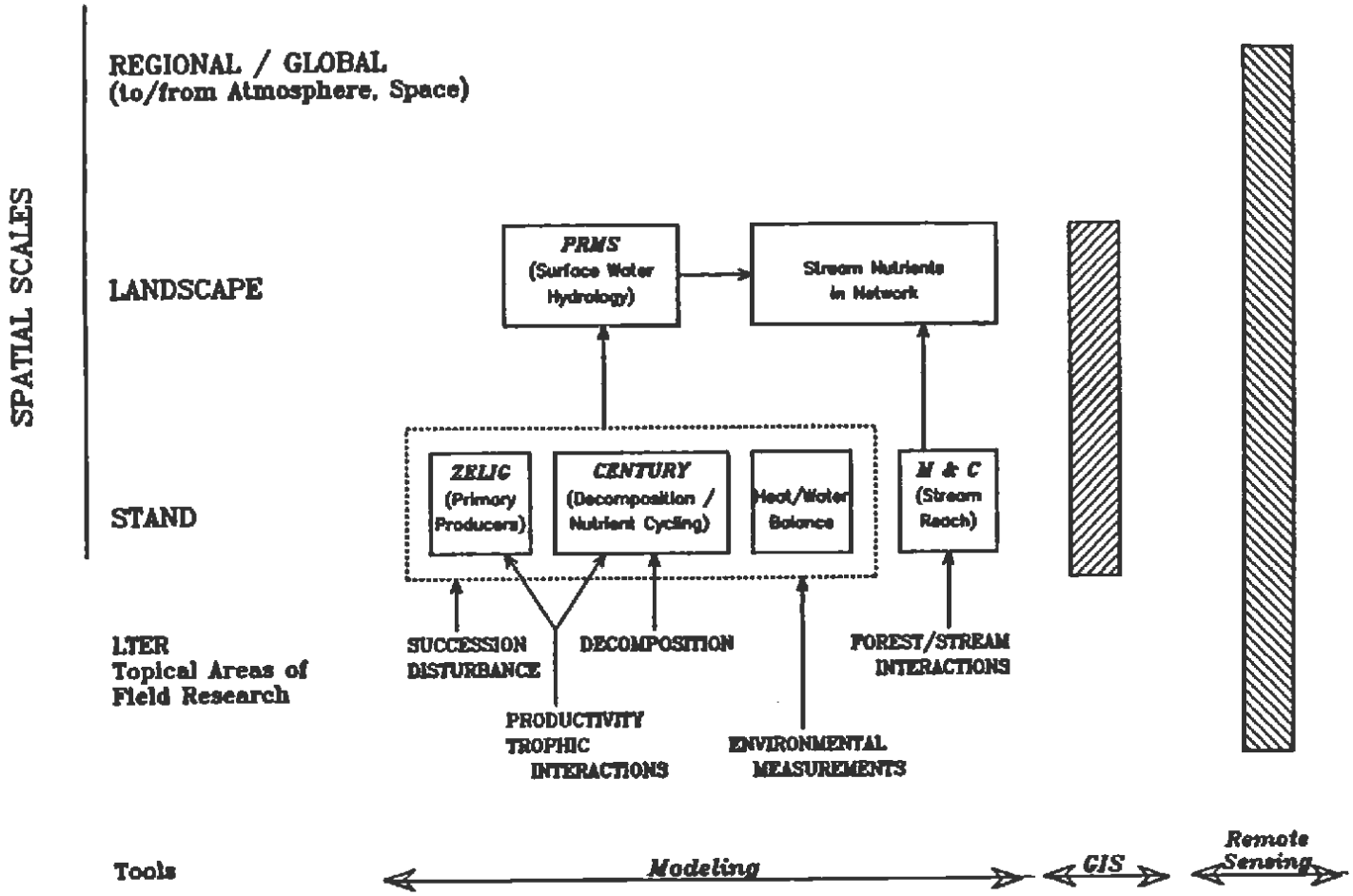


Figure 9. Relations among stand-, reach-, and landscape-level models and scales at which modeling, GIS, and remote-sensing techniques will be applied.

routing, propagule dispersion, and disturbance propagation, both influence and are influenced by stand-level processes. The synthesis links to regional and global research efforts by providing estimates of variables that are thought to strongly influence climate change. Further, LTER researchers will work closely with several NASA- and Forest Service-sponsored remote-sensing programs in verifying model predictions at the landscape and regional scales.

The time scale of interest in synthesis activities must extend from decades to at least several centuries, because this is the time scale of land-use and climate change, ecosystem response at the stand and landscape scales, and the lifespan of dominant trees. Moreover, centuries are required for some important ecosystem components to equilibrate after disturbance (*e.g.*, levels of CWD after a natural forest is converted to intensive management--Sachs and Sollins 1986, Spies *et al.* 1988). The spatial scales of interest range up to 10,000 ha, an area roughly the size of the Andrews Forest and which spans the range of climatic, hydrologic, and ecological conditions present in the central Cascade Range.

These synthesis activities could not possibly be carried out solely with LTER funding. Collaboration is essential and is already well underway with participation by researchers from Andrews, other LTER and non-LTER sites, and four Federal agencies (USFS, USGS, and EPA). Examples include work by Dean Urban (Univ. Virginia) and Mark Harmon (OSU) on applying ZELIG to Andrews forests, and work by USGS and USFS researchers on hydrologic modeling at Andrews Forest (see letters of commitment--Appendix H). The EPA Global Change Research Program in Corvallis has embarked on a major modeling effort at stand, landscape, regional, and continental scales using Andrews as a case study. Ron Neilson is our principal contact with this group and a collaborator on this proposal. Two post-docs, to be hired to help with Andrews modeling, would be funded in part by EPA and USFS PNW Station projects.

These synthesis and modeling activities add little to the cost of LTER 3, yet pay off handsomely. Except for the two new post-docs, all other personnel requirements will be

met by reallocation of OSU- and PNW Station-funded FTE from other activities (*e.g.*, P. Sollins and G. Grant).

Below we describe first the models (available and proposed) to be used at the scale of the stand and stream-reach as well as two models specific to landscape-level interactions (Fig. 9). We then give three examples of how the models will be used in conjunction with landscape-change scenarios to gain insight into landscape-level response to disturbance, land use, and climate change, insights that we expect will be generalizable well beyond the boundaries of the Andrews Forest.

1.3.1. Stand and stream-reach models (Sollins, Gregory, Neilson)

Here we describe the models that consider interactions between above- and below-ground portions of the forest ecosystem and between forests and adjacent stream reaches (Fig. 8). The stand and stream reach models contain the same three basic parts: heat/water balance, primary production, and nutrient cycling/decomposition (Fig. 8). Site parameters include the disturbance history and site physical condition. Driving variables are meteorological conditions and the disturbance and management regime that are imposed on the site. Output variables are those that are of special interest to us or to others working at regional and global scales.

The models we describe here are mainly coarse-resolution with long time steps (*e.g.*, yearly). We recognize also the need for fine-resolution models (*e.g.*, daily time step) that deal explicitly with detailed physiological processes or trophic relations. Some work on such fine-resolution models is in progress already and more will be initiated (described below under the appropriate topic headings), but for the most part this fine-resolution modeling falls outside the scope of LTER funding.

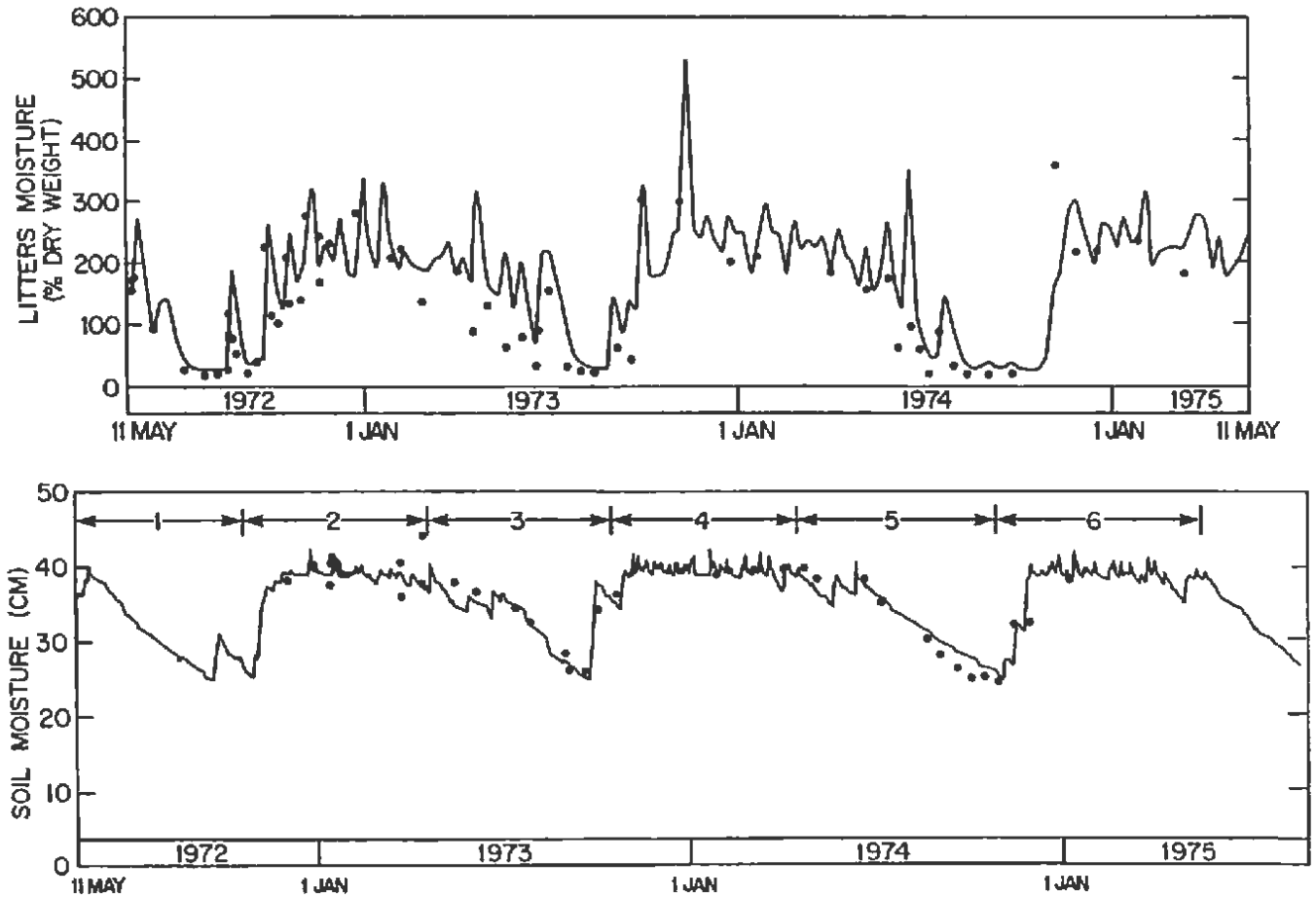


Figure 10. Observed vs. simulated litter and soil moisture at WS 10, H.J. Andrews Experimental Forest. Simulations based on Conifer model (Sollins *et al.* 1979).

1.3.1.1 *Stand water/heat balance* (Sollins, Grant, Leavesley)

A water/heat balance model considers effects of climate, site physical condition, and soil and canopy structure on heat and water fluxes and thus on temperature and moisture content of canopy, litter, and soil. Temperature and moisture are, of course, critical inputs to primary producer and decomposition/nutrient cycling models.

Literally dozens of hydrology models exist in the literature; four were developed under IBP for the Andrews alone (Running *et al.* 1975, Overton and White 1978, Sollins *et al.* 1979, Rogers unpublished). All work reasonably well (Fig. 10), but none meet our needs completely. A basin-scale hydrology model currently being adapted for the Andrews Forest by George Leavesley (USGS-Denver) and Gordon Grant (see 1.3..2.1), also provides a partial starting point.

We plan to construct a new stand-level model building on work to date, but improving representation of effects of canopy structure. Collaborating will be Gordon Grant (PNW), George Leavesley (USGS-Denver), Phil Sollins (OSU), Dean Urban (Univ. Virginia), and Danny Marks (EPA-Corvallis). Work at Andrews (Harr 1981, 1986, Berris and Harr 1987) provides a solid base for efforts to better represent effects of stand structure on heat and water balance, especially on the accumulation and melting of the wet snow typical of the PNW. Model implementation and testing will be aided greatly by the availability of long-term datasets for Andrews sites on climate and streamflow and on moisture content of litter, soil, and CWD.

1.3.1.2 *Primary producers* (Harmon, Urban, Neilson)

We plan to use ZELIG (Smith and Urban 1988), a FORET-type stand simulation model (Shugart and West 1977, 1980) that relates growth of individual trees to temperature and availability of water, light, and nutrients. Unlike FORET, ZELIG simulates transects as well as forest gaps. The strength of ZELIG is that it allows modeling of inter- and intra-specific competition. This will allow us to examine the effects of land-

use and climate-change scenarios on species composition as well as on primary production. In addition, by coupling ZELIG to water/heat balance and nutrient cycling/decomposition models, we will be able to examine many of the feedbacks among these broad classes of processes (Fig. 8).

Dean Urban (Univ. Virginia) and Mark Harmon (OSU) have made considerable progress in adapting ZELIG to the Andrews. Initial attention has focused on defining temperature limits and maximum growth rates for 30 important tree species, building on previous work at Andrews Forest (Dale and Hemstrom 1984; Dale *et al.* 1986). Data on tree allometry (biomass estimates for 1500+ trees) and growth and mortality throughout the PNW region (1.2.2) are being used to parameterize and validate ZELIG. Effects of nutrients on tree growth and allocation will be incorporated into the model based on simple relations developed by Levin *et al.* (1989) and Agren and Ingestad (1987), then tested against data produced in the LTSP and Young-stand Studies (1.2.4). Data from these experiments will also allow us to examine the feasibility and value of incorporating small-scale spatial pattern in soil properties and vegetation ("legacies") into stand-level models. The reciprocal effects (of plants on nutrient availability) will be investigated by coupling ZELIG to a decomposition/nutrient cycling model (CENTURY), as discussed below.

We recognize that ZELIG is not the appropriate context in which to consider detailed plant physiological processes or the interactions between these and moisture and nutrient availability. A fine-resolution model that focuses on single trees of various species is needed. Such models are under development: for example, TREEGRO produced by Dave Weinstein and colleagues (EPA/Cornell ROPIS project). Working in collaboration with Weinstein, Dean Urban, and Robert Dixon (EPA-Corvallis), we expect to use such models to improve the empirical functions used in ZELIG to relate growth to resource availability. This work, however, falls outside the scope of this proposal.

1.3.1.3 *Decomposition/nutrient cycling* (Sollins, Hart, Harmon, Turner)

The CENTURY model (Parton *et al.* 1988) describes C, N, and P cycling in grasslands on an annual time step. Adapted recently to forest conditions (W. Parton, pers. comm.), CENTURY will allow us to examine effects of disturbance and climate change on pools and fluxes of C, N, and P and thus changes in nutrient availability and CO_2 fluxes. Extensive data for calibrating CENTURY for Andrews sites are available including litter decay (Fogel and Cromack 1977), mass and nutrient content of litter and branch fall (Grier and Logan 1977, Sollins *et al.* 1980), mortality (Sollins 1982, Franklin *et al.* 1987, Franklin and DeBell 1988), and root turnover (Santantonio and Hermann 1985), although additional data are still needed (1.2.2). We plan to improve representation of coarse woody debris by allowing for several stages of decay (*e.g.*, Graham 1981, Sachs and Sollins 1986). A major challenge will be incorporating effects of temperature, moisture and substrate availability on fluxes of CH_4 and NO_x, especially since factors controlling NO_x fluxes are still under debate (*e.g.*, Firestone and Davidson in press, Davidson *et al.* in press b), and work on CH_4 controls has only just begun to appear (*e.g.*, Steudler *et al.* 1989). We plan to initiate measurements of these processes in conjunction with the LTSP experiments (1.2.4.3).

Data on C and N stores, to be collected in LTER 3 across a fairly wide range of sites (1.2.2), will provide one test of CENTURY under current climatic conditions. The LTSP experiments (1.2.4) will provide additional stand-level tests of predictions concerning effects of stand structure and debris loading on nutrient cycling and decomposition.

As with primary production, finer resolution modeling will also be essential in dealing with intra-seasonal patterns and with the role of individual species in below-ground processes. Ideally, this fine-resolution modeling helps keep a coarse-level model such as CENTURY firmly rooted in reality. We will explore the possibility of adapting Hunt's (Hunt *et al.* 1977, 1987, 1989) foodweb model to PNW forests in order to examine effects of bacteria, fungi, and soil fauna on nutrient availability.

1.3.1.4. *Stream-reach model* (Gregory, McIntire, McKee, post-doc)

The M & C stream model (McIntire and Colby 1978, McIntire 1983) depicts interactions among processes in stream ecosystems (*e.g.*, primary production, decomposition, herbivory, detritivory, predation) in a hypothetical square meter of stream. Effects of changes in nutrient concentrations, water temperature, and solar radiation resulting from climate warming can be examined with this model, as can effects of reduction of shade caused by events such as disturbance of streamside vegetation. Interactions among these variables can be examined simultaneously. The model has been calibrated and validated for artificial laboratory streams during the Stream Herbivory project (Gregory, McIntire, and Lamberti--BSR 8907968). A large-scale nutrient enrichment study funded by this grant is scheduled for 1990-1992; fertilization of a 500-m stream reach will provide field data on trophic response to altered nutrient levels.

In LTER 3 we will improve the M&C model's spatial representation of geomorphic features of natural streams and the linkages between successive stream reaches (1.3.2.2). Other modifications will allow light levels and litterfall to be regulated by the composition and productivity of the streamside forest rather than simply entered as table values. This will make it possible to model more realistically the effects of forests on streams.

1.3.2. Landscape Synthesis (Swanson, Grant, Gregory)

The Pacific Northwest region is particularly appropriate for analysis from a landscape perspective (Swanson *et al.* 1990). The forest landscape changes as patches of vegetation (distinctive in composition and structure) change through time as a result of succession and disturbance. Disturbance occurs by design (forest management) or by natural processes (*e.g.*, wind and wildfire). Natural disturbances in this high-precipitation, wildfire-prone, geologically unstable region strongly affect landscape patterns and

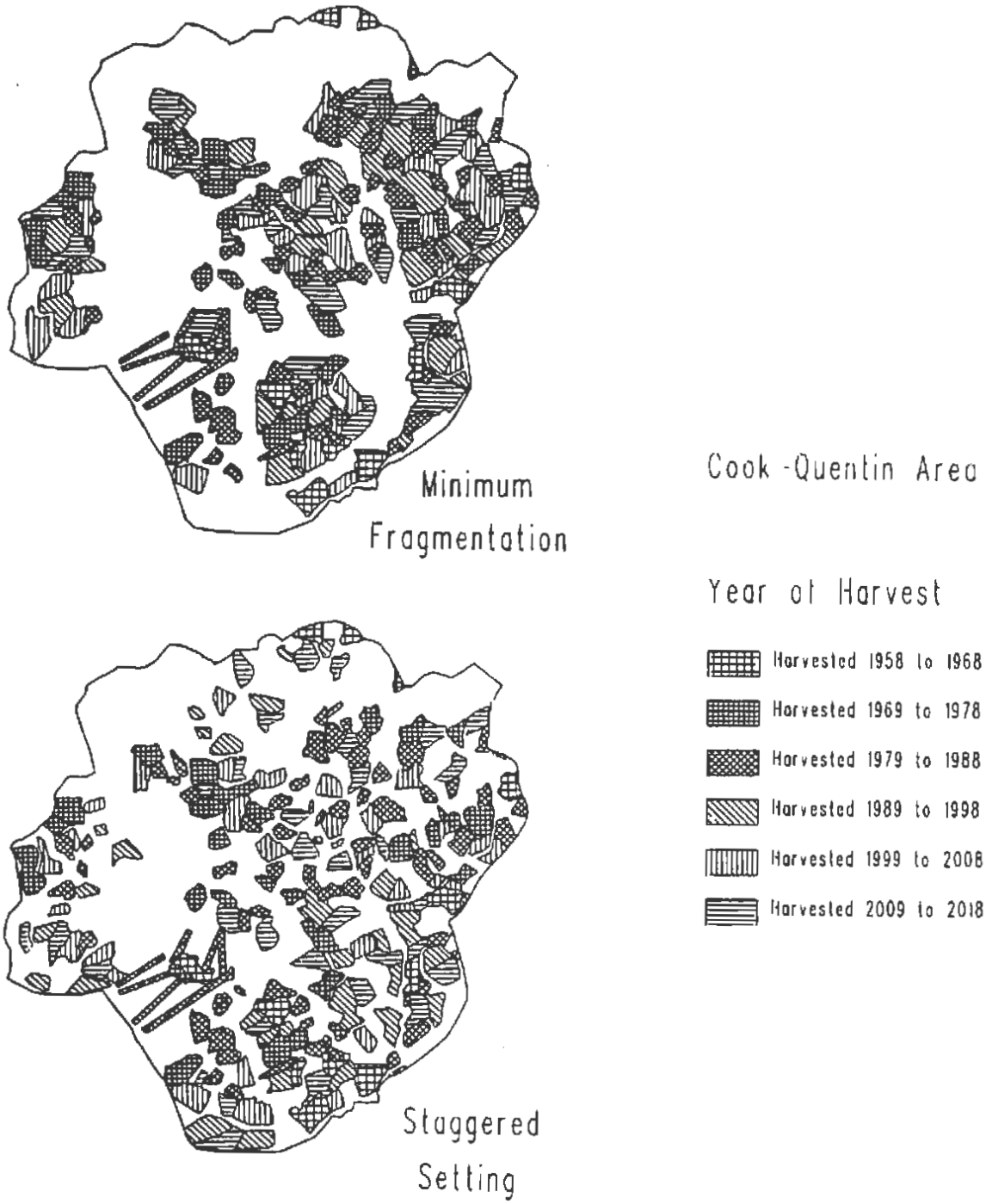


Figure 11. Pattern of dispersed ("staggered setting") and aggregated ("minimum fragmentation") cutting units in the 5000-ha Cook-Quentin area adjacent to Andrews. Three decades of cutting of natural forest is represented plus projections of the next three decades of cutting, resulting in a total cut of about 50% of the area.

processes. A long and dynamic history of landscape change is recorded in PNW forest stands, which can exceed 800 years in age, and in other media. Human disturbance by logging is creating conspicuous landscape patterns (Fig. 11) with potentially profound ecological consequences (Franklin and Forman 1987).

Synthesis at the landscape scale will focus on ecosystem response along a series of scenarios of change in landscape pattern and climate through time (Table 8, Fig. 12). Ultimately we would like to have the capability to predict effects of a broad range of land-use practices and climatic conditions, but for simplicity we will begin with a limited set. The reference scenario will be a projection of the natural disturbance regime created by projecting historical patterns (*i.e.*, frequency, severity, and extent) of wildfire and geomorphic disturbances into the future based on relations with landform (1.2.1). Other scenarios will be developed in which the natural disturbance regime is replaced by hypothetical but plausible patterns of land use (forest cutting) and climate change (warming) considered alone and in varying combinations (*i.e.*, different land-use patterns with and without climate change) (Table 8). Each landscape scenario will thus consist of a sequence of maps (data sets in GIS) showing landscape pattern at 5- or 10-year intervals over at least 200 years (Fig. 12).

Accompanying the landscape-level scenarios will be descriptions of tree species composition, which can be generated in several ways. Most simply, we can assume that species composition depends only on stand age, and is unaffected by climate or management. Alternatively, we can divide the Andrews into topographic units on the basis of elevation, aspect, and slope (probably using an adaptation of Band's [1989] system), and run ZELIG for the 200 years for selected units, thus taking into account change in climate and effects of management. A third approach would be to use ZELIG in transect mode to project species composition along topographic gradients taking into account possible interactions between plots, such as dispersal processes, propagation of fire, and insect

Table 8. Rules and approaches for determination of stand and landscape pattern scenarios for analysis of ecosystem response to land-use and climate change.

	Rules and approaches		
Landscape-modifying agents	Stand level	Landscape level	References
Natural disturbances Wildfire	Two levels of disturbance severity/frequency: 1) Complete stand- replacement at 400-yr recurrence intervals 2) Several live trees per acre retained with burning at 100-yr recurrence intervals	Actual wildfire pattern for 1700-1900 AD, based on fire history reconstruction	Teensma 1987; Morrison and Swanson 1989
Geomorphic processes Landslides and associated debris flows.	Frequency determined by areal-averaged failure rate by land unit type	Time-averaged failure rate, based on landslide inventories	Swanson and Dyrness 1975; Marion 1981; Swanson and Grant 1982
Floods and riparian disturbances		Reach-dependent restructuring of riparian stands at 10-yr intervals	Vest 1988; Grant and Swanson in prep.
Forest management	Two levels of disturbance severity/frequency: 1) Intensive forestry with complete clearcut, no retention of CWD, complete broadcast burn, 60-yr rotation	Dispersed arrangement of 10-20 ha cutting units (Fig. 11), which is current U.S. Forest Service system.	
	2) Less intensive cutting with retention of 6-10 live trees per acre, retention of CWD, light broadcast burn (50% coverage), 120-yr rotation	Aggregated arangement of cutting units (Fig. 11)	

outbreaks. This will be difficult, but we will begin this task within the timeframe of LTER 3 in collaboration with others.

At least two types of analysis will be conducted on each scenario (Fig. 12). The structure of the landscape and corresponding vegetation will be characterized at varying stages of development using a program developed by Li (1989) that calculates various indices of landscape geometry (Romme 1982, Gardner *et al.* 1987, Turner and Ruscher 1988). Second, mechanistic process-oriented models will be used at each timestep of each scenario to examine implications for system behavior at various spatial scales. For example, at the landscape scale, we will use the basin-scale hydrology model (PRMS), described below, to examine how landscape pattern (as depicted in the various landscape scenarios) affects timing and volume of streamflow. At a finer scale, we will use ZELIG in conjunction with models of heat and water balance to infer patterns of canopy and soil microclimate, and then examine implications of this for above- and below-ground trophic relations. We will therefore be able to analyze changes in key ecosystem processes and variables over the entire projected 200+-year scenarios.

We distinguish two classes of phenomena which require different approaches for analysis at the landscape scale: a) phenomena **not involving** lateral movement of water, materials, or organisms between patches on the landscape; and b) processes **involving** lateral movement of water, material, organisms, and disturbances across landscapes. In the first case, we can scale up from stand-level estimates (above section) by simply summing across space with GIS or other tools. In the second case, models and statistical techniques designed specifically for landscape-level questions must be used. We discuss these landscape-level techniques next.

Table 8 (continued)

Landscape-modifying agents	Rules and approaches: Stand level	Rules and approaches: Landscape level	References
Interaction of natural disturbances with dispersed and aggregated cutting patterns		Analyze history of blowdown and escaped slash fires that have led to cutting (salvage logging) of forest areas adjacent to earlier cutting units to determine topographic positions susceptible to such processes. Use this information to estimate location and extent of potential future natural disturbance in the managed forest landscape.	Gratkowski 1956; Franklin and Forman 1987
Climate change	2° and 4° C linear increases over 50-yr period.	Analysis of sensitivity of past fires to climatic variations at various time scales (single dry summer, multiple years of drought, ENSO), based on records of fire and climate. Paleofire interpretations will be used to project possible future fire patterns based on climate change scenario and adapted to the Andrews topographic and vegetative setting.	Teensma 1987; Morrison and Swanson 1989; proposed Ph.D. dissertation project by Univ. of Washington student funded by Forest Service Climate Change Program.

1.3.2.1. *Surface water hydrology model* (Grant, Leavesley, Harr)

A basin-scale hydrology model is now being parameterized using data for Andrews sites spanning a range of topography, vegetation, and climate, through a cooperative project with George Leavesley and colleagues (USGS-Denver). This model (Precipitation-Runoff Modeling System [PRMS]) is a distributed-parameter model based on energy balance considerations. Modular in design, it is currently being adapted for use with GIS, and has been proposed as a common modeling framework for comparative analysis of LTER sites (see Appendices G, H).

PRMS is being applied in Andrews drainage basins of 10, 700, and 6000 ha where our long-term discharge and climate records provide opportunity for parameterization and validation. Some modifications are needed to better represent effects of canopy structure on evapotranspiration, interception, and snowmelt. This work will be done first for a range of Andrews stand conditions with the stand-level water/heat balance model (1.3.1.1), then incorporated into PRMS on the basis of hydrologic response units within GIS. An example of planned basin-scale analyses in which PRMS will be coupled with other models is presented in section 1.3.3.3.

1.3.2.2. *Stream network nutrient dynamics* (Gregory, McIntire, post doc)

The longitudinal dynamics of nutrients in streams are a fundamental component of ecosystem nutrient cycling patterns; elemental concentrations measured at weirs reflect not only terrestrial influences on solute chemistry but also the uptake and transformation of nutrients within the stream channel. Recent studies in more than 20 stream reaches at the Andrews Forest reveal that landforms and adjacent riparian forests strongly influence longitudinal patterns of N uptake. In many stream reaches, N additions (100 g NH_4-N/L) are completely assimilated within 300 m. Land-use effects on aquatic biota, particularly aquatic primary producers, can thus greatly alter the dynamics of essential elements, such as N.

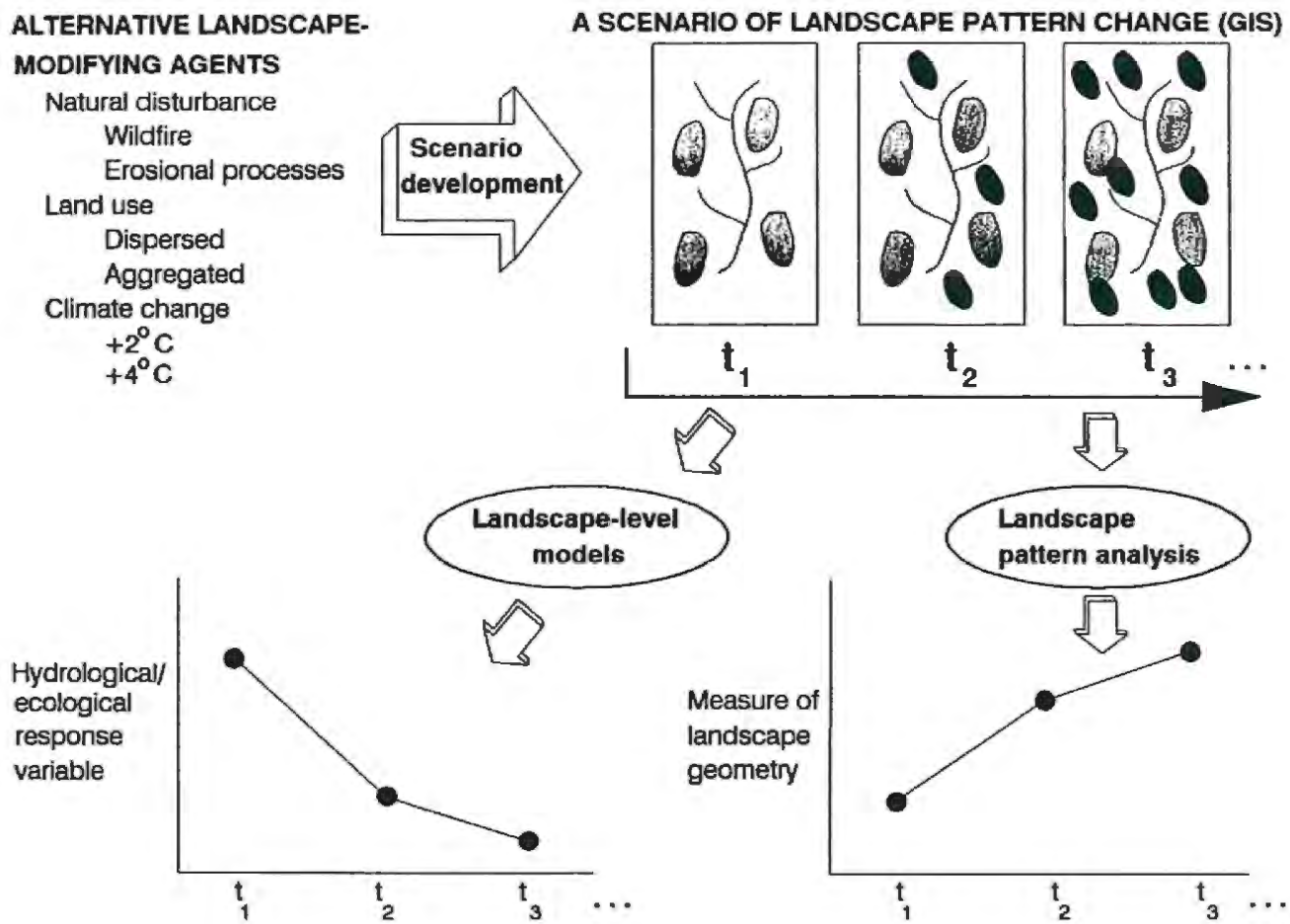


Figure 12. Relations among landscape scenarios, process modeling, and pattern analysis. An individual scenario is generated by a suite of factors that drive landscape change (Table 8).

The field studies of N uptake in Andrews streams provide the basis for developing a transport-diffusion model of solute dynamics in surface waters. The solute dynamics model will represent patterns of nutrient uptake along a stream reach for distances of a few meters to tens of kilometers. Model development will be a collaborative effort involving K. Bencala and G. Leavesley (USGS-Denver) as well as local Andrews researchers. The model will build on concepts of solute dynamics in streams developed by USGS (Bencala and Walters 1983) in a workshop that included researchers from six LTER sites and USGS (Solute Dynamics Working Group in press).

Output from the surface water hydrology model (PRMS) will project hydrologic patterns which will influence dilution and dispersion in the solute dynamics model. Simulated patterns of water chemistry in soil solution from the terrestrial decomposition/nutrient cycling model will be used as inputs to the solute dynamics model for surface waters. Influences of adjacent terrestrial ecosystem on aquatic biota will be simulated with the existing M&C model of stream ecosystem processes at the reach scale (McIntire 1983), thus providing estimates of biological activity required for the solute dynamics model. Responses of stream ecosystems to increased nutrient inputs will be evaluated empirically in the stream nutrient-enrichment project (Stream Herbivory project, Gregory *et al.*--BSR 8907968). Results of these field studies will also be used to validate primary producer, invertebrate, and fish components in the M&C model (1.3.1.4).

At the landscape scale, we will model changes in water temperature resulting from variation in riparian canopy cover and climate warming. The temperature model will be based on work by Beschta (1984) modified so that stream temperature is controlled by light levels, regulated in turn by topography and riparian canopy shade. In addition, water temperature will be controlled directly by width:depth ratio of the channel. The revised temperature model will then be coupled to PRMS within GIS so that stream network temperatures can be predicted and compared with measured values.

1.3.2.3. *Landscape pattern analysis* (Swanson, Grant, post-doc)

Little is known quantitatively about the effects of natural disturbance regimes, alternative forest cutting patterns, and climate change on landscape structure or on the ecological consequences of alternative landscape structures.

Our approach to such questions will be based on the alternative scenarios of landscape change, described above (1.3.2, Table 8, Fig. 12). It will be important to verify that the landscapes depicted in these scenarios are realistic. To do this, we will make use of a computer program developed at OSU by Li (1989) that calculates various measures of landscape structure, including patch size and shape distributions, edge density, patch geometry, and landscape diversity. Multiple additional scenarios will be constructed with Monte Carlo techniques based on the management and climate options specified in Table 8. The measures of landscape structure will then be calculated for each landscape and compared with values for real landscapes. The variance through time of these measures provides indices of the stability of landscape structure under alternative land-use patterns and climatic conditions.

These indices of landscape structure will also be used to contrast and compare landscape patterns created under different climatic and management options. We hypothesize, for example, that natural disturbances create landscape patterns with more spatial variation in patch size and temporal variation in structure than do management-driven disturbances. For cases in which the landscape-structuring disturbance regime changes radically (*e.g.*, wildfire to cutting), it will be important to examine the period of transition between disturbance regimes, as well as the period during which the new disturbance regime is fully established.

Finally, these landscape scenarios will be used in conjunction with the mechanistic models described above to examine how landscape pattern affects stand- and landscape-level processes. Examples of such analyses are presented next.

1.3.3. Examples of analysis of ecosystem responses

1.3.3.1. *Terrestrial primary producers and decomposition rates*

Natural disturbance, management, and climate change will have major impacts on rates of NPP and decomposition (and therefore CO_2 flux). Forecasting these impacts is a complex problem, and some simplifying assumptions about the factors controlling these processes at different spatial scales are needed in order to avoid "reductionist gridlock". Careful definitions of concepts are also important. We must distinguish between the potential NPP at a site, which depends on climate and soil conditions, and the realized NPP, which depends in addition on stand species composition and age. Species composition and age are determined mainly by the disturbance regime at a site, itself a function of climate and site physical conditions. Thus, different factors affect NPP, depending on the spatial scale of interest and any synthesis effort must take this into account.

Our working hypothesis is that major trends in site (potential) productivity over broad areas of the PNW region are caused primarily by differences in moisture and temperature (Gholz 1982). Differences in nutrient availability may control large-scale pattern if, for example, a site has been occupied by N-fixing trees or shrubs. For the most part, however, nutrient availability correlates with productivity primarily at fine spatial scales (1.2.4). Variations in light levels are assumed to account for little spatial variation in overstory site productivity. Actual primary productivity is controlled by all of the above plus the disturbance history of the site, which determines stand age and species composition (see Turner and Long 1975, Grier and Logan 1977, Gholz *et al.* 1985).

Major corollaries of the above are that climate change will affect primary productivity mainly by altering the disturbance regime and not through direct effects on primary producers and decomposers (c.f., Franklin *et al.* in press, Overpeck *et al.* 1990). Moreover, changes in land use will generally outweigh effects of climate change. For example, projected warming trends might increase decomposition rates by perhaps 20%

(based on a Q_{10} of 2), whereas clearcutting could easily double decomposition rates, primarily by changing substrate quality (*e.g.*, conifer foliage loses about 30% mass/yr vs. >60%/yr for many early seral herbs).

To scale up from stand to landscape, we will first generate the environmental field of the Andrews in a GIS, based on spatial interpolation of existing climate data and digitized elevations for the area. ZELIG will be used to predict the present distribution and growth rates of plant species by grid cell based on this field. The resulting distribution map will then be compared with actual cover (Zobel et.al. 1976). Growth and mortality will be compared with the extensive data available from the permanent plots throughout the Andrews Forest (1.2.2) and from our LTER experiments (1.2.4). Differences between predictions and observations will help highlight deficiencies in our understanding of factors controlling growth of the individual species (as represented in ZELIG) or point to problems with characterization of the environmental field.

Once predicted vegetation distributions reasonably match observed, we will alter the environmental field, based on the projected climate-change scenarios (Table 8), run ZELIG for the altered climate field, and then predict growth, mortality, and species distributions. CENTURY and the stand and landscape-scale hydrology models described above can then be used in conjunction with ZELIG to examine effects of changing patterns of stand composition and structure on nutrient availability and hydrology, the latter at both stand and landscape scales. (In the last few months, D. Urban and W. Lauenroth (CPER site) have linked ZELIG and CENTURY over the Internet, with ZELIG running at Univ. Virginia and CENTURY at Colorado State.)

Such analyses do not take into account the possibility that changes in climate and land use will alter the migration rates of plant species. For example, distance from seed source may be affected dramatically by climate change and forest cutting patterns, and mycorrhizae and other symbionts necessary for tree growth may not be present everywhere (Perry *et al.* 1989b). Additionally, changes in climate and land use may alter levels of

Table 9. Examples of data available on biological diversity in the H.J. Andrews Experimental Forest and vicinity. Numbers in table refer to numbered references, "e" indicates that a broad range of environments was sampled, including reference stands that span the environmental field of the Andrews.

	Successional Stage				
	Natural			Managed	
Life forms	Young	Mature	Old Growth	Clearcut 1-10 yr	Plantations 10+ yr
Trees	13e	13e, 14	10, 13e, 14, 17e, 18e	10, 17e, 18e	10, 17e
Shrubs	13e	13e	10, 13e, 17e, 18e	10, 17e, 18e	10, 17e
Herbs	13e	13e	10, 13e, 17e, 18e	10, 17e, 18e	10, 17e
Fungi	9	9	9e		
Invertebrate					
-soil	12	12	12	12	
-canopy	12	12	11, 12, 16	11, 12	11, 12
Herpeto fauna					
-aquatic	2e, 3	2e, 3	2e, 3	3	3
-terrestrial	3, 7	3, 7	3e, 7e	3	3
Birds	6, 8	6, 8	6e, 8		
Small mammals	1e, 4, 5	1e, 4, 5	1e, 4e, 5e	4	4

References 1) Aubry et al. in press; 2) Bury et al. in pressO; 3) Bury et al. 1988; 4) Corn et al. 1988; 5) Gilbert in press; 6) Gilbert and Allwine in press b; 7) Gilbert and Allwine in press a; 8) Huff and Raley in press; 9) Luoma in press; 10) Schoonmaker and McKee 1988; 11) Schowalter 1989; 12) Parsons et al. 1990; 13) Spies in press a; 14) Spies in press b; 15) Spies et al. in press; 16) Voegtlin 1982; 17) Halpern 1987; 18) Dyrness 1973.

herbivory and disease. Increased plant moisture stress could promote herbivory by arthropods, but this effect could be offset by changes in rates of predation. Such questions may be addressed late in LTER 3 if they seem important and tractable at that time.

1.3.3.2. *Biological diversity*

Biodiversity is an issue of major importance to the general public and land managers in the PNW region and elsewhere. Effects of climate change on plant species diversity have been considered at least qualitatively. For example, recent analyses suggest that proposed warming trends resulting from a doubling of CO_2 might shift temperature-controlled, elevational limits of plant species upwards 500-1000 m in the PNW region (Neilson *et al.* 1989, Franklin *et al.* in press). However, the potential effects on overall biological diversity have not been examined in any quantitative sense.

A wealth of data on distribution and abundance of a variety of life forms exists for the Andrews across environmental and successional gradients (Table 9). Such data can form the basis for at least an empirical analysis of potential effects of land use and climate change on biodiversity in a PNW landscape. From this, inferences are then possible about how changes in species composition might affect ecosystem processes.

We propose to address questions of biodiversity at both stand and landscape scales; attention to the latter scale is particularly important given the uncertainty surrounding migration rates. First, we will summarize existing information to identify correlations between faunal distributions (vertebrate and invertebrate) and stand structure, stand composition, and site microclimate. ZELIG will then be used to project how tree species composition might vary under the alternative disturbance, land-use, and climate-change scenarios (Table 8). Effects of changes in forest composition and structure and microclimate on other life forms would then be inferred assuming that the correlations remain the same as they are now.

Overpeck *et al.* (1990) used a gap model to study potential effects of climate change on disturbance regime and tree species composition in several forest types. Our procedure will be similar and differences in the forest systems, such as the marked historical importance of catastrophic disturbance in PNW landscapes, should make for interesting comparisons.

A major area of uncertainty surrounds the dispersal and establishment of propagules in a changing environment (Perry *et al.* in press). Our null hypothesis is that these two processes do not limit migration. Neither process is especially difficult to model--dispersal, for example, has been described reasonably well as a diffusion process (Fahrig submitted). However, the data needed to parameterize and verify such models are generally not available. In the case of passive dispersal, we plan to use artificial seeds or insects of various sizes and shapes that can serve as analogs of real species. This will eliminate the impossible task of identifying the source or the original concentrations of propagules, data needed in order to implement a diffusion-based model. Our task can also be simplified by identifying key taxonomic groups likely to have limited potential for migration. We must also consider the plant establishment process. Most likely, all species will not disperse at equal rates, resulting, for example, in a situation in which plant and soil biota are non-compatible (Perry *et al.* 1989b), which could inhibit plant establishment.

In addition to biodiversity *per se*, we are interested in the role that key species play in regulating ecosystem function. Thus, knowing which species might disappear is only part of the story; the effects of changes in species composition must also be considered. What would happen if species of woody plants or N-fixing shrubs were lost? For species that can be assigned readily to functional groups, effects of their disappearance on ecosystem function are easier to predict. For example, several early seral (*e.g.*, snowbrush) and late seral (*e.g.*, *Lobaria oregana*) nitrogen fixers, might disappear under some land-use and

climate-change scenarios. Effects of this will be evaluated by running ZELIG and CENTURY in tandem. Work on other functional groups is critically important but additional funding will be needed in order to move beyond preliminary phases.

1.3.3.3. *Stream systems--hydrology and ecology*

Warming will markedly alter the hydrology of PNW stream systems, affecting aquatic and riparian systems and downstream water use. Hydrology of the Andrews landscape, representative of many PNW areas, ranges from a rain-dominated system below 200-m elevation, through a transient snow zone at middle elevations where snow accumulates and melts several times each winter, to a seasonal snow zone at elevations >1200 m. Rain-on-snow events in the transient snow zone are a major cause of large floods in the region and clearcutting can lead to increased peak flows (Harr 1981, 1986, Christner and Harr 1982). Climate warming would shift these hydrologic zones upward, reducing the areal extent of the seasonal snow pack and affecting the timing and magnitude of streamflow at both storm and seasonal time scales.

In LTER 3, we will consider effects of forest cutting rates and patterns, with and without climate warming, on streamflow at basin scales of 10 to 10,000 ha. To do this, we will run the PRMS model for the hypothetical forest stand and landscape scenarios as defined in Table 8. Important questions concern the magnitudes of peak flows (which affect channel form and sediment transport) and low flows (which limit the extent of aquatic habitat) for given precipitation events under alternative cutting and climate conditions. At the scale of the Andrews drainage basin, we hypothesize that climate change will have a greater influence than forest cutting patterns on the magnitude of peak and low flows. Our rationale is that the effects of forest cutting on snow hydrology are relatively small because the entire basin is not affected at any one time. In contrast, climate warming affects the entire area simultaneously. These ideas can be examined

through modeling and, for land use questions, by comparing discharge records for basins with differing cutting histories.

More generally, the effect of warming on direction and magnitude of change in peak or low flow depends strongly on the location of boundaries between snow hydrology zones relative to basin topography (*e.g.*, expressed as hypsometric curves). Because of this, warming may have strong basin-specific effects on snow hydrology, which points to the need to examine a range of alternative scenarios and basin topographies.

Effects of disturbance size and the spatial scale of system response pose a second important hydrologic question. Dispersed vs. aggregated cutting patterns (Fig. 1a) should have different effects on peak flows in basins of different sizes. We hypothesize that the maximum difference in peak flow will occur at the basin scale at which basin size equals the size of aggregated cutting units. At both smaller and larger basin sizes, cutting pattern (dispersed vs. aggregated) has less effect on hydrology.

The physical changes in stream systems that result from changing land use and climate warming will have dramatic effects on stream ecosystems. For example, changes in discharge, nutrient concentrations, and water temperature are likely to significantly affect biotic processes and communities. We hypothesize that aquatic primary and secondary productivity will increase in response to increased nutrient delivery from uplands and increased metabolic activity associated with higher stream temperatures. We expect that nutrient concentrations in stream water will change little, because increased input of nutrient from uplands will be offset by elevated rates of biological activity. Changes in water temperature may alter the composition of fish and invertebrate communities whose competitive interactions and life history cycles are thermally regulated. Reduced levels of summer-flow (due to increased upland evapotranspiration and reduced area of snow accumulation) will greatly alter aquatic communities.

These hypotheses concerning effects of climate change and land use will be explored by coupling decomposition/nutrient cycling models (1.3.1.4) with the solute

dynamics model (1.3.2.3) and the surface water hydrology model (PRMS) (1.3.2.1). Inputs from the soil solution can thus be routed through the stream network for the various land-use and climate-warming scenarios in order to study basin-level responses to disturbance.

In addition, plans are maturing for a long-term, landscape-level field experiment involving managed and natural disturbance patterns to be conducted on land adjacent to the Andrews Forest by USFS and OSU personnel. The project will build on landscape work in LTER 3 but will be mainly USFS funded. The concept is to direct forest cutting patterns under two contrasting sets of rules (dispersed vs. aggregated--c.f., Fig. 11) in 2000-ha basins (at least two replications) and then examine effects on hydrology, selected wildlife species, and aquatic and riparian systems at a series of spatial scales. Parts of the Andrews will serve as control areas. Plans are in progress but are not sufficiently developed to incorporate into this proposal.

1.4. OVERVIEW OF LTER 3

Andrews LTER 1 and 2 emphasized long-term field experiments (disturbance, succession, trophic interactions, primary production, decomposition, and forest-stream interactions) and environmental measurement programs (hydrology and climate). Synthesis during this period resulted in numerous overview and concept papers. In LTER 3, we will continue this work and use it as a basis for increased emphasis on effects of natural disturbance, land use, and climate warming on forest/stream ecosystems. Results will be published as individual process-oriented studies, synthetic analyses of the effects of changes in potential land use and climate, and management guides for forest and stream resources. We expect that results from the Andrews Forest will be applicable across a range of ecosystems and landscapes. Intersite comparisons, planned and in progress, and research by Andrews LTER investigators at other sites in the PNW region and worldwide will allow us to test the generality of our results.

Table 10. Relationships of the Andrews Forest LTER components to the five core research areas identified by the National Science Foundation. E = Topical Area's primary research emphasis addresses core topic; e = Topical Area's research addresses elements of core topics.

CORE RESEARCH AREAS	LTER Core Areas				
Andrews Forest Topical Areas	Pattern and control of primary productivity	Population dynamics of species representing trophic structures	Organic matter accumulation in surface layers	Nutrient inputs and movement	Disturbance regime of research sites
1) Disturbance regime	e	e	e	e	E
2) Vegetation succession	E	E	E	e	E
3) Trophic interactions	e	E	e	e	e
4) Controls on productivity	E	E	E	E	e
5) Decomposition	E	E	E	E	--
6) Forest-stream interactions	E	E	E	E	E

2.0. DESCRIPTION OF THE H. J. ANDREWS LTER

2.1. The five core areas

The relationship between the Topical Areas of Andrews LTER research and the 5 Core Areas is shown in Table 10. Most studies bear directly on two or more Core Areas, and many address all five. This section describes activities in each Core Area.

Pattern and control of primary production. Primary production is being measured in three Topical Areas: Succession, Controls on Productivity, and Forest-Stream Interactions. The Succession research concerns the changes in rates of NPP over time and in key processes such as mortality. Research in Controls on Productivity examines effects of resource availability (nutrients, water, and light) on tree growth and tree species composition. The Forest-Stream Interactions research examines the balance between allochthonous inputs and autochthonous production in relation to light and nutrient levels in stream ecosystems, and rates of recovery of production after disturbance.

Spatial and temporal distribution of populations selected to represent trophic structure. This Core Area is addressed in all of the Topical Areas except Disturbance. The Vegetation Succession studies directly examine the population dynamics of the primary producers through time and space. The Trophic Interaction studies concern soil and litter invertebrates and arthropod herbivores. The Decomposition work examines the succession of arthropods and fungi in rotting logs. The Forest-Stream Interactions program includes sampling of primary producers, aquatic invertebrates, fish, and amphibians.

Pattern and control of organic matter accumulation in surface layers and sediments. Four of our 6 topical areas deal directly with this Core Area, and the other two indirectly. Emphasis in LTER 1 and 2 was on CWD (in both terrestrial and aquatic systems). Work in LTER 3 will be expanded to include forest floor, roots, and soil organic matter.

Patterns of inorganic inputs and movements of nutrients through soils, groundwater, and surface water. Most of our Topical Areas bear directly on this Core Area, especially the Productivity, Decomposition, and Forest-Stream Interactions studies. In addition, our

Table 11. Long-term experiments currently maintained under LTER.

Experiment	Objective Duration	interval	Sampling (yrs)
Young stand	Test influence of structure and nutrient availability on production	1981-	5
Snowbrush	Test effect of the N fixing shrub snowbrush on soil properties and tree growth	1981-	5
Long-term Site Productivity	Test effects of vegetation and litter removal on productivity	1987 -	1
Terrestrial Log Decomposition	Test effect of substrate quality and decomposer colonization on decomposition and nutrient cycling	1985 - 2185	1 - 2
Stream/Terrestrial Log Decomposition	Test effect of moisture in controlling log decay	1985 - 2005	2
Woody liter size	Test effect of size on composition and nutrient cycling	1985 - 1997	1
Quartz Creek Log Introduction	Tests effects of logs on channel morphology and fish populations	1988 -	1
Watersheds 1,2,3	Test effects of clearcut/ burning and road construction on hydrology, sediment, nutrient balance		See Table 12
Watershed 9,10	Test effects of clearcut/no burn on hydrology, sediment, nutrient balances at low elevation sites		See Table 12
Watersheds 6,7,8	Test effects of clearcut/ burning and partial cutting on hydrology, sediment, nutrient balance at high elevation sites		See Table 12

core monitoring program includes long-term measurements of sediment storage and transport, soil movement by various processes, atmospheric deposition, hydrology, and streamwater chemistry which permit both temporal and spatial analysis, such as expressed in sediment budgets. Experiments included under Controls on Productivity are designed to examine patterns of nutrient movement, particularly N, through forest ecosystems of different stand ages, management regimes, and debris loadings.

Patterns and frequency of disturbance to the research site. The Disturbance Regime studies are designed to characterize past patterns of natural- and management-caused disturbance (type, severity, frequency, and scale). In addition, work in all other topical areas bears on the response of our forest-stream systems to disturbance. In LTER 3, we shift from a descriptive to a more synthetic mode, using models and statistical techniques to examine probable effects of disturbance regimes on pattern and process at stand and landscape scales.

2.2. Long-term experiments

Long-term experiments were critical to Andrews LTER 1 and 2 and we continue these in LTER 3 (see 1.2, Table 11). These include three major experiments concerning controls on primary production, three log decomposition experiments in terrestrial and aquatic systems (see Table 6), and several long-term studies of forest-stream interactions (see Table 7). The longest-term experiment, planned to last 200 years, examines the role of arthropod and fungal succession in determining patterns and rates of decay and nutrient cycling in logs.

In addition, three sets of long-term watershed experiments involving eight watershed experiments (Table 12) established prior to Andrews LTER are being carried forth, in part by LTER. These experiments concern effects of cutting and burning practices on water, nutrient, and sediment budgets (Swanson *et al.* 1982b).

Table 12. Experimental watersheds and associated programs of long-term measurements in the Andrews Forest. Forest vegetation in watersheds 1,2,3,9, and 10 was predominantly 400-500 year old Douglas-fir/western hemlock. Watersheds 6,7, and 8 were 100-130 year old Douglas-fir.

Watershed no.	Area (ha)	Elevation (m) Min.	Max.	Management history	Start of long-term measurement record[1/] W	C	S	B	V
1	96	460	990	100 percent clearcut (1962-1966)	1953	1962	1957	1957	1962
2	60	530	1070	Control	1953	1962	1957	1957	1981
3	101	490	1070	6 percent roads (1959) 25 percent clearcut (1963)	1953	1962	1957	1957	1962
6	13	880	1010	100 percent clearcut (1974)	1964	1972	1972	--	1971
7	15	910	1020	100 percent partial cut (1974)	1964	1972	1972	--	1971
8	21	960	1130	Control	1964	1972	1972	--	1971
9	9	425	700	Control	1967	1969	1969	1973	1971
10	10	425	700	100 percent clearcut (1975)	1967	1969	1969	1973	1973

[1/] W = water discharge; C = water chemistry, typically N, P, K, Ca, Na, Mg; S = suspended sediment, C and S sampled with grab samples and proportional sampler (Fredriksen 1969); B = bedload sampled in ponding basin; V = vegetation sampled every few years on permanent plots.

Future long-term experiments will include participation in the 10-year LTER intersite study of fine litter decay to be installed at 21 sites (mainly LTER) in North and Central America (Mark Harmon--Coordinator).

2.3. Long-term data sets

The Andrews group continues to maintain the Forest Science Data Bank (FSDB) (Stafford *et al.* 1984, 1988), containing over 1800 data sets. About half (46%) of the total volume of FSDB data (200Mb) is LTER related (Table 13).

An extensive set of climatic records exist for the Andrews Forest, some dating to 1958 (Table 14). The primary met station, a level-3 station established in 1972, provides the most complete dataset. Precipitation chemistry has been measured as part of the NADP program at this station since 1981.

Data on standing crop, tree growth and mortality, and plant succession have been collected in permanent plots representing seral stages and vegetation zones throughout the PNW region (Table 3). These plots include those established under IBP (1970's) and LTER (1980's) as well as many plots dating to the early 1900's (see 1.2.2). With more than 4000 hectare-years of observation, these measurements represent one of the most extensive long-term forest data sets in the world.

Streamflow, water chemistry, bedload, and suspended sediment levels are being monitored on nine watersheds (Table 12). Geomorphic data, including stream-channel cross-sectional and longitudinal profiles, location of geomorphic surfaces, and levels of CWD, have been remeasured at 2-3 year intervals at 7 sites since 1978. Movement of six large, slow-moving landslides has been measured continuously since 1974. GIS databases for the Andrews Forest and adjacent areas include: stand age and habitat type, elevation, stream position, soil type, and patterns and dates of past disturbance by logging, wildfire, and landslides (Table 2). Locations of experiments, plots, and meteorological stations are being added.

Table 13. Summary of LTER data sets currently stored in Forest Science Department Data Bank.

General category	Subject keywords	Locations	PI's	Dates (19xx)	No. of Datasets	No. of Mbytes
Aquatic Terrestrial/ Aquatic	Substrate decomposition, secondary production, biomass, stream chemistry, throughfall, lysimetry	Andrews OR Coast	Gregory. Sollins	69 to present	90	2.5
Geomorphology Geology	Erosion, vegetation/erosion	Andrews OR Coast	Swanson, Grant	75 to present	25	1.5
Hydrology	Snow surveys, soil moisture streamflow	Andrews	Harr, Sollins, McKee, Grant	53 to present	67	5.7
Meteorology	Temperature, precipitation, solar radiation	Andrews	McKee, Waring, Harr, Fogel	53 to present	65	10.7
Terrestrial	Decomposition, litterfall, nutrients, nutrients cycling, biomass, disturbance	Andrews	Sollins, McKee, Cromack, Perry Waring	77 to present	62	2.0
Vegetation	Plant succession, plant communities, stand dynamics, stand structure, growth and yield plots, tree mapping, standing dead, understory population dynamics	Andrews OR Cascades WA Cascades OR Coast	Franklin, Sollins, Perry, Means, Greene, Waring, McKee	62 to present	290	21.0
Fauna	Small mammals, arthropods	Andrews	Jansen, McKee, Doyle, Lattin	80 to present	25	2.5

2.4. Data and research information management

Andrews LTER continues its major commitment to managing research information and data. Data management facilities have recently been upgraded with funding from NSF, OSU, and the U.S. Forest Service (see Appendix E). Datasets are kept accurate, current, well-documented, and available to other users. Andrews LTER has led efforts to develop protocols for managing research information (Stafford *et al.* 1986a)--a leadership role we hope to continue in LTER 3. The quantity, quality, and accessibility of the Andrews LTER data have attracted users and helped promote several cooperative research efforts (Klopsch and Stafford 1986, Stafford *et al.* 1986b). Our long-term data sets are proving invaluable for model parameterization and validation, including hydrology modeling projects with U.S. Geological Survey (1.3.1), and vegetation modeling projects with University of Virginia/Colorado State University (1.3.2, Appendix H).

Administratively, our data management effort consists of two coordinated parts. The Quantitative Sciences Group (QSG), under the direction of Dr. Susan Stafford, includes a statistical consultant (T. Sabin), data bank manager (G. Spycher), GIS Specialist (B. Marks), and network/hardware manager (M. Klopsch). A GIS Post-Doc will be added in 1990. Two of these positions have been supported by LTER (1.5 will be funded by LTER 3, with OSU picking up the difference). In addition, we have been able to attract short-term resources for additional personnel (roughly 0.5 FTE/yr) (*i.e.*, visiting scholar), with the remainder funded by OSU and other sources.

The second part of the data management effort is a 5-person USFS group, supervised by F. Swanson. The OSU and USFS groups work together closely and share hardware and databases through a local area network (LAN) and a commitment to sharing resources (Stafford and Swanson 1989).

The entire Forest Science Data Bank (FSDB) resides on one file server. For each of our studies, data and documentation are stored in a subdirectory identified by a unique

Table 14. Meteorological stations at H.J. Andrews Experimental Forest and nearby Research Natural Areas.

Station type	Elevation	Variables	Time resolution	Time span of data set
Primary met. station (a level-3 LTER station)	400 m	wind speed, incoming visible radiation, ppt., air temp., rel. humidity, dewpoint	hourly	since 1972
NADP	400 m	ppt. chemistry	weekly	since 1980
High-elevation met. station (a level-3 LTER station)	1300 m	wind speed and direction, incoming visible radiation, ppt., air temp., rel. humidity, snow depth	hourly	since 1986
Precipitation network	400 - 1500 m	ppt., 3 recording gauges, 21 storage gauges	hourly - monthly	earliest 1954
Thermograph network (with snow courses)	420 - 1500 m	25 stations with air/soil temp. (snow depth and water equivalence taken when snow present)	hourly - daily	since 1970

study code. Documentation and data are backed up weekly on magnetic tape cartridges. We are exploring the possibility of using a WORM drive for secondary backup. Documentation is kept in data base management system (DBMS) files. Programs are now available that print study documentation, check documentation for errors, and check data for outliers (datalimits program).

Procedures for quality control of data vary, depending on the data source. Data from various recorders are screened for possible problems such as apparent equipment malfunctions and for data outliers by data limits programs. Most manually entered data are double-keypunched and then checked automatically for outliers. Data sets that require extensive manual editing by researchers are entered only once, then corrected manually, and checked for outliers.

Most users have read-only access to the FSDB, allowing them to copy and read files (catalogs, documentation, and data). Write-access is restricted to FSDB personnel. Thus all additions or revisions to data and documentation are checked first by the FSDB data manager before incorporation into FSDB. Data can be accessed by LTER and non-LTER sites over Internet with FTP (file transfer protocol). The recipient of the data must know the path and the data set name before downloading. The recipient can either obtain this information from the data manager or can instruct him to send the data to an address. Access to LTER datasets is NOT restricted, but proper safeguards insure that publication rights of the original researchers are not compromised. Remote access via Internet has great potential for enhancing research efficiency. Thus, facilitating remote access is an important criterion for us in selecting new hardware and software.

An extensive review of all LTER data sets and documentation began in early 1989 and should be completed by fall 1990. This review includes checks on documentation and data integrity, restructuring of certain data bases (*e.g.*, permanent plots and meteorological data), and in some cases, establishment of support files and programs to facilitate data management and access.

We are reevaluating the LTER data-management 'dogma' that data should be flat ASCII (non-binary) files. Emerging SQL-server technology and the fact that major analysis systems (*e.g.*, SAS and ARC-INFO) provide interfaces to prominent DBM systems (*e.g.*, Oracle and DB2) has prompted this re-examination.

That data management applications should not be bound to current technology is becoming increasingly obvious, particularly for medium- and long-term research projects. Programs should provide highly automated data base maintenance and archival, as well as 'painless' data access including queries across tables. The time it takes to write such programs is well spent--data management protocols are planned in advance, documentation files are used fully, and rote manual work is eliminated for the duration of the data collection period.

Although "in-house" software development has been avoided for the most part, we have recognized a deficiency in the commercially available software products. To rectify this, we have developed in LTER 2, and will continue in LTER 3, a User Interface providing on-line access to the catalogs, documentation, and data. The interface supports entry of data and documentation by users and facilitates export of data to a variety of analysis programs (*e.g.*, SAS, Cornell Ecology Program Series). With it, users can find, document, enter, check, and export data with little need for assistance from the data manager. This User Interface, demonstrated at the 1989 LTER Data Managers Workshop, has as a goal "portability" across the LTER network. It cannot now be invoked from a remote site; rather, the interface has been developed as a model that attempts to provide the minimum set of tools needed to operate a data bank.

2.5. Synthesis and modeling

Our synthesis efforts have taken four forms: 1) external communication of interdisciplinary and broad-implication perspectives in books, papers, and videotapes, 2) highly interdisciplinary design of field studies, 3) modeling, and 4) prescriptions for management of forest stands and landscapes, based on results of ecosystem research.

Synthesis Papers--To date, the Andrews group has produced several synthesis papers (*e.g.*, Harmon *et al.* 1986, Swanson *et al.* 1988, Perry *et al.* 1989b), two books (Waring and Schlesinger 1985, Perry *et. al.* 1989a), a forest ecology text (Perry in prep.), and 17-min and 2.4-hr videotapes distributed by OSU. These products serve to synthesize and integrate results of LTER and allied research. A longer-term objective is a book on structure and function of PNW ecosystems, building largely on work at the Andrews Forest. About 20% of this 12-chapter, 15-author effort is in first draft. In addition, regional-scale assessments of the contribution of forest cutting to CO_2 flux (Harmon *et al.* in press) and potential effects of climate change (Franklin *et al.* in press) have been completed (see 1.2.2).

Integrated Field Studies--Several long-term Andrews LTER projects have been designed to serve as prototypes for ecosystem experiments and monitoring programs to be established region-wide by management or regulatory agencies. Our program of coordinated measurements of channel hydrology and geomorphology, streamside forest structure and dynamics, and instream biology underway at Mack Creek is one example. The Long-term Site Productivity experiment, currently being implemented, is expected to serve as a prototype for a network of such studies to be installed by the USFS PNW Station.

Modeling--Modeling efforts, begun at the Andrews Forest under IBP and LTER 1 and 2, will be expanded considerably in LTER 3. These studies are described in detail in section 1.3, along with proposed uses of GIS and statistical techniques of landscape analysis. In addition, with funding from the LTER Coordinating Committee, P. Sollins, J. Westall and G. Furrer (Chemistry, OSU) have developed a simple, mechanistic model that

correctly predicts steady-state soil solution pH at Andrews, Hubbard Brook, and Cedar River (Washington) from information on major ecosystem processes including production, decomposition, respiration, CO_2. degassing, nitrification, and weathering, plus 17 equilibrium reactions (Furrer *et al.* 1989, submitted; Sollins and Westall in prep.).

Management Prescriptions--The Andrews Forest researchers and forest managers are involved deeply in many major natural-resource management issues. Past research on the Andrews Forest on topics such as spotted owls and old growth-forests has been crucial in the current debates over management of PNW forests. Andrews Forest research has led to the development of "New Forestry"--new, more ecologically sound, approaches to management of forest stands, landscapes (cutting patterns), riparian zones, and streams. We believe that management prescriptions arising from ecosystem research constitute an important form of synthesis and application of research findings. These management concepts have been communicated widely (2.11).

2.6. Intersite and network activities

The Andrews Forest group has had a long-standing commitment to intersite science, to leadership within the LTER network, and to communication concerning LTER, as exemplified by the activities listed below.

Stafford is Chair of the LTER Data Management Committee, member of the first NSF Advisory Committee on Scientific and Technological Planning for LTER (Shugart *et al.* 1988), and has helped organize numerous data management workshops for LTER personnel and symposia at AIBS/ESA meetings. She has participated in SCOPE/MAB-sponsored meetings on management and exchange of data by biosphere observatories in IGBP.

Andrews personnel have published general descriptions of the LTER programs (Swanson and Franklin 1988; Franklin 1989a, b; Franklin *et al.* in press; Swanson and Sparks in press) and intersite research (*e.g.*, Caine and Swanson 1989; Swanson *et al.* 1988,

in press; Solute Dynamics Working Group in press; Lattin *et al.* in prep.). We have made presentations on interLTER site science at national and international meetings (Franklin, Harmon, Lattin, Moldenke, Stafford, Swanson) and in NSF briefings in Washington, DC (Franklin, Harmon, Swanson). Andrews scientists have led and participated in interLTER site research efforts on litter decay (Harmon--coordinator of 21-site decomposition experiment), log decay (Harmon and Schowalter), tree mortality (Franklin and Harmon), tree-fall gaps (Franklin and Spies), taxonomy and ecology of soil biota (Lattin and Moldenke), solute dynamics in streams (Gregory) and soil solutions (Sollins), integration of invertebrate communities (Schowalter), function of mycorrhizae in forested systems (Cromack, Griffiths, Ingham, Perry), disturbance and geomorphology (Swanson, Grant), and stable isotope techniques (Gregory, Hart). Andrews researchers have organized intersite workshops on gaps, tree mortality, soil and litter biota, and disturbance.

Andrews personnel participate in the science and management at other LTER sites. Art McKee and Wayne Martin (Site Manager, Hubbard Brook) exchanged positions for one year. Franklin has served on the external advisory committee of Hubbard Brook LTER and Swanson on CPER and Sevilleta LTER sites. Swanson is a researcher in the Luquillo LTER program (disturbances). Gregory is coordinating with the Toolik Lake LTER site on stream fertilization projects. Lattin has a cooperative program with the National Biological Survey of Canada on the biota of transcontinental conifers. Sollins serves on the Advisory Committee for the OTS La Selva Biological Station (Costa Rica). Links with other LTER-like sites in other countries include cooperative field studies at Misam fu Research Station in Zambia (dry tropical forest) and the Smithsonian Station in Puerto Morelos, Mexico (dry tropical forest), and close ties with the Changbai Biosphere Reserve (NE China) program (Harmon and Chen submitted). We have consulted with the Chinese Academy of Sciences in their effort to establish a LTER-like system there.

Our commitment to intersite work in common with other Cohort 1 LTER sites is stated in Appendix G.

2.7. Related research projects

LTER plays an important role in the larger Corvallis ecosystem scene by providing continuity, expertise, focus, coordination, and infrastructure support for numerous other research projects (Figure 2).

NSF Grants--A number of recent and current NSF grants tie with LTER. The NSF tree-fall gaps project (Spies [PNW, OSU], Franklin [PNW, UW], Vogt [Yale]) links with the forest succession and site productivity LTER studies. Two large grants for riparian studies (Gregory, Cummins, Swanson) have been closely linked with the LTER forest-stream interaction research component. A new aquatic plant/herbivore research grant (Lamberti [Notre Dame], Gregory) will provide an opportunity for LTER intersite comparison of effects of stream fertilization. A log decomposition grant (Schowalter, Harmon, Lattin) capitalized on the LTER log decomposition experiment and is contributing to the USDA Western Regional Project on bark beetle-fungal interactions in North American conifer forests. Other related NSF projects include: "Nutrient effects of phytophagous invertebrates" (Schowalter), "Extent and roles of fungal mats in forest systems" (Cromack, Griffiths, Ingham), "Role of mycorrhizal fungi in ecosystem processes" (Perry, Molina, Trappe), and "Rhizosphere islands in forest soils" (Bledsoe, Perry, Ford). An important educational project is the Research Experiences for Undergraduates program (Beatty, McKee, Moldenke) begun in 1989.

US Forest Service--The primary Forest Service project associated with LTER is Research Work Unit 4356, Pacific Northwest Research Station (Swanson-Project Leader). This group of seven scientists and their support staff focuses much research effort on the Andrews Forest and LTER-associated activities, including hydrology, geomorphology, and permanent vegetation plots. A new US Forest Service Long-Term Site Productivity Program (Bormann, Project Leader--basic science component) has roots in common with the LTER site productivity study. A large USFS sponsored project on spotted owl

populations, prey species, and habitat (Meslow, USFWD and OSU) has been based at the Andrews Forest, but works over a much larger area. One aspect of the Spies/Ripple NASA project is GIS analysis of spotted-owl habitat based on thousands of radio-telemetry data on owl locations.

The emerging USFS program on New Perspectives in Forestry is of potentially great significance to Andrews LTER. Under this program, the Andrews group will undertake stand- and landscape-level manipulations to examine ecological consequences of various rates, types (*e.g.*, portion of green trees removed), and patterns (dispersed vs. aggregated) of cutting (1.3.2.3). This will be a major medium for demonstration and evaluation of the application of findings from our LTER ecosystem research.

Other Grants/Projects--Four NASA-sponsored projects are now conducting work associated with Andrews Forest LTER. The NASA projects use remote sensing to examine landscape pattern and wildlife habitat (Spies and Ripple) and tree/forest physiology on the OTTER transect across Oregon (Waring, McCreight, Running). LTER data provides ground truth for these studies and the remote sensing work provides opportunities to address new problems and to expand the geographic range of LTER-based findings. The Andrews Forest is one of three sites in a study of competition between red alder and Douglas fir (Hibbs, Radosevich [OSU]) funded by NAPIAP and USDA.

2.8. Archives and inventories

Recognizing the long-term value of samples, collections, and data sets over and above the goals of the individual LTER studies, we maintain an extensive archival program to ensure their careful preservation and documentation. Moreover, we have been successful in obtaining NSF support (BSR 8706192) to construct archive storage facilities at the Andrews Forest. These include a warm, dry storage room as well as a walk-in cooler (250 ft^2 each). Data management has been described elsewhere (2.4); here we deal first with archived samples and collections, then with inventory information.

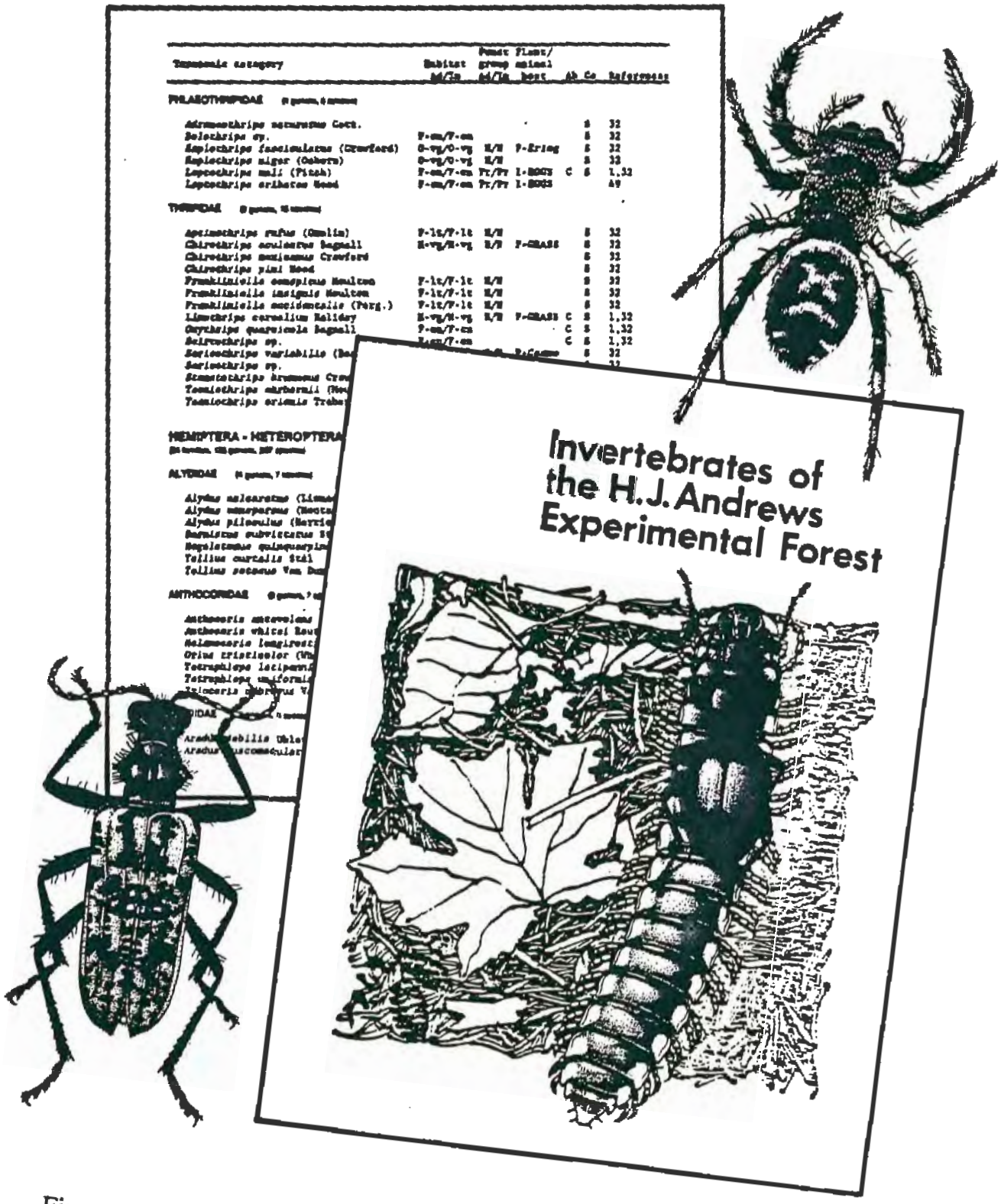


Figure 13. Example of information contained in an in-press publication on invertebrates of the H.J. Andrews Experimental Forest.

Arthropods are extremely important members of the higher trophic levels at the Andrews Forest (1.2.3). Over 3600 species have been collected and identified as part of the research program. Specimens are curated in the Andrews Forest Arthropod Collection, a separate part of the OSU Systematic Entomology Laboratory (Lattin, Director) which is one of the major entomology collections in North America (ca. 2,500,000 specimens). In addition, 5568 litter and pitfall samples are archived. These represent a 3-way matrix of successional stage (old-growth plus 3 early seral stages) by moisture gradient (8 habitats) by 4 seasons. Finally, an annotated species list is soon to be published with documentation by habitat, abundance, functional group, host/prey, and collection and literature references (Fig. 13).

An herbarium, located at the Andrews Forest, contains specimens of most local vascular plants, along with voucher specimens from several vegetation succession studies.

Soil samples collected on all the LTER circular plots (1.2.2) have been catalogued and will be moved to the archives at the Andrews Forest. In addition, wood samples collected annually for the log decomposition study (1.2.5), and a subset of the monthly litter samples (1.2.2) are being prepared for archival at the Andrews.

Several types of inventory information have been obtained and archived in the FSDB or elsewhere. Detailed documentation of past logging and silvicultural activities at the Andrews Forest exist in hard copy and computer both at the Andrews Forest and FSDB. An atlas of maps and map overlays displaying many site attributes, and a library of Andrews Forest and related publications are housed at the field headquarters site. A library of Andrews Forest publications is also located in Corvallis, as are maps of many site attributes, stem maps of reference stands, and other documentation of the area. A library of all aerial photographs and other types of aerial imagery (U-2, landsat) for the Andrews Forest area is housed in Corvallis.

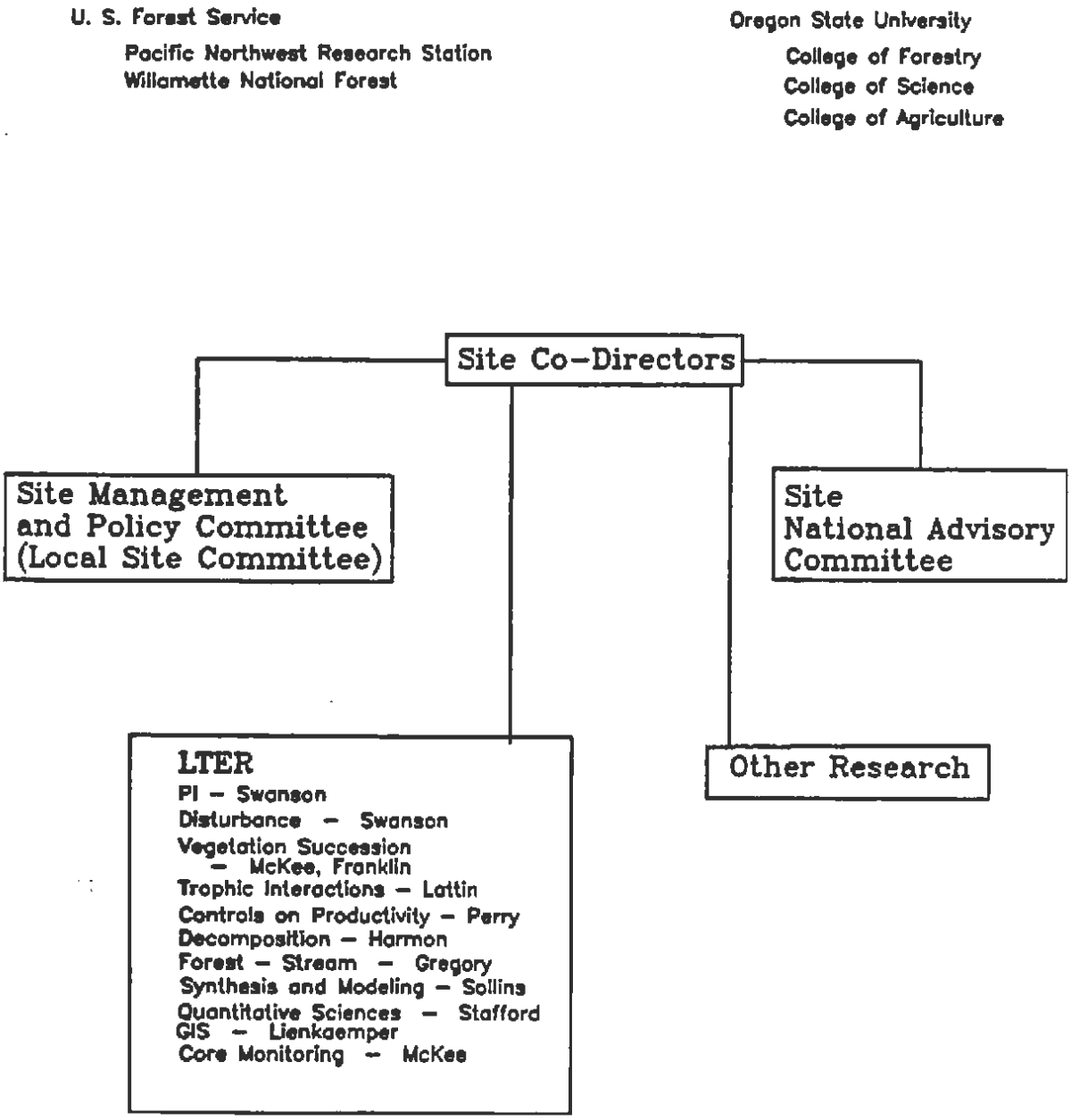


Figure 14. Andrews administrative organization.

Citations of publications associated with the Andrews Forest (approximately 1000) are compiled in Pro-cite bibliographic format. Two publication lists have been published (McKee et. al. 1987, Blinn et. al. 1988) extending from 1948 to 1988, and a third is in preparation.

The Andrews Forest comes under the purview of several monitoring systems run by other organizations: stream gauging and geologic mapping by USGS; forest management records (TRI system) of USFS; Weather Service stations run by NOAA; and the Snow Survey by the Soil Conservation Service. We regularly obtain copies of records that relate to the Andrews Forest and vicinity and incorporate them into the FSDB or other archives.

2.9. Project leadership, management, organization

The Andrews Forest LTER program and site are administered by a group of researchers and managers from OSU and the USFS PNW Station and Willamette National Forest (WNF) (Fig. 14). The Andrews Forest management group consists of OSU faculty members from eight departments in three colleges, PNW scientists, and the District Ranger and Andrews Silviculturist from the Blue River Ranger Station (WNF). Fred Swanson (Professor in Departments of Forest Science and Geosciences at OSU and Research Geologist and Project Leader in PNW) is PI. Art McKee (Forest Science Dept.) is Site Director of the Experimental Forest. The management group meets monthly. Written minutes are distributed to 70 people in OSU, PNW, WNF, and EPA. Many other scientists and administrators from OSU, USFS, and EPA attend as their time permits; as a result, the meeting and communication system provide an important forum for ecosystem and ecological science in the Corvallis area.

Andrews LTER leadership is broad based. The program is divided into topical areas and synthesis projects, each with one investigator in charge and a separate budget (Fig. 14). A core budget, managed by the PI and Site Director, covers site costs, routine monitoring, data management, national travel, and other infrastructure expenses. This management

system has functioned well during LTER 1 and 2, and we plan to continue it in LTER 3. Other group members have the skills, experience, and institutional backing that would allow them to move into leadership roles, should we wish to make a change.

Institutional support for the Andrews LTER continues to grow. Salary for the Site Director, most project leaders, and several data management and GIS personnel, is now provided by OSU and PNW Station (see Appendix C). As of Oct. 1989, the College of Forestry began covering 0.6 of Sollins' salary, which has allowed him to greatly expand his role in the LTER program. In addition to support of salaries and maintenance of the Andrews property (*e.g.*, road system), USFS funding for facilities improvement at the Andrews Forest was $137,000 in 1990 (Appendix H), indicating a continuing commitment to support the Andrews LTER.

Our National Advisory Committee for Andrews LTER is composed of M.G. Wolman (Johns Hopkins), Jim Gosz (U. New Mexico), Dave Schimel (Colorado State), and Mel Dyer (private consultant).

2.10. New projects and technologies

In 1989 we developed complete GIS capability with four systems (Appendix E). This capability figures prominently in proposed work for LTER 3, which will involve modeling of hydrological and ecological processes across the Andrews landscape. Innovative computing applications include development of graphics-oriented identification keys for soil invertebrates (Moldenke and colleagues) and an expert system for predicting stream channel adjustments to changes in stream flow (Grant and colleagues).

Time lapse movies have been made of stream, riparian, and landslide environments. We intend to make a movie "A year in the life of a stream", showing floods, leafout/leaf fall, and light patterns on the stream and forest floor.

Andrews LTER has also made a major effort to use new technologies to decrease the cost of routine data collection. Data loggers are being used for remote measurements

of temperature, soil moisture, and stream hydrologic stage. Bar-code readers, digital calipers, and digital scales linked to PCs have been used to process samples from the log decomposition studies.

Andrews LTER continues to use state-of-art data transfer and electronic-mail techniques to facilitate intra- and inter-site collaboration. As of January 1990, nearly all participants were accessible through Internet and most had Internet connections supporting FTP and remote login.

2.11. Dissemination of information

Research results from the Andrews Forest that have been communicated to the public include: 1) interesting scientific findings, 2) implications of research results for land management practice and policy, and 3) the example of how researchers and managers work together to develop better approaches to natural resource management. Many Andrews research topics have high public profile. Information on old-growth forests, landscape ecology, and spotted owls originating from the Andrews has been prominent during the great forestry controversies of the late 1980's in the Pacific Northwest. In 1989, for example, Spies and Franklin presented testimony before Congressional committees and the Chief and staff of the Forest Service. We have conducted numerous briefings and field tours for congresspersons and staffers, students of all levels, land managers, elected officials, foreign government officials in natural resource management, and other groups.

Public contacts have been diverse and extremely numerous. These include: over 3 full pages on Andrews-based forest ecology in the science section of the *Oregonian* newspaper (Portland, Oregon) and consultations with reporters from *National Geographic, NY Times, Washington Post*, Canadian Broadcasting Co. "Nature" program, and ABC's "Prime Time" concerning articles and programs on old-growth forests and ecosystem management. Andrews Forest research results, photographs, and scientists have figured

prominently in at least six recent books on old-growth forests. A color brochure has been prepared (see proposal cover).

Contacts with elements at all adminstrative levels of the USFS National Forest System, Bureau of Land Management, Oregon State Department of Forestry, and other management agencies have led to significant changes in management systems and forest practice rules and guidelines at state and federal levels.

The extension of basic information to application is facilitated by the participation of practicing land managers as integral members of the Andrews team. The Blue River Ranger District, which contains the Andrews Forest, serves in part as an extensive demonstration area for many concepts developed from basic science within the Andrews. The Andrews Forest group has received high levels of recognition from USFS for its efforts in "technology transfer".

The overriding theme of these contacts with the public has been that LTER is the basic science source from which to draw new information and insights which can then be translated into public enjoyment and use.