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# The Delaware River Basin Collaborative Environmental Monitoring and Research Initiative: Foundation Document

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## Abstract

In 1998 the U.S. Forest Service, the U.S. Geological Survey, and the National Park Service formed the Collaborative Environmental Monitoring and Research Initiative (CEMRI) to test strategies for integrated environmental monitoring among the agencies. The initiative combined monitoring and research efforts of the participating Federal programs to evaluate health and sustainability of forest and freshwater aquatic systems in the Delaware River Basin. Forest ecosystem health issues addressed by the CEMRI effort include urbanization and forest fragmentation, productivity and carbon sequestration, nitrogen saturation and calcium depletion, vulnerability to exotic insects, and the effects of interactions among these factors. Ongoing monitoring programs were enhanced with supplemental sampling locations and measurements, and models were developed or modified to associate intensive process-level information with extensive landscape-scale information from satellite, aerial, and ground monitoring systems. The CEMRI project illustrates a powerful approach for integrated tracking of environmental conditions, development of models for predicting responses of forest and aquatic processes to perturbations, estimation of future forest conditions, and identification of threats to watershed health and forest sustainability. This paper discusses the development of the CEMRI in the DRB and methods to address environmental issues across multiple spatial and temporal scales.

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**Chapters 2-10 are included in the foundation document  
available online only at: <http://www.nrs.fs.fed.us/pubs/>**

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# 1.0 EXECUTIVE SUMMARY

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## 1.1 Introduction

The Delaware River Basin (DRB) in the coastal mid-Atlantic region of the United States covers 12,700 mi<sup>2</sup> of primarily forested land. The DRB is home to 7.2 million people, and an additional 7 million people in New York City and northern New Jersey rely on surface water diverted from the DRB for their water supply. Major watershed issues in the DRB are urbanization and forest fragmentation, abiotic and biotic stressors, diminished condition of forest soils and plants, and invasive exotic species.

In 1998 the U.S. Forest Service (USFS), the U.S. Geological Survey (USGS), and the National Park Service (NPS) formed the Collaborative Environmental Monitoring and Research Initiative (CEMRI) to test strategies for integrated environmental monitoring among the agencies. The initiative combined monitoring and research efforts of the participating Federal programs to evaluate the health and sustainability of forest and freshwater aquatic systems in the DRB. Forest ecosystem health issues addressed by the CEMRI effort included urbanization and forest fragmentation, productivity and carbon (C) sequestration, nitrogen (N) saturation and calcium (Ca) depletion, vulnerability to exotic insects, and the effects of interactions among these factors. Ongoing monitoring programs were enhanced with supplemental sampling locations and measurements, and models were developed or modified to associate intensive process-level information with extensive landscape-scale information from satellite, aerial, and ground monitoring systems. The CEMRI project illustrates a powerful approach for integrated tracking of environmental conditions, development of models for predicting responses of forest and aquatic processes to perturbations, estimation of future forest conditions, and identification of threats to watershed health and forest sustainability. This executive summary is an abridged version of the foundation document that discusses the development of the CEMRI in the DRB, with a focus on methods to address environmental issues across multiple spatial and temporal scales. The main body of the foundation document is available on the Internet at: <http://www.nrs.fs.fed.us/pubs/>

## 1.2 The Need for Multiscale, Multiparameter Monitoring

Resource management agencies are often expected to take a holistic approach to management of ecosystems, but few have the resources to support multicomponent ecosystem-level research and monitoring. As a result, agencies focus on ecosystem data needed to support their primary mission, and sharing of data among agencies is constrained by differences in protocols or sampling schedules that render the data incompatible for fully integrated interpretation (Committee on Environment and Natural Resources 1997). Lack of compatible multiresource (terrestrial, aquatic, atmospheric) and multiscale (temporal and spatial) data has become a limiting factor for developing whole-ecosystem approaches to resource management. In addition, process-level understanding of ecosystem responses to land use change and a changing environment needs to be integrated with large-scale observations of changes in ecosystem health indicators.

The CEMRI approach began with an evaluation of the capabilities of existing monitoring programs, followed by identification of opportunities and approaches to enhance these programs for addressing specific issues. By supplementing and adjusting existing monitoring

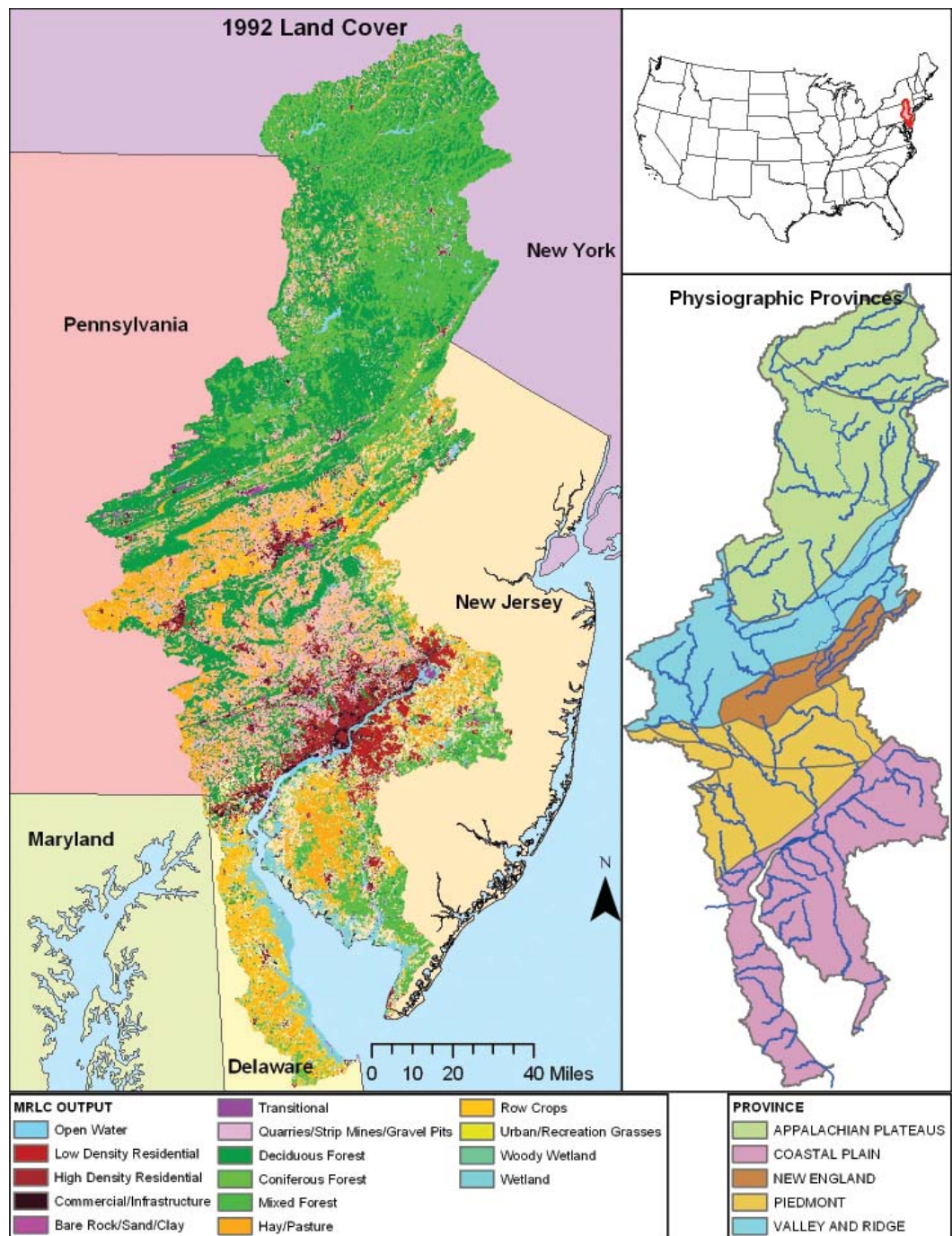


Figure 1.1.—Land cover and physiographic provinces of the Delaware River Basin.

and research strategies, collaborating programs can continue to meet specific agency missions while also contributing to multiscale, multiresource inventory and monitoring systems. To demonstrate this approach, three Federal agencies developed the CEMRI strategy to evaluate the condition of forests and associated waterways in the DRB (Fig. 1.1).

Databases derived from an ecologically and spatially integrated monitoring system, and incorporated into an analytical modeling framework, should allow for more accurate parameterization of scientific and resource management models to improve predictive

capabilities. The ultimate goal was to improve our ability to detect environmental change rapidly and accurately, as well as predict future forest conditions under different environmental conditions and management strategies.

### **1.3 Rationale for Selecting the Delaware River Basin**

The DRB in the Eastern United States was chosen as the study region because:

- Watersheds are logical conceptual units for integrating environmental information on a local to regional scale because aquatic systems integrate the biogeochemistry of large areas with well-defined physiographic boundaries.
- The DRB contains several intensive monitoring and research areas (IMRAs) maintained by the USGS and NPS, representing several of the major physiographic provinces typical of the mid-Atlantic region of the U.S., with ongoing long-term research and monitoring of ecological components and processes.
- Three existing agencies with programs operating in the basin accepted the challenge of designing an integrated monitoring strategy to address specific issues, based on existing monitoring systems.

Ecologically, the DRB is very diverse, with five physiographic provinces and multiple forest types that represent most of the major eastern type groups (Fischer et al. 2004). The mostly flat Coastal Plain in the south has soils underlain by unconsolidated sediments and is the northern limit of the southern pine forest type (Fig. 1.1). Further north are rolling lowlands and a series of broad uplands in the Piedmont Province, with soils underlain by metamorphic rock and covered by oak-hickory forests. North of the Piedmont, the New England Province and the Valley and Ridge Province consist of rock layers that have been deformed into a series of steep ridges and parallel folds that trend more northeast-southwest. Forests of this region are characterized by a mixture of oak-hickory, northern hardwoods, and northern conifers.

Analysis of 1992 satellite-derived Thematic Mapper (TM) land use data estimated that about 60 percent of the DRB is forested land, 24 percent is agricultural, 9 percent is urban and residential, and 7 percent is surface water bodies and miscellaneous land uses. Eighty percent of the population lives in the Piedmont and Coastal Plain Provinces in the southern portion of the DRB, which encompasses only about 40 percent of the total area.

### **1.4 Multi-tier Integrated Monitoring Strategy**

The USFS and USGS conceived of evaluating several important watershed health issues in the Delaware Basin using a multiple spatial scale, multiresource approach, primarily by enhancing and integrating existing forest and aquatic resource monitoring programs. Shortly thereafter, the CEMRI was joined by the NPS Delaware Water Gap National Recreation Area (DEWA), and the National Aeronautics and Space Administration (NASA).

As originally conceived, the CEMRI approach assumed that specific monitoring strategies are required for effective monitoring at a given spatial or temporal scale (Fig. 1.2), but that those monitoring programs could be linked through common measurements or sampling schedules to allow a multicomponent, multiscale assessment of issues. Most current environmental monitoring programs primarily address issues of one resource type at one spatial scale, but could be enhanced or modified to share data effectively with other monitoring programs without losing the ability to meet their original mission.

## REGIONALIZATION HIERARCHY

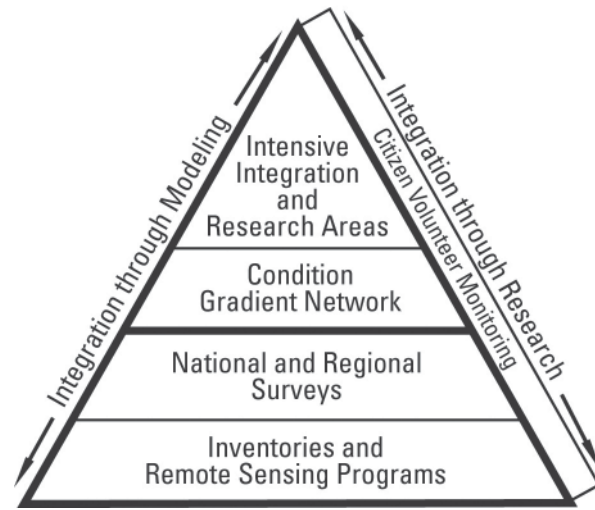


Figure 1.2.—Conceptual framework for achieving the multiple goals of environmental monitoring and research. (Committee on Environment and Natural Resources 1997)

The CEMRI pilot study integrated environmental data collection from intensive study sites (the Neversink Watershed, the DEWA and its tributary watersheds, and the French Creek Watershed) with regional ground-based monitoring networks using stream monitoring stations and a randomly distributed network of forest sampling locations. Remote sensing was used to characterize the land area on a spatially explicit basis over time, and the spatially integrated field datasets were used as ground truth. Four monitoring tiers were defined for the CEMRI:

- Tier 1 - Frequent monitoring and intensive research on ecosystem components and processes, and determination of cause-and-effect relationships at a limited number of intensively monitored sites within relatively small areas. The purpose is to determine key forest processes and to understand how these processes interrelate, how stressors affect these processes, and how these processes relate to macroindicators that could be monitored at large spatial scales. An example of a Tier 1 site is the intensive water-quality monitoring by USGS in the Neversink Watershed.
- Tier 2 - Medium-intensity monitoring at a network of points or watersheds representing a range of conditions for a specific issue. This is a new landscape monitoring concept developed for this study. Data collected provide statistical relationships between key stressors and land or water characteristics. The information may also be used to link process-level information to landscape-scale characterizations and to provide ground verification of remotely sensed parameters. An example of an existing Tier 2 network is the “synoptic” network of streams sampled by the National Water Quality Assessment program (NAWQA), designed to collect water quality and habitat data from rivers draining watersheds that represent a range of development (Gilliom et al. 1995).
- Tier 3 - Extensive ground-based monitoring (randomly selected sample plots and surveys) at large regional scales. The purpose of monitoring at this tier is to

document the extent, status, and change of resource conditions based on systematic sampling and field observations. Examples are the USFS Forest Inventory and Analysis (FIA) network of monitoring locations (Bechtold and Patterson 2005) and the surveys designed by the U.S. Environmental Protection Agency (EPA) Environmental Monitoring and Assessment (EMAP) program (USEPA 2002).

- Tier 4 - Large-scale mapping and monitoring with satellite remote sensing and aerial photography. Primary objectives at this tier are development of spatially and temporally continuous information, such as land use and land cover change, forest species distributions, and forest fragmentation. An example is the NASA Landsat satellite monitoring program (Cohen and Goward 2004).

### **1.5 Intensive Monitoring and Research Areas to Link Processes with Monitoring**

Three watersheds in the DRB were selected as IMRAs for the process-level studies in forested landscapes. Each IMRA site contained existing process-monitoring infrastructures supported by the USGS, NPS, New York City Department of Environmental Protection, or other data collection programs. Land sampling and water sampling were enhanced at these sites to provide concurrent and integrated data with the Tier 2 and Tier 3 field surveys. The three IMRAs represent the range of climatic and forest conditions found in the Delaware Basin upstream of the Coastal Plain (Fig. 1.3).

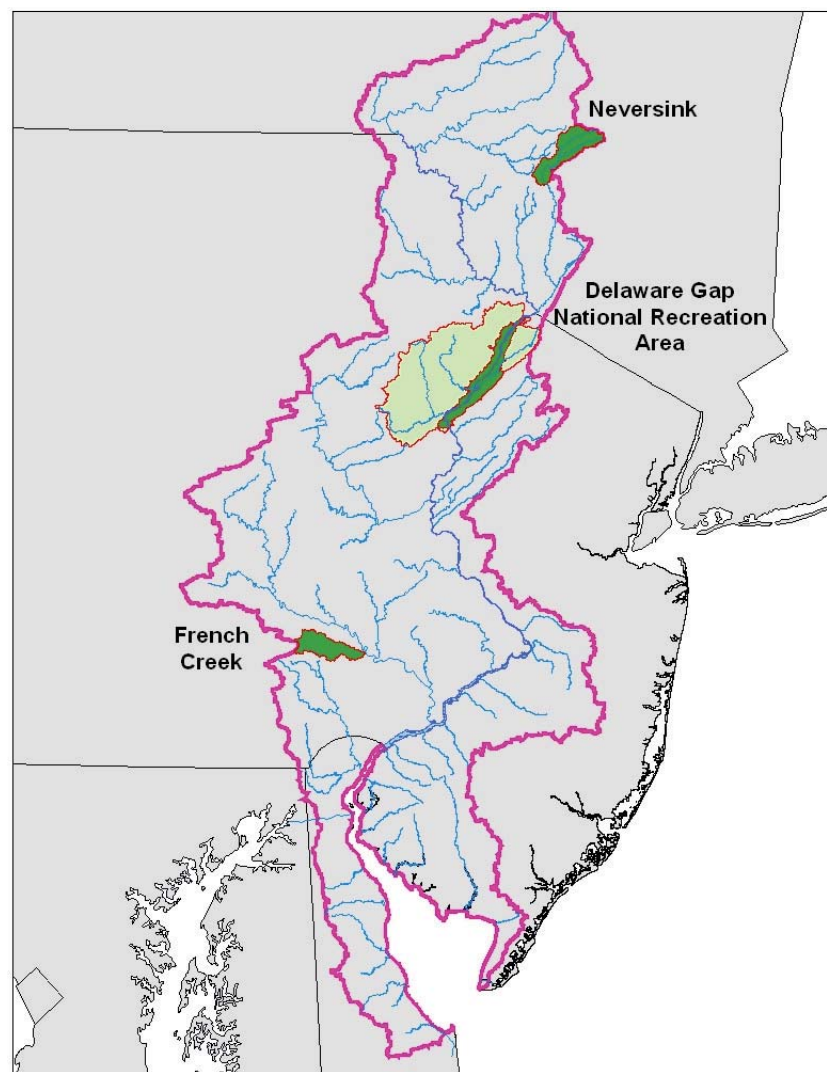


Figure 1.3.—Locations of intensive monitoring and research areas within the Delaware River Basin.

The IMRA sites selected for the CEMRI pilot were the following:

- 1) Neversink River Basin: Biogeochemical and hydrologic processes in the watershed of the Neversink River have been monitored by the USGS district research program since 1982. The Neversink lies within the northern, mostly forested region of the Appalachian Plateau Province and contains a set of nested discharge and water quality monitoring stations in basins ranging in size from 130 km<sup>2</sup> to 1 km<sup>2</sup>. Research on terrestrial and aquatic acidification and best management practices for sustaining the quality of water in the New York City reservoirs has been going on since 1982.
- 2) The watersheds of the Delaware Water Gap National Recreation Area: These watersheds that drain through the DEWA lie within the central Appalachian Plateau Province, which is also mostly forested but rapidly developing outside of the park boundary. Discharge and water quality monitoring stations have been operated on tributaries and the main-stem Delaware River for several years and have been integrated into the NAWQA program since 1994 (Gilliom et al. 1995). The NPS established special forest plots within the park for studying the long-term effects of the introduced insect hemlock woolly adelgid.
- 3) French Creek Watershed: The French Creek Watershed is located in the midbasin Piedmont Province and contains a partially forested landscape that is being rapidly suburbanized. Discharge has been monitored continuously at French Creek since 1968, and water quality has been monitored periodically by the NAWQA program since 1994.

Tier 2 and Tier 3 monitoring was also intensified within the IMRAs to provide finer resolution data collection within the small watersheds where the long-term, process-level research was located, and to identify sampling locations for gradients of disturbance and forest type. Some forest sampling plots were intentionally placed directly within process-level research and monitoring studies to support the extrapolation of process-level results to the regional scale.

Finally, to provide an independent set of data to test scaling results for vegetation and carbon (C) estimates, additional regional “validation plots” and stream monitoring stations were established. A streamlined set of measurements was collected at these plots and withheld from the development of relationships among variables that can be used to scale up from intensive study areas to the region.

## **1.6 Identification of Resource Issues**

Numerous meetings of the lead agencies, and the results of a stakeholder meeting hosted by the multi-state Delaware River Basin Commission, led to the identification of forested landscape issues that required data from multiple spatial scales and multiple resource groups:

- Measuring and monitoring forest C stocks and fluxes
- Identifying and monitoring forests vulnerable to non-native invasive insect species
- Monitoring effects of calcium (Ca) depletion and nitrogen (N) saturation in forests subjected to acidic deposition in the Appalachian Plateau
- Measuring and monitoring forest fragmentation and land use change, and associated ecosystem changes

- Integrating the effect of terrestrial ecosystem health and land use on the hydrology, habitat, and water quality of the Delaware River and Estuary

Addressing these five issues was the focus of the Delaware CEMRI pilot study. Descriptions of the measurements involved in addressing each issue, the capabilities of existing programs to provide pertinent data, and the approaches adopted for integrating and enhancing those programs as part of the CEMRI project are presented in this foundation document. A brief summary of the information in individual chapters is provided here.

## **1.7 Measurement and Monitoring of Forest Carbon Stocks and Fluxes**

The goal of the CEMRI C study was to improve our capabilities to compute regional C budgets by integrating and augmenting terrestrial and aquatic data collection and analysis programs. Forests are thought to store close to 90 percent of Earth's terrestrial vegetation biomass (Dixon et al. 1994) and are important controllers of atmospheric carbon dioxide (CO<sub>2</sub>) concentrations and thus the global C cycle. The rate of forest growth also affects the quality and quantity of water reaching streams, because photosynthetic rates are directly proportional to water use by plants, and thus the rate of tree growth also influences streamwater quantity. Finally, changes in river export of C to the ocean can significantly alter the biogeochemistry of coastal and estuarine ecosystems.

To create an approach for estimating C stocks and fluxes that incorporated terrestrial and aquatic C transformations, the CEMRI sought to

- 1) Improve the ability of the ground-based monitoring networks to more completely assess regional forest C stocks and fluxes
- 2) Integrate disparate monitoring networks to develop complete site-level and Basin-level C budgets including C loss by water transport
- 3) 3) Ground-truth estimates of forest biomass and net primary production (NPP) from available remote sensing products (Tier 4) with multiscale inventory data (Tiers 1, 2, and 3)
- 4) Characterize the effects of land use change and forest fragmentation on cumulative C stocks and fluxes

Tier 4 monitoring was available for the DRB through satellite-derived MODIS and Landsat thematic imagery and was augmented with AVIRIS imagery from aircraft in the northernmost sub-basins. Funding from NASA allowed improvements in the calibration of MODIS datasets for remote identification of eastern forest types. For Tier 3 monitoring, the foundation program was the USFS Forest Inventory and Analysis (FIA) network of sample plots (Bechtold and Patterson 2005). Research plots for intensive study of C fluxes within the IMRAs, and gradient sampling sites representing a range of forest types and condition for Tier 2 monitoring, were embedded within the FIA network to allow cross-scale comparisons. For Tier 1 C stock and flux estimation, a set of 10 research plots at each IMRA was established. These carbon plots featured, in addition to regular inventory measurements, collection of data on litterfall and annual stem increment and additional sampling of woody debris and soil. Enhanced measurements were made at plots within the Neversink River Basin in New York, the DEWA, and the French Creek River Basin in Pennsylvania. Terrestrial C budgets (sequestration and flux) were computed for each IMRA,

and integration of the data across all four tiers of monitoring allowed for the development of a C budget for the entire DRB.

The NAWQA program and long-term river monitoring networks of the USGS provided CEMRI with the foundation data for C flux in surface waters, including C and sediment flux measurements at stations where stream discharge was already being measured. Trends in river C export were determined from long-term water quality and flow records for the head-of-tide on the Delaware River at Trenton, New Jersey, and in the headwaters of the Neversink River near Claryville, New York. The USGS added a survey of dissolved organic carbon (DOC) during the spring and fall in first-order forested streams throughout the upper DRB. The combined network allowed the assessment of basinwide estimates of C flux in surface waters.

## **1.8 Monitoring Methods for Forests Vulnerable to Non-Native Invasive Pest Species**

The goal of the CEMRI invasive pest study was to develop methods for anticipating forest damage and associated surface water degradation by pests through mapping forest vulnerability to infestation and determining the hydrologic and biogeochemical conditions that would allow surface water degradation from forest disturbance. Non-native forest pests and pathogens are a great concern for forest ecosystems in the DRB. Some of the most destructive forest pests introduced into North America inhabit the region. For example, the gypsy moth was introduced into the United States well over 100 years ago and first appeared in the DRB around 1940, and the hemlock woolly adelgid was first noticed in the northern DRB less than 15 years ago (Liebhold et al. 2005). The Asian longhorned beetle is not known to be established in the basin, but it does attack forest types prevalent there and has entered North America through the port of New York City. Two major shipping ports near or within the DRB, New York City and Philadelphia, are a continuous source of potential new introductions. Exchanging overstory species in a riparian habitat through selective mortality induced by a non-native invasive species can alter water quality in the stream below.

Invasive species research in the DRB had three primary objectives:

- To develop and evaluate monitoring protocols for selected pests and resulting ecosystem damage at the IMRAs that could be cost effectively implemented as part of extensive monitoring programs
- To test a collaborative monitoring strategy for assembling pertinent information to track pest movement and mitigate the impacts of pest infestation in the DRB
- To develop maps of forest conditions in the DRB that depict areas most vulnerable to specific pests

Existing gypsy moth programs provided large-scale monitoring of the status and impacts of non-native invasive species and are an example of a Tier 2 foundation program used in the CEMRI. Gypsy moth monitoring in the DRB consisted of aerial sketch mapping of visible defoliation areas and autumn surveys to count egg masses. Data on other aspects of pest damage or environmental impact were limited, and physiographic, chemical, or climatic conditions that might influence defoliation intensity were not being documented. The existing program for hemlock woolly adelgid was a collaboration among the three State agencies bordering the upper DRB and the USFS. The State of Pennsylvania, the USFS, and

the NPS maintain permanent monitoring plots to facilitate the documentation of tree health decline in the host trees over time. Existing monitoring programs for hemlock woolly adelgid provided information at the tree and small plot levels but not on the spatial distribution of the pest on a regional scale. Several types of remotely sensed information were investigated for development of tools to assess the degree of adelgid infestation and hemlock decline (Pontius 2004, Royle and Lathrop 2002). Pest-related tree damage was recorded at FIA plots for all trees larger than 5 inches diameter at breast height (dbh).

The CEMRI developed tighter links between large-scale spatial information and plot-level process studies. A pre-CEMRI history of damage resulting from hemlock woolly adelgid infestation was developed for the DRB using Landsat Thematic Mapper images (Bonneau et al. 1999, Royle and Lathrop 1997). Ground monitoring of the adelgid in the Delaware Gap IMRA was initiated with 14 pairs of plots (hemlock and hardwood) within the DEWA. Trees were evaluated annually using the FIA crown rating guide. Consistent and extensive monitoring of regional pest populations, extent, and damage over time, combined with indepth process-level research at intensive study sites, was needed to begin to address the ecosystem effects of invasive pests at large scales. The CEMRI study accomplished this by enhancing data collection within the hemlock intensive monitoring sites at the Delaware Water Gap IMRA, simplifying and augmenting regional sampling methods, developing forest vulnerability maps, and linking physical and chemical environmental data with data on pest infestation. Soil chemistry and water quality studies conducted by the USGS, assessment of pest infestation at FIA and NPS monitoring plots, and ancillary data from weather stations and other monitoring networks within the region were used to develop strategies for collaborative monitoring of the causes, extent, and consequences of forest pest infestation, and to form an initial regional assessment of the environmental parameters associated with pest outbreaks and an analysis of the resulting effects of those outbreaks on environmental quality.

## **1.9 Monitoring of Recovery from Calcium Depletion and Nitrogen Saturation**

The goal of the CEMRI Ca-depletion/N-saturation study was to determine the cause-effect relationship between forest stress and soil Ca depletion in research plots representing multiple soil conditions, and to correlate forest health, soil chemistry, and surface water chemistry at a regional scale. Acid rain has been implicated in acidification of sensitive waterways, nitrate (NO<sub>3</sub>) enrichment of surface waters, and fish population declines in poorly buffered mountain streams (Baldigo and Lawrence 2000, Murdoch et al. 1998). Scientists are also discovering that acid rain has had additional lasting and negative effects on soil and stream chemistry, and that the changes in soil chemistry may impact tree growth rates (Hallett et al. 2006). Determination of regions within the DRB where N saturation and associated Ca depletion are most acute would allow resource managers to plan forest harvest and development in those areas in ways that would limit the further degradation of the ecosystem.

The goals of this research and monitoring development project were to:

- Develop relationships between soil and foliar Ca, soil and stream Ca, forest N saturation, and tree productivity at IMRAs to quantify and verify the impact of Ca depletion on forest growth
- Develop methods for regional-scale monitoring of forest and stream recovery from acidification, Ca depletion, and other stressors

- Develop integrated map products of forest condition, soil chemistry, and stream chemistry for the Appalachian Plateau Province of the DRB where acid rain is having its greatest effect
- Develop methods for early detection of forest and ecosystem stress due to factors such as N deposition and soil Ca depletion

The USGS had been monitoring the effects of acidic deposition on forested watersheds and streams in the Catskill Mountains since the early 1980s and thus had significant monitoring infrastructure to serve as the foundation for collaborative study in the Neversink IMRA. Information about air quality, surface water quality and quantity, and forest growth have been collected by the EPA, USGS, USFS, and State agencies within the upper DRB. The USGS and USFS FIA programs have collected soils from a few locations within the basin, and the USDA Natural Resources Conservation Service has mapped soils in the basin based on limited pedon data, but data sufficient to draw accurate maps of soil Ca depletion were not available. At the time of the CEMRI, new methods for assessing tree stress were being developed by the USFS, but use of these methods was restricted to research plots.

The Neversink River Basin IMRA was chosen as the location for Tier 1 studies on the causes and effects of Ca depletion. Foliar chemistry, tree growth and dendrochemical history, wood polyamine content, soil chemistry, and drainage water quality were the primary components of the ecosystem measured as indicators of Ca and N stress. Research by the USFS was also conducted at the Neversink IMRA to develop methods for detecting tree stress, before visible signs appear, using foliar polyamine concentration in trees exposed to Ca depletion (Minocha and Long 2004). This research was nested within data collected from a network of watersheds (Tier 2) representing a range of stream and foliar Ca concentrations, a new survey (Tier 3) of soil chemistry at each of the FIA forest plots in the upper DRB, and a survey (Tier 3) of streams draining the nearest forested, first-order watersheds to the FIA plots. Maps of deposition rates were generated through modeling of data from deposition monitoring stations in the Northeastern U.S. by researchers at Pennsylvania State University (James Lynch 2003, written communication). Remote sensing methods for determining foliar chemistry (Tier 4) were under development during the CEMRI period (Pontius et al. 2005), but pilot areas in the upper Delaware River Watershed allowed the integration of all four tiers of monitoring in selected sub-basins. These combined measurements provided the first regional database in the United States to integrate forest condition, soil condition, and associated surface-water quality.

### **1.10 Monitoring of the Status and Impacts of Forest Fragmentation**

The goal of the CEMRI forest fragmentation study was to improve the mapping of forest fragmentation features in the DRB and to relate those refined findings to water quality and habitat conditions in the basin's surface waters. Forest fragmentation in this study was defined as the spatial breakup of forest land by developed land uses. The proximity of humans and human development to forest land increases the use of the forest by people for recreation and other activities, changes the local hydrology, alters the types of forest management that can be used, and facilitates the invasion of exotic species. The type, density, and distribution of developed land uses within the surrounding area have the potential to change the physical and biochemical characteristics of the terrestrial and aquatic ecosystems, and to alter many of the ecological processes at work.

This project sought to:

- Identify and characterize forest fragmentation over large areas with the detail and accuracy required for studies of wildlife habitat, plant composition, and water quality
- Identify potential impacts of fragmentation on water quality
- Develop appropriate methods for achieving the first two objectives, with a focus on:
  - o Identifying appropriate ways of describing and quantifying fragmentation
  - o Identifying measures of and standards for accuracy assessment

Before this study, research focused on developing methods to quantify forest fragmentation using remotely sensed imagery. Two datasets being used in this region were 1:40,000 aerial photography and Landsat Thematic Mapper (TM)-derived land use/land cover classifications (Riitters et al. 2000). These monitoring strategies, while providing a relative measure of fragmentation for comparison with other areas within the region, provided little information about the impact of fragmentation on ecosystem health. Calculations from TM-derived datasets, while available over broad areas, were not necessarily consistent with reality at plot or stream locations on the ground and were highly dependent upon the accuracy of the original classification (e.g., Wickham et al. 1997).

For CEMRI, the French Creek and Delaware Gap IMRAs were chosen for Tier 1 monitoring in part because residential development had been occurring rapidly outside the greater Philadelphia area and the park, respectively, and there was concern that the development might affect water quality. Streamwater was monitored for signs of disturbance from development, and an intensified network of forest measurement plots was established in each watershed (Tier 2). The USGS NAWQA program had established measurement stations at 42 medium-scale tributaries to the Delaware River representing a gradient of development intensity in their watersheds (Tier 2), where water and sediment had been sampled and habitat had been assessed during the previous 3 years over a range of seasons and flow conditions (Fischer et al. 2004). Datasets containing fragmentation indicator variables were developed for each of the selected study watersheds by the USFS, and correlations were established between those indicators and aquatic chemistry, flora, and fauna. These watersheds were nested within the broader FIA network of forest plots and a regional random survey of stream chemistry (Tier 3). Data from other sources, such as the USGS National Hydrologic Database (NHD) and TIGER/Line roads database, were also used in this analysis (Tier 4). The data from these nested networks and fragmentation maps were used to develop improved correlations between forest fragmentation and stream habitat condition and to re-interpret satellite data on land use and land cover for developing regional forest fragmentation maps (Tier 4). This study helped determine to what extent TM- and MODIS-derived land use-land cover classifications are sufficient for quantifying parameters of forest fragmentation and established guidelines on TM classification protocols or requirements to improve the ability of TM-derived datasets to provide such fragmentation and context information.

### **1.11 Integrated Analysis and Scaling Methods**

Because some common variables were collected among all monitoring tiers (i.e., at all spatial scales) and all within the same watershed framework, the relationship between biogeochemical processes and indicators developed at the IMRA sites could be used to interpret the condition of the forests at the larger spatial scales (Stolte et al. 2004). For example, a system for integrating process-level information on C cycling rates with data from the regionally extensive forest monitoring network and the USGS surface water monitoring programs was developed at the three IMRAs. Variables such as fine foliar litterfall, coarse woody debris production, foliar chemistry, and soil C and N stocks were measured at the Tier 1 sites, and relationships were developed between these variables and indicators such as forest type and basal area that can be efficiently measured at Tiers 2 and 3.

Because the USFS Tier 3 sampling is national in scope, the enhanced Tier 3 data within the DRB can also be compared to forest conditions in similar ecological strata outside the DRB. The CEMRI program integrated data across spatial scales (Tiers 1, 2, and 3) using two primary models on landscape and surface water data in the DRB: the SPARROW model developed by the USGS, and the PnET model developed by the USFS and the University of New Hampshire (Alexander et al. 2001, Ollinger et al. 1998, Pan et al. 2004).

The SPARROW model (SPAtially Referenced Regressions of contaminants On Watershed attributes) used data on watershed conditions from different programs collecting environmental data within the basin to predict downstream water quality (Alexander et al. 2001). The model can link process data from small-scale watershed studies with monitoring data from large-scale river sites. The SPARROW model used the CEMRI data collected on a watershed-wide basis in forested watersheds to estimate the river export of specific constituents from the forested landscape, and it compared that modeled export to estimates developed by the USGS NAWQA program for urban and agricultural landscapes. In this way, the model created overall estimates of watershed export of chemical constituents within the DRB. The model output could then be compared to measured export values computed at USGS monitoring stations nested within the DRB.

The PnET model is a process-based ecosystem model that uses spatially referenced information on vegetation, climate, and soil to predict the functioning of forest processes that control C storage, net primary production (NPP), water yield, and N leaching loss. The model was well validated for NPP and water yield predictions at locations within the Northeastern U.S. (Ollinger et al. 1998). In addition to general input information, the model also requires data on N deposition, ozone (O<sub>3</sub>), and atmospheric CO<sub>2</sub> to predict the impact of changing atmospheric chemistry on forest ecosystems. Ecosystem processes were analyzed at large spatial scales in the DRB using a combination of the new CEMRI databases and existing modeling of climate change scenarios and N deposition rates in forested regions of the mid-Atlantic and Chesapeake River Basin (Hom et al. 1998, Pan et al. 2004).

### **1.12 Preliminary Results**

Although data analysis and final reporting are still in process, work to date is pointing toward some significant results emerging from the CEMRI process. Here are some examples:

- Initial results show that the basin is a small net C source. Within the basin, southern areas are losing C while northern areas are gaining C primarily because of historical

patterns of land use change. Initial estimates of transfer of C via streams show small quantities relative to uptake by trees.

- Correlations between pest infestation and changes in stream chemistry were observed during the short period of the CEMRI assessment, and methods for tracking the effects of pest outbreaks on forest soil and stream biogeochemistry were developed and tested.
- Mapping and data analysis revealed important biogeochemical correlations among foliar chemistry, tree stress indicators, and both stream and soil Ca concentrations in the Neversink IMRA. There is a common pattern of low soil Ca concentrations and low stream acid neutralizing capacity in the western Pocono Mountains and the eastern Catskill Mountains, the areas receiving the greatest amount of acidic deposition.
- Analysis of macroinvertebrate and stream chemistry data along with forest fragmentation and landscape composition data from interpretation of color infrared aerial photography showed a much stronger correlation between declining water quality and increasing urbanization and forest fragmentation than was possible using land use data derived from satellite remote sensing, even at relatively low levels of disturbance.
- Modeling of forest biogeochemistry with the PnET-CN model showed how N leaching from forests is responsive to levels of N deposition, and it indicated high levels of N leaching from forested landscapes to streams in the upper DRB.

### 1.13 Conclusions

The CEMRI approach of a) integrating and enhancing existing monitoring programs to address key forest health and sustainability issues at multiple spatial scales and b) using a large watershed as a common frame of reference is a practical solution for compiling the data from diverse monitoring systems necessary to address complex regional environmental issues. Implementation requires sponsorship by participating agencies, clearly identified issues to be evaluated, and a willingness to modify or enhance existing monitoring systems and analytical models. Once established, the integrated research and monitoring system results in a desirable template to attract other monitoring and research programs to this data-rich arena and greatly expands the interpretive capabilities of the individual programs involved.

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## 2.0 INTRODUCTION TO THE DELAWARE RIVER BASIN PILOT STUDY

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*Peter S. Murdoch, Jennifer C. Jenkins, Richard A. Birdsey*

### 2.1 Objectives of the Study

The past 20 years of environmental research have shown that the environment is not made up of discrete components acting independently, but rather it is a mosaic of complex relationships among air, land, water, living resources, and human activities. The data collection and analytical capabilities of current ecosystem assessment and monitoring programs are insufficient to measure how multiple components of the ecosystem interact. Since the mid-1990s, resource managers have been called upon to adopt “ecosystem management” practices for land stewardship, but seldom have had the multicomponent, ecosystem-level information needed to achieve this goal. Much of the information currently being collected is fragmentary and incompatible because it is collected through programs designed and conducted at different scales or for different objectives, because data confidentiality issues can limit data sharing and field collaboration, and because protocols for sampling and data management are inconsistent. Similarly, much of the information currently collected cannot be used to answer regional ecosystem-level questions because the scale of process-based research is incompatible with the larger scales of typical monitoring and assessment. Science capabilities must be expanded to increase our capability for drawing connections between processes taking place at intensively studied research areas and trends in the resources typically monitored at larger scales (Gosz and Murdoch 1999).

To be effective, ecosystem management, environmental assessment, and monitoring of environmental health must take into account the mosaic of complex relations among air, land, water, living resources, and human activities, making connections between processes occurring at multiple spatial and temporal scales. Narrowly targeted monitoring programs based mainly on observations and empirical analysis are poorly suited to developing an understanding of these complex relationships.

One suggested solution to the problem of multiple, nonintegrated monitoring programs is to create a single Federal agency in charge of monitoring the Nation’s natural resources. This scenario would ensure integration but would require significant resources to establish and could not completely replace the issue-specific monitoring required to meet current agency missions. This scenario also fails to address the scientific and analytical capability required to take full advantage of the myriad data types that must be collected for a full understanding of ecosystem-level processes at multiple scales. An alternative proposal endorsed by the Committee on Environmental and Natural Resources in 1997 (Committee on Environment and Natural Resources 1997) was to develop a concept for “virtual” integration in which existing monitoring programs would fill specific niches in a monitoring hierarchy, the sum of which could be used for tracking environmental problems in a more holistic manner than currently possible (CENR 1997). By supplementing and adjusting existing monitoring and research strategies, those programs could continue to meet specific agency missions while also contributing to a national multiscale, multiresource tracking system, and they could do so for the least additional expense relative to the other scenarios being proposed. A test of this latter concept is the subject of this report. In developing this concept, we focused on key issues that express themselves at a larger scale and demand integration among researchers not only for

understanding the causes and consequences of the ecosystem processes taking place, but also for monitoring the status and trends of those processes at the landscape scale.

During the first 4 years of the new century, the U.S. Geologic Survey (USGS), the U.S. Forest Service (USFS), the National Park Service (NPS), and the National Aeronautics and Space Administration (NASA) tested strategies for multiagency collaboration by establishing a Collaborative Environmental Monitoring and Research Initiative (CEMRI) in the Delaware River Basin (DRB). The goal of the initiative was to test potential collaborative strategies for multiagency monitoring and research networks that could be applied throughout the United States. The Delaware CEMRI followed a 1-year test of integrating regional probabilistic survey programs in eastern Oregon by the USFS and the USGS (Goebel et al. 1998). The Delaware CEMRI expanded on the results of that study by testing a framework for integrating environmental data collected across a range of temporal and spatial scales, from process-level research sites such as the Hubbard Brook Experimental Watershed in New Hampshire to regional surveys and remote sensing programs such as those tested in the Oregon demonstration project (Goebel et al. 1998).

The objectives of this report are a) to describe the applicability of existing monitoring programs, monitoring data, and scientific analytical capability to assess five environmental issues of critical importance in the DRB and b) to describe a proposed network design based on those assessments for the collaborative monitoring and research effort. These descriptions clarify gaps in existing data and highlight data comparability issues that currently limit our ability to gather appropriate information for effective detection and monitoring of cross-resource environmental trends at appropriate spatial scales. The report also recommends actions that could be taken in existing programs to improve data comparability.

Further information on CEMRI can be obtained at <http://www.nrs.fs.fed.us/pubs/>.

## **2.2 The Framework Concept behind CEMRI**

In 1995 an interagency working group of scientists and program managers was established by the National Science and Technology Council's Committee on Environment and Natural Resources (CENR) and directed to "recommend a framework for an integrated monitoring and research network that allows evaluation of the Nation's environmental resources (e.g. air, water, soil, plants, animals, and ecosystems)." The conceptual framework articulated by the working group (hereafter called the "framework") was designed to address limitations and capitalize on the strengths of existing monitoring programs to build a national ecosystem monitoring system based on collaboration among Federal, State, local, and nongovernment programs (Committee on Environment and Natural Resources 1997).

The premise of the framework is that an effective national environmental monitoring strategy can be assembled largely by creating a conceptual structure within which independent monitoring and research programs can take advantage of their complementary activities to address environmental questions across multiple scales and multiple resources (Fig. 2.1). In general, the committee concluded that existing programs fit into three broad categories of spatial and temporal monitoring:

## REGIONALIZATION HIERARCHY

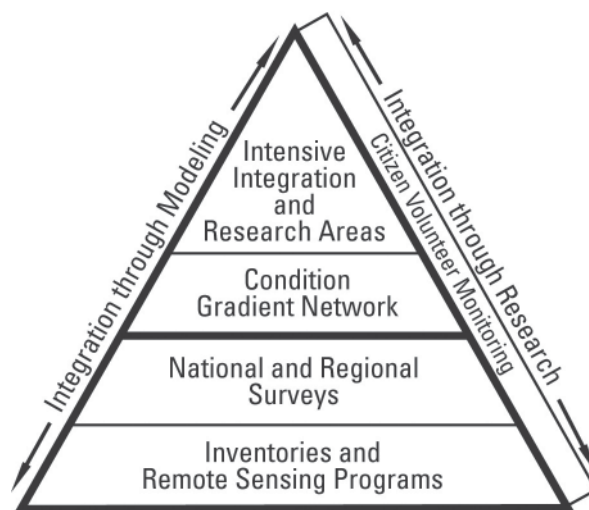


Figure 2.1.—Conceptual framework for achieving the multiple goals of environmental monitoring and research. (Committee on Environment and Natural Resources 1997)

- Tier 1 - Frequent monitoring and indepth research on processes, cause and effect, and trends at a limited number of intensively monitored sites within relatively small areas; these sites are referred to in the CEMRI as intensive monitoring and research areas (IMRAs)
- Tier 2 - Infrequent multipoint ground monitoring (such as national and regional resource probability surveys) and inventories
- Tier 3 - Temporally and spatially continuous monitoring and analysis (such as satellite remote sensing, aerial photointerpretation, and mapped data developed from fixed site networks)

After the framework exercise was completed at CENR, a refinement to the second monitoring tier was proposed to differentiate two distinct methods of extrapolating process-level information to the regional scale. The proposed additional data-collection tier represents gradient networks of monitoring stations that are deliberately selected to represent a range of conditions for a specific environmental issue and that are monitored at a range of temporal intensities for parameters specific to that issue. The framework ultimately used for the CEMRI study is a conceptual structure for a systematic linkage of existing inventories and remote sensing with national and regional resource surveys, gradient-based studies, and whole-ecosystem, intensive monitoring and research sites, using modeling as a tool for integrating data across temporal and spatial scales. As a general guide for this integrated work, we developed specific goals for research and monitoring at each of the four tiers.

At Tier 1 IMRAs, the goal was to conduct process studies to define relationships among key ecosystem parameters and processes. For example, in the DRB we combined program resources to conduct collaborative, ecosystem-level research studies at common study sites to determine the effects of pest infestation on soil nitrogen (N) cycling rates, to relate rates of forest carbon (C) sequestration to factors such as forest type and soil nutrient capital,

and to investigate the relationship of tree health to soil nutrient status. Also at this scale, an explicit goal of the project was to link measurements of terrestrial and aquatic ecosystems to develop better strategies for integrated monitoring at larger scales. Process studies such as these typically require detailed site-specific information that is too costly to collect over a broad region. Process research involves substantial investments of time and money, and the number of such research sites nationwide is therefore limited. However, to be relevant to environmental policy for a given region, the process-level understanding developed at these IMRAs must be extrapolated to the regional scale.

At Tier 2 (gradient study sites), the goal was to extrapolate the relationships from the Tier 1 process studies to the regional scale through regression of critical response variables against parameters that can be regionally mapped. In this tier, a number of monitoring stations representing the range of conditions for a given environmental issue are sampled with sufficient frequency or detail to use the combined data from all sites to correlate ecosystem response to a range of disturbances from a specific stressor. For example, an experimental manipulation at the IMRAs may determine that forest removal and development result in higher stream runoff, streambank erosion, and water quality decline. A gradient network of watersheds representing a range of deforestation and development could be sampled in Tier 2 to determine thresholds of fragmentation above which stream degradation occurs, and the regional extent of degradation could then be determined through mapping of forest fragmentation and development. The USGS and the USFS collaborated through CEMRI in establishing gradient networks for forest fragmentation and ecosystem calcium (Ca) depletion in the DRB. A final goal of work at Tier 2 was to conduct ground verification of remotely sensed parameters defined at Tier 4.

At Tier 3 (probabilistic regional surveys), the relationships from the Tier 1 process studies to the regional scale condition are extrapolated through random or stratified, probability-based surveys of environmental conditions or of responses related to a specific stressor. For example, research at the IMRAs may determine that tree species composition in a forest stand is an important driver of forest productivity. Using this relationship in conjunction with species composition data collected from ground surveys at Tier 3, we can estimate forest productivity at the regional scale. If a survey of soil nutrient status is also done, regional patterns of productivity (response) in relation to soil Ca depletion (stress) can also be mapped. These data can allow for the spatial identification of special cases where additional information may be needed to understand regional ecosystem processes.

At Tier 4 (spatially and temporally continuous remote sensing and mapping investigations), the primary objective was to develop spatially continuous information. Atmospheric N deposition, land use, and forest species distribution are examples of spatially continuous information that may help to define the regional extent of relationships described in Tiers 1, 2, and 3. Also, investigations at Tier 4 may be used to interpolate between survey points at Tier 3. Geostatistical techniques for interpolating tree species composition from ground survey points are an example of one such study. A final goal of investigations at Tier 4 was to develop methods to quantify indicators of interest for research studies at Tier 1. For example, through CEMRI we developed methods for quantifying forest fragmentation from remotely sensed imagery for small research areas that have extensive field observations (ground truth),

and these findings will in turn be used to provide information for studies on the regional relationship between fragmentation and water quality.

This tiered approach to monitoring and assessment, using extensive inventories to link intensive sites with wall-to-wall measurements, has been adopted and modified by other national-scale monitoring efforts. For example, the North American Carbon Program (Wofsy and Harris 2002), used this approach for measuring and monitoring C stocks and fluxes in the Nation's forested ecosystems. The CEMRI application sought to integrate terrestrial and aquatic information for whole-ecosystem assessments.

In summary, intensive research studies at Tier 1 are used to define key ecosystem process relationships, and these relationships can be extended to the regional scale using ground-based gradient studies from Tier 2 and survey data collected at Tier 3. Information from Tier 4 can be used to interpolate between survey points, develop maps that help define the regional extent of relationships revealed at Tier 1, and develop methods for quantifying indicators of interest for study at both Tiers 1 and 2. Tier 2, the ground-based regional extrapolation tier, should be seen as a key link between the Tiers 1 and 3; this nested approach to our monitoring strategy allows us to span multiple spatial scales with confidence.

### **2.3 Unique Characteristics of the CEMRI Framework**

To date, cross-tier linkages have been attempted by few programs because each program lacks the resources to provide a comprehensive approach, and robust methods for linking site-specific and regional data have not been fully developed. The multi-tier framework approach used collaboration among multiple programs to create the comprehensive, indepth, cross-resource monitoring impossible with a single program and yet required to understand complex environmental problems and thus make better informed policy decisions.

The framework concept also differs from other environmental monitoring and assessment programs in the following ways:

- The framework concept is not a new monitoring program; rather it is an organizing structure for conceptualizing how data from existing programs can be integrated through cross-agency collaboration. New funding would be used to fill gaps in existing programs, not to develop entirely new monitoring systems.
- It is not a single-issue or single-resource-driven monitoring scheme; rather, it calls for the development of collaborative strategies among existing monitoring programs to assess, evaluate, and forecast trends in the condition of whole ecosystems. It can, however, also be used to organize existing programs around a single issue in a scientifically rigorous manner.
- It provides a scientifically rigorous method for scaling ecosystem process information between single study sites and larger landscapes, and was the first such strategy to be tested explicitly in a pilot region.

The DRB study described here was the first attempt at using this framework approach.

## **2.4 Rationale for Selection of the Delaware River Basin as a Frame of Reference**

The DRB in the Eastern United States was chosen as the framework's first pilot region because:

- The river basin hosts several existing agencies and programs that were willing to take on the integration challenge in designing and examining their monitoring strategies.
- The river basin-to-estuary landscape delineation was a logical conceptual unit for integrating environmental information on a regional scale because the water of the system serves as an integrated indicator of many environmental trends.
- The DRB is a relatively simple version of such a watershed system, with a single large river entering the estuary, as opposed to more complicated systems such as the Chesapeake Bay drainage where multiple rivers discharge freshwater into the bay ecosystem.

The primary focus of the CEMRI was not to complete a one-time comprehensive environmental assessment; rather, it used data collection and analyses targeted at specific environmental issues to illustrate the value of integrated monitoring among existing programs and to establish a scientifically rigorous long-term strategy for integrated monitoring in the DRB.

## **2.5 Collaborating Agencies**

Lead Federal agencies on the DRB pilot included the U.S. Forest Service (USFS), the U.S. Geological Survey (USGS), and the National Park Service (NPS), with additional funding provided by the National Aeronautics and Space Administration (NASA). Explicit collaboration among these agencies allowed for planning data comparability, filling in data gaps, and integrating data among programs. The New York City Department of Environmental Protection also contributed to the CEMRI through their established collaborations with the USGS in the Delaware headwaters, the primary source of the New York City water supply.

## **2.6 Environmental Issues Addressed During the CEMRI Pilot**

The CEMRI concept was tested at a regional scale by incorporating monitoring and research efforts at all four tiers of the framework to address the following five environmental issues specific to forested landscapes:

- Measuring and monitoring forest C stocks and fluxes
- Identifying and monitoring forests vulnerable to non-native invasive pest species
- Monitoring recovery from Ca depletion and N saturation in forests of the Appalachian Plateau
- Measuring and monitoring forest fragmentation and associated ecosystem changes
- Integrating the effect of terrestrial ecosystem health and land use on the hydrology, habitat, and water quality of the Delaware River and Estuary

## **2.7 Objectives of this Report**

This report provides the conceptual foundation for testing the CEMRI concept through addressing these five environmental issues, and presents background information that supplements research papers published or in process. Specifically, this report 1) describes the CEMRI integration concept and how it was used to test integration of several Federal monitoring programs, 2) provides an initial evaluation of the five issues listed above using data from the disparate, pre-CEMRI monitoring programs as a baseline for comparison with

CEMRI results, and 3) shows some of the initial results from the CEMRI study. This initial evaluation of the five issues highlights shortfalls and gaps in the pre-CEMRI monitoring programs and shows how the CEMRI approach to integrated monitoring can improve our ability to monitor ecosystem change across a range of scales, thus detecting and predicting environmental change earlier and more accurately.

## **2.8 Study Area Description**

The DRB encompasses more than 12,700 mi<sup>2</sup> and includes parts of Pennsylvania (6,465 mi<sup>2</sup>), New Jersey (2,969 mi<sup>2</sup>), New York (2,363 mi<sup>2</sup>), Delaware (968 mi<sup>2</sup>), and Maryland (8 mi<sup>2</sup>) (Fig. 2.2). About 7.2 million people live within the basin, and an additional 7 million people in New York City and northern New Jersey rely on surface water diverted from the DRB for their water supply (Fischer et al. 2004).

Topography varies from the relatively flat Coastal Plain Physiographic Province, where soils are underlain by unconsolidated sediments, to rolling lowlands and a series of broad uplands in the Piedmont Province where soils are underlain by metamorphic rock. North of the Piedmont, the New England Province and the Valley and Ridge Provinces consist of rock layers that have been deformed into a series of steep ridges and parallel folds that trend northeast-southwest. The Appalachian Plateau Province occupies the upper one-third of the basin and is characterized by rugged hills with intricately dissected plateaus and broad ridges. Bedrock in the Appalachian Plateau consists of interbedded sandstone, shale, and conglomerate. Elevation in the basin increases from sea level in the south to more than 4,000 feet in the north. During the last major glacial advance, the Appalachian Plateau and parts of the Valley and Ridge and New England Provinces were glaciated. North of the line of glaciation, valleys typically are underlain by thick layers of stratified drift and till (Fischer et al. 2004).

Average annual precipitation ranges from 42 inches in southern New Jersey to about 50 inches in the Catskill Mountains of southern New York; annual snowfall ranges from 13 inches in southern New Jersey to about 80 inches in the Catskill Mountains (Jenner and Lins 1991). Generally, precipitation is evenly distributed throughout the year. Annual average temperatures range from 56 °F in southern New Jersey to 45 °F in southern New York.

From 1992 satellite-derived Thematic Mapper (TM) land cover data, it is estimated that about 60 percent of the DRB is forested land, 24 percent is agricultural, 9 percent is urban and residential, and 7 percent is surface water bodies and miscellaneous land uses. Eighty percent of the population of the study unit lives in the Piedmont and Coastal Plain Provinces in the southern part of the DRB, which cover only about 40 percent of the total area (Ritters et al. 2000).

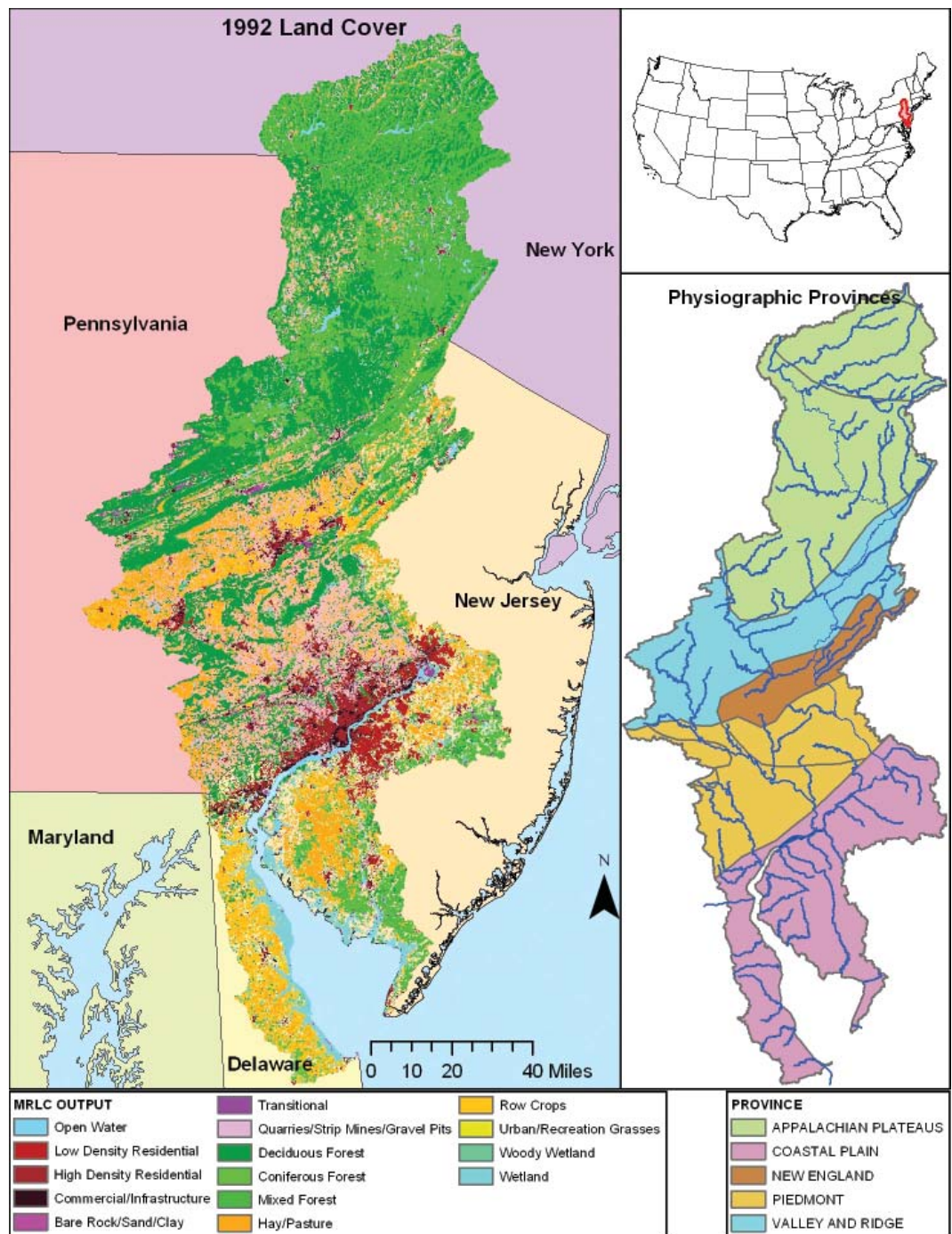


Figure 2.2—Land cover and physiographic provinces in the Delaware River Basin.  
(From Fischer et al. 2004.)

## 3.0 FOUNDATION PROGRAMS FOR THE DELAWARE CEMRI FRAMEWORK

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*Peter S. Murdoch*

A complete review of all the national monitoring programs that could possibly contribute to the Delaware River Basin (DRB) CEMRI Framework is beyond the scope of this report. The U.S. Environmental Protection Agency (EPA) Mid-Atlantic Integrated Assessment developed a Web-based annotated inventory of such monitoring programs for the mid-Atlantic region. Olsen et al. (1999) also provide a detailed assessment of the major national environmental surveys and how they might be integrated. Presented below is a brief description of the major monitoring programs that were used to initiate the Delaware CEMRI and that served as foundation programs for the core of the framework in the DRB.

### **3.1 Tier 1: Intensive Monitoring and Research Areas (IMRAs)**

Areas of intensive multidisciplinary research were limited within the DRB before the CEMRI, but were sufficient to serve as a base program for three IMRAs in forested landscapes (Fig. 3.1). Participating agencies agreed to conduct collaborative monitoring and research at temporal and spatial scales sufficient to assess the processes and controlling factors relevant for one or more of the environmental issues selected for analysis. A brief description of the existing infrastructure on which the IMRAs were established is presented here.

#### **3.1.1 USGS Neversink Research Watershed, New York**

The USGS maintains several field offices throughout the U.S. where watershed research and basic monitoring of surface and ground waters are conducted. The program in the DRB provides not only several long- and short-term research projects that contributed data or infrastructure to the CEMRI pilot, but also a network of stream discharge and water quality stations that generate long-term data for tracking trends. The USGS New York District research program has been conducting studies on streams draining forested watersheds in the Neversink River Basin since 1982 and has established a set of 12 nested discharge and water quality monitoring stations on watersheds ranging from 130 to 1 km<sup>2</sup> in area. Past projects in the Neversink Basin established detailed monitoring programs for forest condition, soil condition (chemistry, pedology, and temperature), soil water quality, stream volume and quality, deposition volume and quality, and climate variables. Deposition, ground water, soil water, and snowmelt monitoring equipment are also operating in the Neversink IMRA as part of various research projects. A research laboratory for processing low-ionic strength water samples is located in the New York District office in Troy, New York. For this region the longest records of discharge and water quality, including total organic carbon (TOC), dissolved organic carbon (DOC) concentrations, base cations, and acid anions are on the main stem Neversink River above the Neversink Reservoir (50 years of record); two headwater stations have 20 years of water quality and discharge data and several other sites have up to 12 years of records.

The Neversink watershed also serves as an analog for other northeastern forests experiencing disturbances such as acidification, soil calcium (Ca) depletion, and forest pest infestation. These issues were among those chosen for testing the collaborative strategy in the DRB.

The Catskill Mountains receive the highest rates of acidic deposition in the Northeast US. (Murdoch et al. 2000), and soil base cation concentrations are among the lowest reported

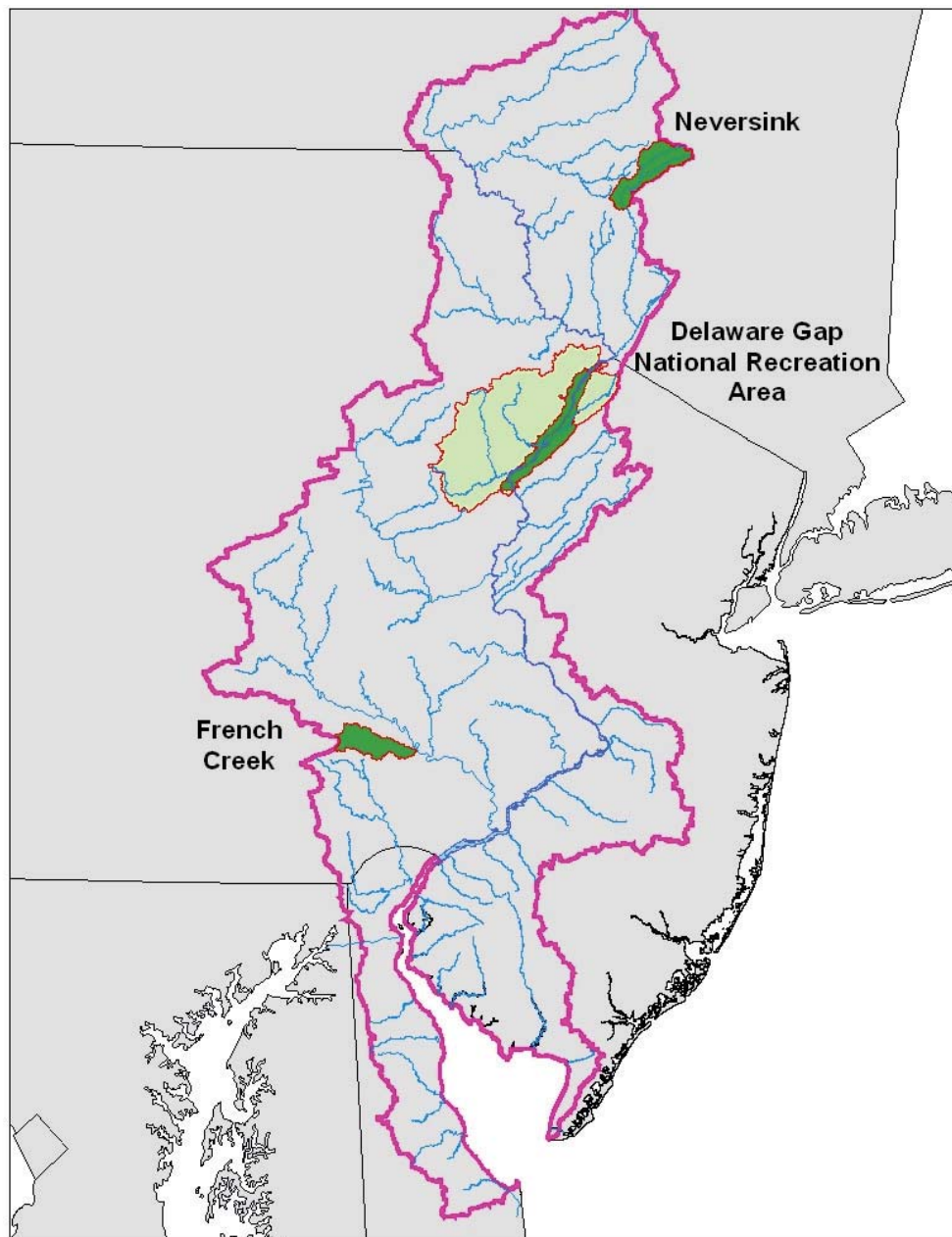


Figure 3.1.—Locations of intensive monitoring and research areas (IMRAs) within the Delaware River Basin.

for the region (Lawrence et al. 1994). Data on episodic changes in stream chemistry have been collected since the mid-1980s. The hemlock woolly adelgid was first observed in the watershed in 2003, allowing researchers to assess both pre- and early-infestation hemlock condition, and girdling experiments within the watershed have simulated the effects of hemlock death on soil chemistry and runoff (Yorks 2001). Logging studies in small sub-catchments of the Neversink Watershed were underway before the CEMRI to determine the threshold percentage of basal area removal above which large amounts of nitrogen (N) are released to surface waters from the logged area. This combination of historical record, monitoring infrastructure, and the availability of landscapes affected by the issues being addressed was the basis for selecting the Neversink River Basin as an IMRA.

### **3.1.2 Delaware Gap National Recreation Area (DEWA)**

Before the CEMRI, the National Park Service (NPS) had established special forest plots at the DEWA for studying the effects of the hemlock woolly adelgid. Fourteen pairs of hemlock and hardwood stands (28 stands total) within DEWA had been selected based on a detailed landscape analysis to maximize similarities of landscape setting between the pairs. Soil and surface water chemistry, forest condition, and invasive species have been documented, and ongoing research and monitoring at the plots was funded through the first 2 years of the CEMRI timeframe. The CEMRI used this paired plot network to establish the DEWA IMRA for forest carbon (C) and invasive pest research. The NPS also has a legal mandate to monitor water quality in streams draining through the DEWA and to take actions to ensure no net degradation of water quality. The park established “boundary control points,” where tributaries to the Delaware River cross the boundary between the DEWA and the private headwaters, as the monitoring points for this mandate. A program of periodic stream discharge and water quality measurement was established through joint USGS-NPS funding during the CEMRI. This program was enhanced by the CEMRI to provide process-level data for the forest fragmentation issue.

### **3.1.3 The French Creek Watershed, Pennsylvania**

French Creek is a tributary of the Delaware River that drains a rapidly suburbanizing watershed west of Philadelphia. Although intensive site research on the effects of forest fragmentation on ecosystem health was not well established within the Delaware Basin before the CEMRI, surface water quality monitoring in rivers such as French Creek, draining landscapes representing a range of disturbances, had been established in several locations by the USGS National Water Quality Assessment (NAWQA) program and other long-term monitoring programs (see Tier 2 foundation programs). The pre-development landscape of French Creek was approximately 40 percent agricultural and 60 percent forest, and the rapid suburbanization made it an excellent field laboratory for assessing the effects of forest fragmentation on river water quality. A USGS stream gauging station on French Creek near its junction with the Schuylkill River in Phoenixville, Pennsylvania, has been monitored for discharge and water quality since 1996 as part of the NAWQA program. Changes in land use since the 1940s were documented by a separate USGS project before and during the CEMRI for the French Creek Watershed ([http://mcmcweb.er.usgs.gov/de\\_river\\_basin](http://mcmcweb.er.usgs.gov/de_river_basin)). The Hopewell Furnace National Historic Site, owned by the NPS, is also located within the French Creek IMRA, ensuring that some protected long-term forest research plots would be available in the French Creek Watershed for the CEMRI network.

### **3.1.4 The USGS National Water Quality Assessment Program (NAWQA)**

The NAWQA program was designed to assess the status and trends in the Nation’s ground water and surface water quality and to determine the human-induced causes of water quality degradation (Gilliom et al. 1995). The basic NAWQA monitoring program included a network of deterministically selected integrator stations on large rivers with multiuse watersheds, indicator stations on medium-scale rivers with watersheds dominated by a single use, and multiple survey-sampling sites that represent a gradient of exposure to a specific land use (Fig. 3.2). The NAWQA monitoring program includes several water quality parameters, including major ions, nutrients, pesticides, and metals; ecological parameters including fish, invertebrate, and algae; and habitat condition. The type of measurements made varies depending on the site type, but the NAWQA program provides an overall baseline dataset for tracking biological and biogeochemical indicators in aquatic environments of the DRB.

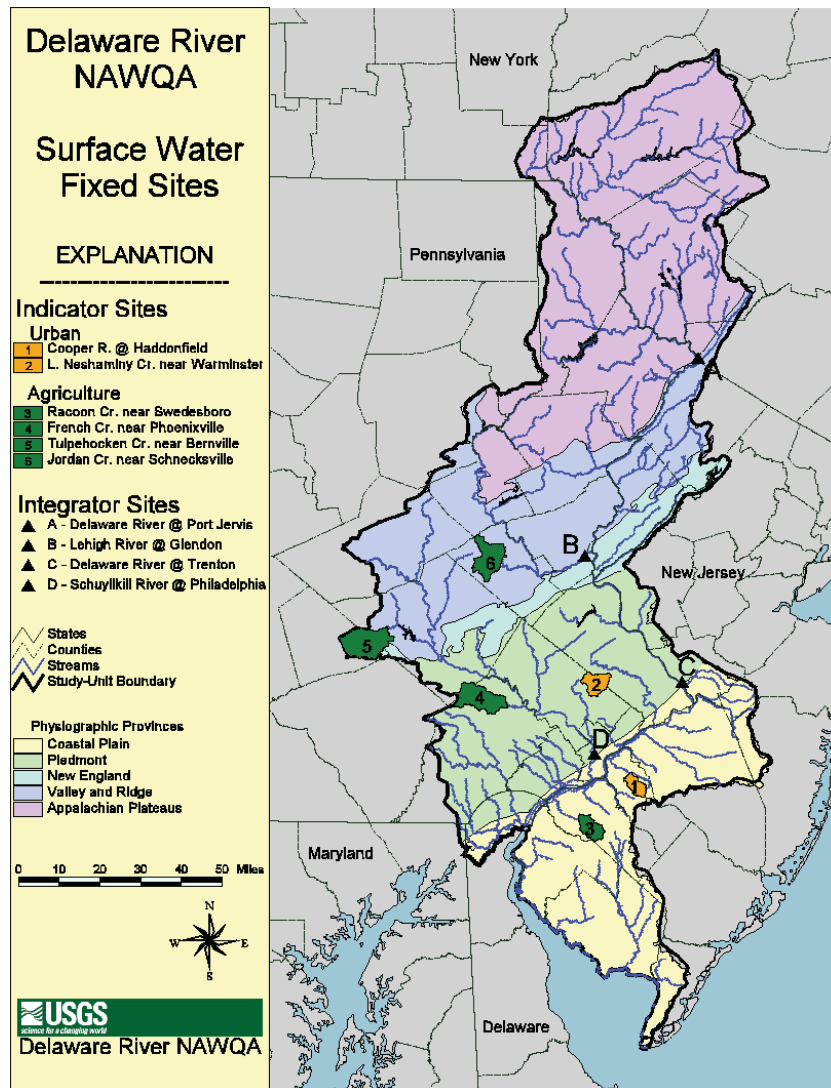


Figure 3.2.—National Water Quality Assessment program stations in the Delaware River Basin. (From Fischer et al. 2004)

Originally 60 mesoscale rivers were selected as the integrating unit for the program, and a 7-year rotational cycle was used to assess 20 of those rivers at a time (Gilliom et al. 1995). Discharge and water quality monitoring stations have been operated since 1996 or longer in support of NAWQA on the main-stem Delaware River at Trenton, New Jersey, and on several tributary rivers draining watersheds representing a range of agricultural and suburban landscapes. The USGS has been tracking discharge since 1912 and water quality since the mid-1960s at the Trenton station (Fischer et al. 2004). Detailed measurement of chemical and sediment exports at the Trenton gauge allows the estimation of chemical exports in surface water for most of the DRB, and thus creates a frame of reference for balancing estimates of C and N flux from the watershed. The Delaware River at Trenton was therefore selected as the largest integrating unit for determining the CEMRI regional C budget.

### 3.1.5 The National Park Service Vital Signs Monitoring Program

At the time of the CEMRI, the NPS Vital Signs program was being designed to track sentinel species and environmental parameters for early detection of environmental degradation. Monitoring sites for this program included park lands in two of the three

IMRAs selected for intensive study (Hopewell Furnace in the French Creek headwaters and DEWA) in the CEMRI assessment. The CEMRI was therefore designed with the needs of this foundation program in mind. Vital Signs monitoring will focus on biological indicators, including herbaceous vegetation and fauna sensitive to environmental change (Marshall and Piekielek 2007).

### **3.2 Tier 2: Gradient Study Sites**

Gradient study sites are points of data collection representing a range of conditions for a specific issue. The intensity and ecological comprehensiveness of the sampling protocol depend upon the issue being addressed and the temporal variability of the parameters being measured. Foundation programs were sought for the Delaware CEMRI that either provided regional gradient datasets from previous studies that could be used to support the CEMRI assessments, or that established networks of sites within the DRB that CEMRI investigators could visit, thus avoiding site installation costs and capturing ancillary data useful to the investigations. These programs are described briefly below.

#### **3.2.1 USGS NAWQA Program Synoptic Stations**

As part of the Delaware NAWQA program, the USGS established fixed-site data collection stations on 43 streams representing a range of development in the surrounding watersheds. Water quality and channel condition data were collected at these “synoptic” stations both before and during the CEMRI through NAWQA funding and thus provided a cost-effective base for developing landscape disturbance data that could be correlated with the available river disturbance data from the NAWQA program. The cyclic nature of the NAWQA program also made it likely that these sites would be measured periodically (Fischer et al. 2004).

#### **3.2.2 US Forest Service Hyperspectral Methods Development Project**

The USFS Research Laboratory in Durham, New Hampshire, has been studying the use of hyperspectral imagery for determining forest condition and foliar chemistry in the White Mountains of New Hampshire and the northern DRB in New York. As part of that study, samples were collected from soil and foliage at plots representing a range of soil nutrient status. These data, collected before the CEMRI, were used to assess the relationship between foliar Ca and available soil Ca without the expense of a gradient-based sampling program (R. Hallet, U.S. Forest Service, oral communication, 2002).

#### **3.2.3 DEWA Hemlock Decline Plots**

The forest research plots established by the NPS at DEWA also represented a gradient of infestation and dieback from hemlock woolly adelgid. These plots were used by CEMRI investigators to correlate soil and runoff chemistry to hemlock decline and assess the potential environmental parameters that either encourage or slow adelgid infestation (R. Evans, National Park Service, oral communication, 1999).

#### **3.2.4 Forest Fragmentation and Suburban Development Study**

Rapid suburbanization just outside the borders of the DEWA is a concern to NPS managers because of the potential effects of suburban development on the water entering and exiting the park. To quantify the relationships between forest fragmentation and water quality, three watersheds representing a gradient of residential development were established for study (see chapter on forest fragmentation).

### **3.3 Tier 3: Regional Surveys**

Several established regional survey programs were available in the Delaware Basin as foundation programs for Tier 3 monitoring in forested landscapes. Each survey network is briefly described here.

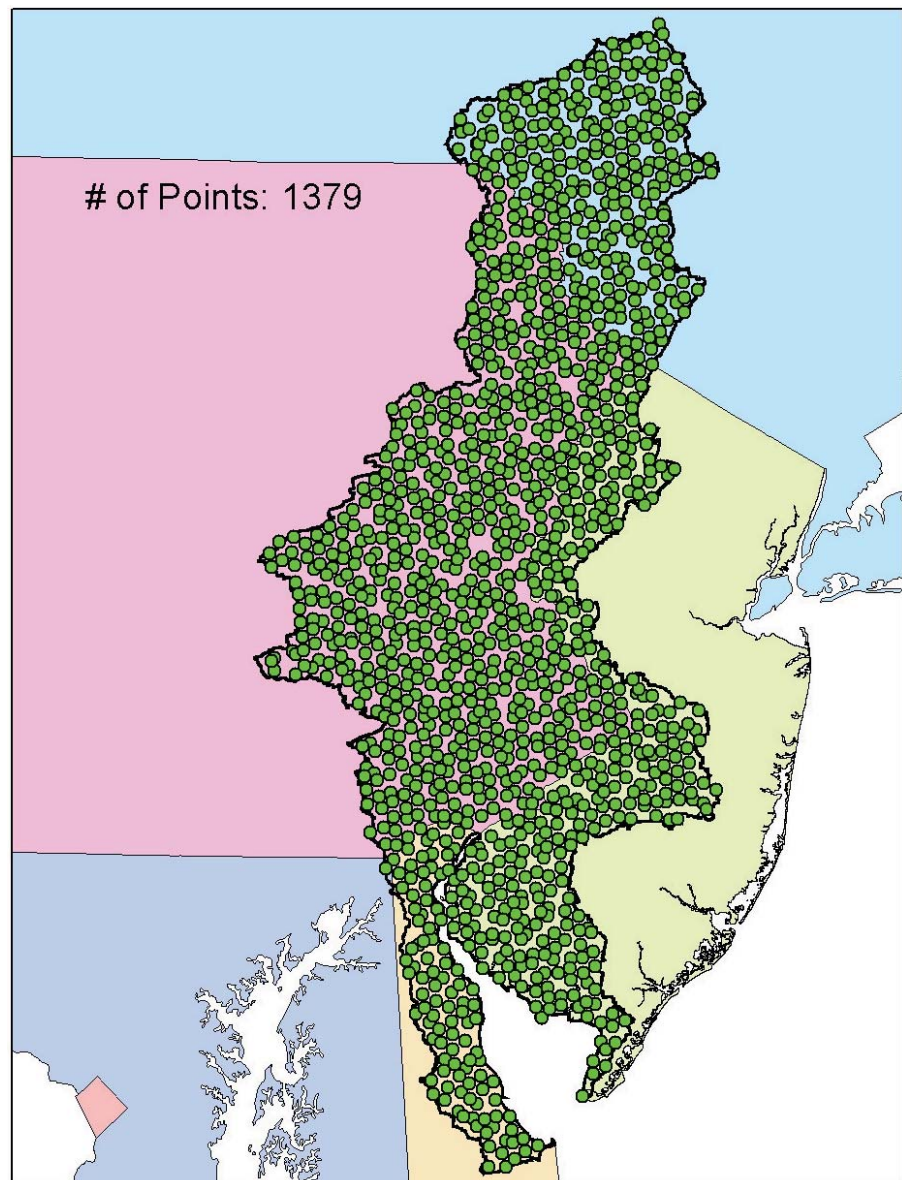


Figure 3.3.—Forest Inventory and Analysis plots in the Delaware River Basin drainage area, as of 2001.

### 3.3.1 Forest Inventory and Analysis (FIA)

FIA provides periodic assessments of the amount, status, and character of the forest resources of the Nation. Since World War II, U.S. forest inventories have used multiphase sampling designs involving remote sensing and ground measurements (Birdsey and Schreuder 1992, Schreuder et al. 1995). Historically, the phase 1 sample consisted of interpretation of high-altitude color infrared photography or other aerial photography, widely available and highly accurate for estimating changes in forest area and locating field sample plots. In recent years the phase 1 area estimate has been made from satellite imagery, typically the Landsat Thematic Mapper. The phase 2 sample consists of more than 150,000 permanent field sample locations that are remeasured periodically (typically once every 5 to 7 years) to provide statistics on disturbance (e.g., harvest, mortality), growth, species composition change, and a host of observed and calculated site descriptors such as ownership and forest type. These measurements are then expanded to the population level using the statistics from the phase 1 sample. Currently there are 1,379 phase 2 sample plots in the DRB (Fig. 3.3).

A third sample phase (formerly known as Forest Health Monitoring) is the basis for more intensive ecosystem measurements. Data on soils, coarse woody debris, understory vegetation, and other ecological variables are collected on these plots, which are linked statistically to the phase 1 and 2 samples. Phase 3 consists of approximately 5,000 sample plots nationally and about 50 sample plots in the DRB. At the intensive research sites in the DRB, and at selected locations in the Allegheny Plateau, about 50 supplemental phase 3 plots were established to increase the sample size. Additional measurements were taken at these plots to provide more complete ecosystem productivity and carbon estimates (described in a later chapter).

### **3.3.2 Forest Health Protection (FHP)**

Disturbance from pests and disease is tracked on a network of State-monitored plots to provide data on the regional extent of pest infestation. Site selection for this network is based on presence/absence of pests. Measurements include pest presence/absence, infestation, and forest condition. ([www.fs.fed.us/foresthealth](http://www.fs.fed.us/foresthealth))

### **3.3.3 USFS Northern Global Change Research Program (NGCP)**

The NGCP is a USFS research program dedicated to understanding, predicting, and mitigating the effects of air pollution and climate change on northern forest ecosystems. This program has national responsibility for estimating how much carbon dioxide (CO<sub>2</sub>) is taken up and released by U.S. forests, evaluating how this uptake may change in the future as a consequence of forest management and natural disturbances, and evaluating policy options for increasing the role of forests as C sinks (R. Birdsey, U.S. Forest Service, oral communication, 2004).

### **3.3.4 Environmental Monitoring and Assessment Program**

The U.S. Environmental Protection Agency (EPA) Environmental Monitoring and Assessment Program (EMAP) established a network of survey sites in the DRB during the early 1990s where aquatic ecology, stream geomorphology, and water quality were measured. The sites were probabilistically selected but too few in number to provide reliable statistics on stream condition in the DRB. The EMAP survey design team gave the CEMRI a probability-based survey design that provided statistics on aquatic resource conditions in three subregions of the upper DRB, as well as a separate survey for the whole river basin. A probability-based survey of first-order streams was also designed for correlation on a sub-regional scale with data collected on forest condition at the FIA forest plots. The EMAP-style probability-based survey served as a foundation water quality monitoring program for CEMRI (Olsen et al. 1999).

## **3.4 Tier 4: Remote Sensing and Mapping**

Programs for collecting remote sensing and mappable fixed-site monitoring data are generally tracking environmental conditions at a scale that is broader than, but inclusive of, the DRB. The resulting coverages are therefore useful as foundation datasets for the CEMRI investigators. The programs used in the CEMRI are briefly described here.

### **3.4.1 The National Atmospheric Deposition Program/ National Trends Network (NADP/NTN)**

The NADP network of deposition monitoring stations provides data on weekly precipitation volume and chemistry at 150 stations throughout the U.S. Several stations within and immediately outside of the DRB make up a baseline monitoring network for deposition, and the nature of deposition chemistry allows data from these sites to be modeled for mapping regional deposition patterns. No additional deposition collection stations were established by the CEMRI. (<http://nadp.sws.uiuc.edu>)

### **3.4.2 USGS Urban Dynamics Program**

The study of current and historical land use change in the greater Philadelphia region conducted by the USGS Urban Dynamics program is being used to create regional maps of land use change through correlation with Landsat imagery. In the CEMRI, these scientists

developed spatially explicit maps of land use history to provide information for the modeling, forest fragmentation, and C cycling estimation efforts. (<http://landcover.usgs.gov/urban/intro.php>)

#### **3.4.3 National Aeronautics and Space Administration (NASA)**

NASA provided funding for the DRB CEMRI through a competitive grant entitled “Large-scale validation of carbon stock and flux estimates from remote sensing.” This grant facilitated the regional interpretation of Landsat Thematic Mapper imagery for estimating forest area and, when imagery representing different periods of time is analyzed, for detecting forest change. MODIS imagery was also interpreted through this grant for estimating annual forest productivity.

#### **3.4.4 USFS Special Monitoring Studies**

The USFS sponsors aerial photo flights and interpretation at locations of interest throughout the United States. Aerial photos of the DRB acquired in 2000 were used by the CEMRI to assess recent changes in forest fragmentation in the watersheds of French Creek, the Delaware Water Gap tributary watersheds, and the NAWQA synoptic watersheds. This aerial photography interpretation capability is a foundation for national collaborative monitoring strategies.

#### **3.4.5 Hyperspectral Imagery**

Interpretation of hyperspectral imagery by the USFS research program and associated contract laboratories represents a new and growing foundation capability that was available to the CEMRI in the DRB. Correlations between forest soil, foliar Ca, and the spectra of forest imagery enabled researchers to develop methods for mapping forest health in broad regions through remote technology. These capabilities were applied in the Neversink Tier 1 site within the DRB during the CEMRI. (R. Hallett, U.S. Forest Service, oral communication, 2002).

### **3.5 Enhancement of the Foundation Programs**

These foundation programs were improved to fill gaps in existing survey data collection capability relative to the assessment issues selected for the CEMRI. Each of the CEMRI IMRAs was selected for intensive study because it contained not only existing monitoring infrastructure or programs, but also features that allowed the partners to address the selected assessment questions. Two of the IMRAs selected for the pilot project—the Neversink River Basin and the DEWA—lie within the Appalachian Plateau Province. The third IMRA—the French Creek Watershed—is located in the mid-basin Piedmont Province. The Neversink Basin is 95 percent forested, with little development pressure, but soils and surface waters have been acidified and depleted of Ca by acid rain. The DEWA and French Creek watersheds are mostly forested but are under intense pressure from summer home development and suburban sprawl, respectively. The three IMRAs span the range of climatic conditions in the Delaware Basin, and forest types in the three areas range from northern hardwoods and spruce-fir in the northern Neversink Watershed to tulip poplar and oak-hickory in the French Creek Watershed. Collaborative research and monitoring for CEMRI began in the Neversink and DEWA IMRAs during the summer of 2000 and in the French Creek Watershed in the summer of 2002.

The foundation gradient- and probability-based surveys were supplemented by the CEMRI to address regional soil and surface water C stocks and fluxes, and supplemental aerial photointerpretation was added to the Tier 4 foundation programs to enable the assessment of forest fragmentation effects, and enhance the land cover data available for comparison to aquatic data provided by the NAWQA program. The integration of these new and foundation data collection activities is described in this report for each issue of the Delaware CEMRI.

## 4.0 MEASURING AND MONITORING FOREST CARBON STOCKS AND FLUXES

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*Jennifer C. Jenkins, Peter S. Murdoch, Richard A. Birdsey, and John L. Hom*

Measuring and monitoring forest productivity and carbon (C) is of growing concern for natural resource managers and policymakers. With the Delaware River Basin (DRB) as a pilot region, this subproject of the CEMRI sought to:

- Improve the ability of the ground-based Forest Inventory and Analysis (FIA) networks to more completely assess forest C stocks and fluxes
- Integrate estimates of forest biomass and net primary production (NPP) from available remote sensing products with FIA data
- Characterize the effects of land use change and forest fragmentation on cumulative C stocks and fluxes
- Integrate disparate monitoring networks to develop complete site-level and Basin-level C budgets including C loss by water transport

### 4.1 Background

Human activities, primarily burning fossil fuels and changing land use and land cover, are increasing atmospheric concentrations of greenhouse gases, which alter the radiative balances in Earth's atmosphere. Global mean temperatures increased by 0.6 °C in the 20th century, and climate models predict a further increase as large as 5.8 °C by 2100 (Intergovernmental Panel on Climate Change 2001), suggesting the potential for substantial changes in food and fiber production, hydrologic regimes, coastal resources, and other natural resource sectors.

Carbon dioxide (CO<sub>2</sub>) is an important greenhouse gas produced as a byproduct of fossil fuel burning, but it is also taken up and released during growth and metabolism by photosynthetic organisms. Because forests are thought to store close to 90 percent of Earth's terrestrial vegetation biomass (Dixon et al. 1994), they are important controllers of atmospheric CO<sub>2</sub> concentrations and are thus critical components in the global C cycle. Current interest in forest C cycling rates is especially intense because of some uncertainty in the magnitudes of terrestrial sources and sinks, as well as continued uncertainty about the lasting effects of land use change and forest disturbance on forest C cycling rates. Furthermore, international agreements such as the Kyoto Protocol, intended to curb greenhouse gas emissions and slow the pace of climate change, require accurate inventories of forest C stocks and fluxes.

In addition to driving the atmospheric C balance, the rate of forest growth may help determine the quality and quantity of water reaching streams. For example, photosynthetic rates are directly proportional to water use by plants, and thus the rate of tree growth may help determine streamwater quantity. Dissolved organic carbon (DOC) is also an important source of nutrients for soil microbes.

At larger scales, C export from the land to surface waters may also be a significant component of the regional C budget. Global estimates suggest that C fluxes from erosion and weathering may transport up to 0.8 Gt C yr<sup>-1</sup> (Carbon and Climate Working Group 1999) from streams

and rivers. Carbon burial in lakes, reservoirs, and peatlands may exceed four times the burial rate in oceans (Dean and Gorham 1998, U.S. Geological Survey 1999).

In terms of human health, DOC in streamwater may compromise water quality for human consumption. Increased export of C from forested landscapes will increase the pool of C available for developing tri-halomethanes in drinking water supplies. Tri-halomethanes are a chlorination byproduct that may pose a human cancer risk. This is a particular concern in the DRB, which supplies drinking water to New York City and northern New Jersey.

## **4.2 Measurement of Forest and Aquatic Carbon Stocks and Fluxes**

Vegetation contains roughly 50 percent C; live trees are thus important C reservoirs in forests. However, significant amounts of C may be stored in harvested wood products, in dead trees, or belowground in roots and soils. In addition, C is released back to the atmosphere as a byproduct of metabolism, and as organic matter decays, the decay rates of different types of organic matter must be taken into account for a complete C budget for forested land. The C cycle is further complicated by changes in land use, which release C to the atmosphere from deforestation or store additional C as vegetation regrows on land that reverts back to forest.

Two kinds of measurements are required to estimate C cycling rates in forests. First, estimates of the total amount of C stored in a forest ecosystem (C stocks) are important because total C stocks represent the amount of C available for harvest or decomposition. Comparisons between C stocks in different forest types, or in similar forests on different site types, and analysis of trends in total C stocks with forest age can also help determine what the total C storage capacity might be for a forested landscape. In addition, it is important to understand the rate of change in different forest compartments (C fluxes) because the sum of these movements of C into and out of the terrestrial system represents net C exchange between forests and the atmosphere.

To accurately quantify forest C stocks at the plot level, detailed information must be collected on: tree dimensions for all trees, soil C pools (including roots), and dead organic matter (including standing and downed dead trees and stumps). The information on tree dimensions can be translated to C terms using conversion factors based on tree allometry. Although collecting the required information to assess aboveground C stocks is fairly straightforward, quantifying C stocks belowground in soil and roots is much more difficult and time consuming.

Quantifying C fluxes accurately is even more difficult because: a) net annual C changes are made up of a series of fluxes controlled by a wide variety of factors; and b) year-to-year C fluxes are difficult to detect because they are often much smaller in magnitude than total C stocks. To quantify annual C fluxes in a forested system, we must collect information on changes in tree dimensions, changes in soil C stocks, total fine and coarse root production, and production of dead material from tree damage or mortality (both large and small material, such as stumps, branches, and twigs as well as leaves and needles). In addition, we must collect information on C lost from the soil as CO<sub>2</sub> via metabolism of soil organisms. Finally, land use change and harvesting for timber products may translocate C to other pools. Each of these fluxes may be controlled by a different factor, such as climate, nutrient

availability, and disturbance regime—as a result, net annual C sequestration rates can vary dramatically in space and time.

In research studies, ecologists typically gather information on a subset of fluxes at a series of experimental plots within a larger forest landscape. One common measure of forest productivity is NPP, an important aspect of the role of vegetation in the global C cycle. NPP is defined as the net rate of C accumulated by vegetation per unit area per year—or, in other words, the difference between the total C fixed from the atmosphere and the portion of that C used by plants in metabolism. Net ecosystem production (NEP) is the difference between NPP and the C used by animals in metabolism—NEP is thus the net rate of C sequestration by a forest system. If we assume our study plots have characteristics representative of the surrounding area, we can then translate plot-level information to the landscape level (for example, if there is a total of 100 Mg C in all forest compartments on a 1-ha plot, we can say there is likely to be 1,000 Mg C in the surrounding 10-ha forest). Finally, we note that net ecosystem C balance is the net result of NEP and any other C losses. This is important because lateral transfers of C between forest stands within a landscape are not captured by physiological measurements such as NEP and NPP. For example, if DOC is leached in ground water from forest soil, it will be lost from the biomass pool and will eventually emerge in streamwater where it can be measured.

As applied in standard research settings, this approach has limitations. First, it is usually impractical, if not impossible, to measure all the relevant fluxes in a standard research study. For example, measuring the C lost from soil typically requires complicated and expensive equipment not easily available to all researchers. Measuring root production is also quite time consuming and expensive. Second, many of the fluxes may vary substantially from site to site (and even from point to point within one site), making it difficult to adequately capture the status and trends in the C resource with scattered site-level studies. Finally, the plots chosen by researchers for detailed study are few in number and represent only selected characteristics of the surrounding forest. When C fluxes from a plot are scaled up to a landscape, this bias usually results in overestimates of C cycling rates because ecologists tend to choose plots covered more densely with forest than the surrounding areas, which tend to have a history of frequent disturbance.

Three types of measurements are commonly used to assess C fluxes in aquatic systems: water quantity, sediment load, and C concentrations in water and in sediment. Together, these measurements provide an integrated picture of the total C transported out of a watershed in streamwater. A fourth measurement, gas flux from the river's surface, is important for C budgets of large, slow-moving rivers, but was not included for the Delaware CEMRI.

Water quantity in rivers of the Northeastern U.S. varies significantly between seasons and is controlled by several factors, including plant photosynthesis, precipitation, bedrock and surficial geology, and soil porosity. The most common way to measure water quantity is by installing a gauge at a point along a river where changes in stream depth are gradual and directly proportional to stream volume. This type of measurement requires expensive installations and labor-intensive calibration and is thus practical only for a finite number of the existing river reaches in the United States. The Delaware River has several stream gauges

established, including the main-stem river at the head-of-tide upstream of the Delaware Bay at Trenton, New Jersey, and on numerous small and large tributaries throughout the watershed.

Carbon concentrations can also vary dramatically in surface waters and are dependent on factors such as water quantity, in-stream nutrient processing, watershed sediment yield, and temperature. As with water quantity, continuous monitoring is the most accurate method for assessing streamwater concentrations. Again, this type of intensive measurement is not practical except under very limited circumstances.

### **4.3 Existing Monitoring Programs and Regional Assessment Capability**

The USFS FIA program provides a comprehensive sample of forests in the United States and is the accepted basis for national statistics about C sequestration in forests (Birdsey 1992, Birdsey et al. 1993, Birdsey and Heath 1995). However, the program measures only a subset of the relevant stocks and fluxes; the remainder must be estimated from measurements made during more detailed plot sampling.

To estimate C storage, the forest ecosystem is partitioned into separate components. One possible way to define these is live trees, dead trees, coarse woody debris, forest floor, soil, and understory vegetation. These definitions of ecosystem components are broad enough to include all sources of organic C in the forest ecosystem. As defined here the tree portion includes all aboveground and belowground portions of all live and dead trees and saplings greater than 1 inch d.b.h., including the merchantable stem, limbs, tops, cull sections, stump, foliage, bark and root bark, and coarse tree roots (greater than 2 mm). The soil component includes organic C in mineral horizons to a depth of 20 cm, excluding coarse tree roots. The forest floor includes all dead organic matter above the mineral soil horizons except standing dead trees and coarse woody debris. Understory vegetation includes live vegetation other than live trees.

Using data from forest inventories and intensive-site ecosystem studies, estimates of average C storage by age or volume classes of forest stands (analogous to a forest yield table) are made for each ecosystem component for forest classes defined by region, forest type, productivity class, and land use history. Equations are derived to estimate C storage in the forest floor, soil, and understory vegetation for each forest class (Table 4.1). Additional details about estimating C storage for different regions, forest types, site productivity class, and past land use are provided in Smith et al. 2006.

The USGS National Water Quality Assessment program (NAWQA) collects data on streamwater DOC concentrations in several locations within the DRB (Fig. 3.2). However, these measurements are mostly limited to medium to large catchments; land use in these catchments varies so much that it is difficult to draw cause-and-effect relationships between terrestrial condition and aquatic DOC export. The USGS Basic Data program periodically collects total C and sediment data from the Delaware River at Trenton, New Jersey, and from the Neversink River at Claryville, New York.

**Table 4.1.—Average carbon uptake after reforestation, by region—includes all forest types and ecosystem carbon pools ( $\text{t ha}^{-1} \text{y}^{-1}$ )**

| Age   | Southeast | South Central | Northeast | North Central | Rocky Mountain | Pacific Coast |
|-------|-----------|---------------|-----------|---------------|----------------|---------------|
| 0-5   | -1.9      | -3.4          | -0.2      | -0.2          | 1.3            | 0.5           |
| 6-10  | -1.8      | -2.0          | 0.7       | 0.5           | 0.4            | 1.0           |
| 11-15 | 2.2       | 2.4           | 0.9       | 0.7           | 0.2            | 1.0           |
| 16-20 | 3.4       | 4.6           | 1.4       | 1.3           | 0.6            | 1.9           |
| 21-25 | 4.0       | 5.0           | 1.3       | 1.4           | 0.6            | 2.0           |
| 26-30 | 3.4       | 4.2           | 1.6       | 1.6           | 0.8            | 3.4           |
| 31-35 | 2.8       | 3.2           | 1.5       | 1.8           | 1.0            | 3.4           |
| 36-40 | 2.8       | 2.8           | 1.7       | 1.8           | 1.6            | 4.0           |
| 41-45 | 2.1       | 2.7           | 1.6       | 1.8           | 1.5            | 3.9           |
| 46-50 | 2.2       | 2.5           | 1.6       | 2.0           | 2.0            | 3.7           |

#### 4.4 Gaps in Evaluation of Forest and Aquatic Carbon Stocks and Fluxes

Although FIA-based forest C estimates are accurate at regional scales, they do contain critical gaps in estimating C stocks and fluxes at smaller scales. Generalized relationships based on geographic region, forest type, and volume must be used to develop estimates of soil and forest-floor C, standing dead biomass, and coarse woody debris. These FIA-based forest C estimates also lack accurate spatially explicit accounting for land use change and other annual dynamics that reflect growth and disturbance.

Important steps have been taken toward addressing these concerns. Studies of dead organic matter dynamics have begun for specific areas, with an eye toward extending them nationwide (Fig. 4.1). Efforts to quantify with more certainty the relationships between tree diameter and tree biomass have yielded a set of national regression equations currently being implemented as part of the USFS national C budget effort (Jenkins et al. 2003). Coarse-

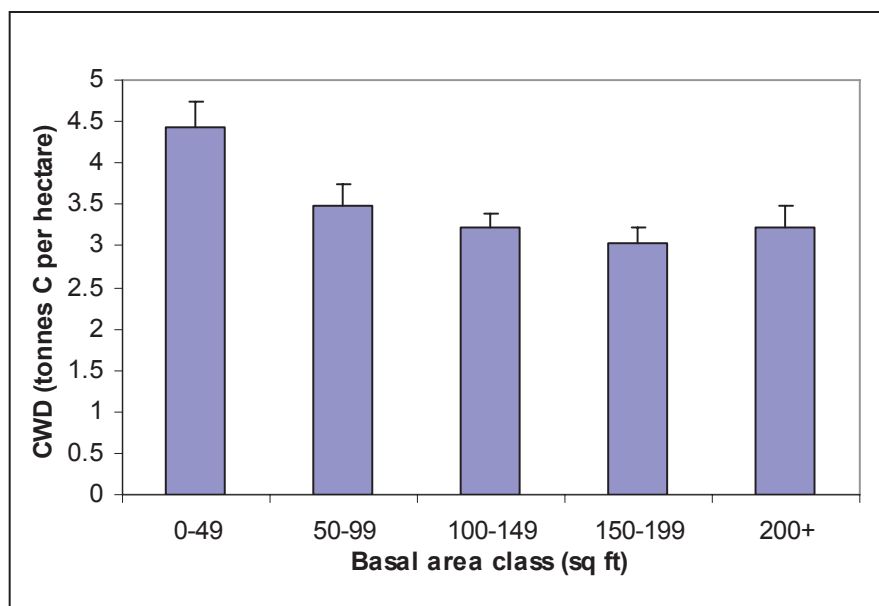


Figure 4.1.—Down coarse woody debris as a function of basal area class for Maine timberlands (Heath and Chojnacky 2000).

**Table 4.2.—Key variables and analyses for assessing carbon stocks and fluxes in the Delaware River Basin, by monitoring tier**

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|                                                                                             |
|---------------------------------------------------------------------------------------------|
| Tier 1: Intensive sites                                                                     |
| Foliar litterfall                                                                           |
| Root production                                                                             |
| Soil carbon dioxide flux                                                                    |
| Relationships between forest type, soil chemistry, and forest carbon stocks and fluxes      |
| Relationships between forest productivity and water quality and quantity                    |
| <br>                                                                                        |
| Tier 3: Regional surveys                                                                    |
| Forest inventory sample plots: biomass and other forest carbon stock variables              |
| Streamwater organic and inorganic carbon                                                    |
| <br>                                                                                        |
| Tier 4: Remote sensing                                                                      |
| Forest species distribution/type (from Landsat Thematic Mapper)                             |
| Land cover classification (from Landsat Thematic Mapper)                                    |
| Satellite-based net primary production estimates (from MODIS)                               |
| Fragmentation and historical land use change statistics (from color infrared aerial photos) |

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gridded estimates of forest biomass and forest NPP have also been developed based on the tree measurements made during the FIA sample (Jenkins et al. 2001) (Fig. 3.3). However, these estimates are limited by what is currently available in the FIA sample: they are based on broad, generalized relationships about quantities such as fine root and litter production, the resolution is still quite coarse, and they do not account for coarse woody debris dynamics, soil C efflux, or soil C stocks and fluxes.

Additional gaps are evident in monitoring the relationships between aquatic and terrestrial resources. Data on aquatic C concentrations in the DRB are limited, and the available data are collected at monitoring stations on medium to large rivers (Ward Hicks, 2000, written communication). Although these medium to large stream C concentrations are influenced by soil C flux from forested landscapes, the number of mostly forested watersheds that could be used to give a signal of the C leaching from forest soil to streams is inadequate for use in regional assessments.

In addition, information about terrestrial processes that control C flux on nonforest land is needed, as streamwater C concentrations in the region are influenced by agricultural and urban/suburban runoff from nonforest land. Forest growth and water quality and quantity are interconnected: a change in one results in changes in the others. However, the lack of data sharing and field collaboration among existing terrestrial and aquatic monitoring programs has limited our ability to track these relationships.

Finally, the science of DOC is still limited: very little is known about the sources, dynamics, and effects of DOC in terrestrial and aquatic systems on a regional scale. An integrated strategy for monitoring this potentially important compound can be achieved only by a multiresource monitoring effort. Our strategy for achieving this important goal is described below.

## **4.5 The CEMRI Integrated Monitoring Program for Carbon Cycling**

Integration of foundation and new data collection programs was tested at two scales—within the IMRAs and for the entire watershed above the stream gauge at Trenton, New Jersey. In each case, supplemental data collection was required at each tier of the monitoring framework to allow for linked terrestrial-aquatic C budgets to be developed (Table 4.2). The integrated data collection strategy is provided here for each monitoring tier.

### **4.5.1 Intensive Site Research (Tier 1)**

At intensive research and monitoring areas (IMRAs), we developed a system for integrating process-level information on C cycling rates with the regionally extensive forest monitoring network and the USGS surface water monitoring programs. At the three IMRAs, plots were established at a finer spatial resolution than in the Tier 3 monitoring programs. At these intensive sites terrestrial variables such as fine foliar litterfall, coarse woody debris stocks, foliar chemistry, and soil C and N stocks were measured. Relationships between these variables and the measurements typically made at FIA plots, such as forest type and basal area, were developed and applied to Tier 3 FIA plots in the region to generate regional estimates of C dynamics. Stream export of C from the watersheds containing these research plots was computed at selected USGS water quality and discharge monitoring stations. The watersheds represented by these stations are nested upstream of large river monitoring stations operated by the USGS NAWQA program, where C flux estimates were also developed.

At the Neversink IMRA site, detailed information about terrestrial C and nitrogen (N) stocks and fluxes was combined with data on deposition, surface water quality and quantity, and soil water quality and quantity collected by the USGS district research program to develop annual input/output budgets for C and N in the Neversink Watershed (Jenkins et al. 2005). Surface water samples were collected at both the nested USGS research and monitoring stations within the Neversink Watershed and the first-order streams that drain the hillslopes containing the FIA forest plots. This combination of the linked-terrestrial/aquatic surveys and the nested-watershed budget approaches tested two different strategies for linking USFS and USGS monitoring data.

Additional Tier 1 assessments of C stocks are associated with the research on forest fragmentation and land use change. This research takes place primarily within the Delaware Gap IMRA and incorporates the monitoring programs of the USGS, USFS, and NPS.

### **4.5.2 Regional Survey Monitoring (Tier 3)**

Information from existing Tier 3 monitoring programs was used to create a large-scale input-output budget of forest C from the full DRB. For this purpose, FIA data from plots falling inside the DRB were analyzed to develop estimates of forest NPP. These were combined with remotely sensed land cover change information and NAWQA data from the Delaware River at Trenton to provide a C input-output budget for the full DRB, integrating terrestrial and aquatic data from the wide variety of land cover types found within the basin.

Regional surveys of first-order streams within the IMRAs and in the Appalachian Plateau Province of the upper DRB were conducted by the USGS as an enhancement of the NAWQA sampling program. The surveys were designed to test linkages between aquatic and terrestrial monitoring for nutrient flux; sampling points were located on the nearest first-order stream to the FIA forest plots throughout the Appalachian Plateau and were thus a random sample associated with the FIA forest plot data. Surveys within the IMRAs were linked to the intensified FIA sampling network. The FIA program also added the collection

of three soil samples at three depths at each FIA plot within the DRB above the Trenton gauge, and these soils were analyzed for total C and N. These data supplement streamwater C concentration data from NAWQA survey stations selected to represent a range of landscape disturbance and development. Data from the IMRA studies were linked to the regional surveys through common sampling and analysis protocols and common parameters measured and through consistent protocols for selecting sampling locations both within and outside of the IMRAs. This information was used to develop the first integrated monitoring plan in the U.S. that can help us understand the relationships between forest productivity, soil C, and water quality and quantity.

#### **4.5.3 Remote Sensing and Mapping (Tier 4)**

Remotely sensed information was used to develop an updated land use classification map for the DRB, to assess past rates of land use change in selected urban and suburban portions of the basin, and to develop methods for assessing the contribution of forest fragmentation to forest C dynamics. In addition, the ground-based plot network provided validation data for satellite remote sensing instruments as well as parameterization and validation data for ecosystem process models. Remote sensing indicators for fragmentation and C sequestration were developed at the French Creek and Delaware Gap IMRAs, applied throughout the upper DRB, and tested through ground-truthing at selected FIA plots and associated small watersheds defined by the USGS stream monitoring stations. Validation areas included the stations sampled during the urban gradient survey of the NAWQA program, thus also linking terrestrial and aquatic monitoring within the NAWQA study basins.

#### **4.5.4 Modeling**

A modeling approach was used to develop spatially explicit estimates of forest productivity at the regional scale (Fig. 4.2). First, field data collected at Tiers 1 and 2 were stratified into forest types and used to parameterize the PnET-II model to predict forest NPP for each of the forest types (Aber and Federer 1992, Aber et al. 1996, Ollinger et al. 1998). A remotely sensed land cover classification was used to assign forest types to fine-resolution pixels, and the model was then run on a forest-type basis (using the parameterizations developed from the Tier 1 and Tier 3 information) for each individual pixel. In this way, we combined Tier 1, 3, and 4 information in our model parameterization strategy for large-scale C cycle estimation.

A model validation step was part of the CEMRI strategy in the DRB. Carbon cycling data (such as foliar litterfall and soil CO<sub>2</sub> flux) collected at IMRAs, as well as at a separate set of randomly chosen forest plots in the Allegheny Plateau, were compared against the PnET predictions developed using the parameterizations described above. As part of the NASA-funded C cycling initiative, we also used CEMRI field data to validate NPP predictions from NASA's new MODIS sensor, a high-spectral remote sensing instrument developed to provide real-time measured information about forest processes (Pan et al. 2006). For this part of the study we used a different variant of the PnET family of models, PnET-CN (Pan et al. 2004).

### **4.6 Preliminary Results**

We combined integrated measurement and monitoring of vegetation, soil, and water with process and empirical models to estimate C stocks and dynamics of the DRB. At the largest scale of the whole river basin, we used remote sensing (Tier 4) and data from existing sample plot networks maintained by the USFS and USDA Natural Resources Conservation Service (Tier 3). We used estimators from the FORCARB-2 carbon accounting model to estimate basinwide change in forest C stocks (Smith and Heath 2005). At the IMRA scale, we added land and water measurements to existing intensive monitoring sites maintained by the USGS

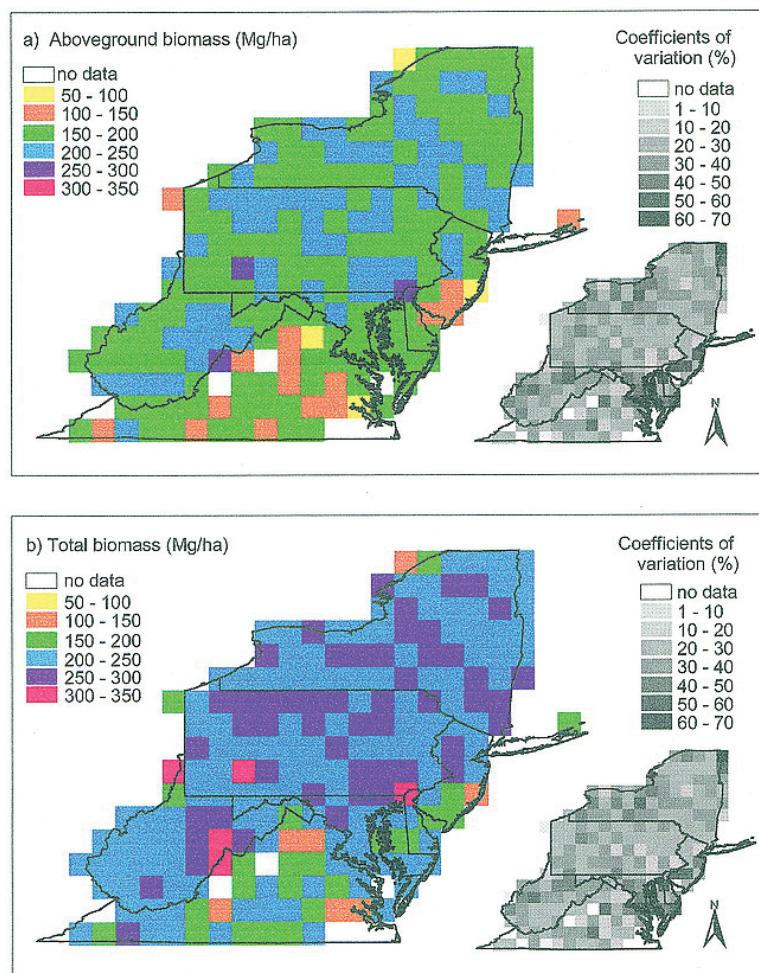


Figure 4.2.—Estimates of carbon cycling rates for the mid-Atlantic region (USA) at the 0.5 scale developed from Forest Inventory and Analysis data (coefficients of variation calculated from data for the plots falling within each 0.5 degree grid cell). A) Aboveground biomass. B) Total net primary productivity (aboveground plus belowground).

and the NPS and we estimated complete land and water C budgets. At an intermediate scale, we used remote sensing and intensive sampling of selected small watersheds that had contrasting conditions defined primarily by degree of residential development. At all scales, we used the PnET-CN ecosystem process model to estimate and map biomass and productivity, and the SPARROW empirical model to estimate C transport by water. Initial results show the basin is a small net C source, although within the basin, southern areas are losing C while northern areas are gaining C primarily because of historical patterns of land use change (Table 4.3). Initial estimates of transfer of C via streams show small quantities relative to uptake by trees.

**Table 4.3.—Total stock of carbon, and change in carbon stock by forest type, in teragrams, 2000**

| Forest type         | Total carbon | Change since 1990 |
|---------------------|--------------|-------------------|
| White/red/jack pine | 13.0         | -25.4             |
| Spruce-fir          | 1.8          | -0.3              |
| Loblolly pine       | 8.8          | -6.4              |
| Eastern redcedar    | 0.1          | 0.1               |
| Exotic softwoods    | 1.1          | 0.0               |
| Oak-pine            | 13.4         | -7.0              |
| Oak-hickory         | 165.6        | 8.4               |
| Oak-gum-cypress     | 5.2          | -1.2              |
| Elm-ash-cottonwood  | 17.3         | -3.2              |
| Maple-beech-birch   | 188.0        | 28.1              |
| Aspen-birch         | 4.1          | -0.2              |
| Nonstocked          | 1.0          | 1.0               |
| Total               | 419.4        | -6.0              |

## 5.0 MONITORING METHODS FOR FORESTS VULNERABLE TO NON-NATIVE INVASIVE PEST SPECIES

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Non-native invasive species pose a serious threat to forest resources, requiring programs to monitor their spatial spread and the damage they inflict on forest ecosystems. Invasive species research in the Delaware River Basin (DRB) had three primary objectives:

- To develop and evaluate monitoring protocols for selected pests and resulting ecosystem damage at the IMRAs that can be cost-effectively implemented as part of extensive monitoring programs
- To test a collaborative monitoring strategy for assembling pertinent information to track pest movement and mitigate the effects of pest infestation in the DRB
- To develop maps of forest condition in the DRB that depict areas most vulnerable to specific pests

### 5.1 Background

Invasion of the United States by non-native species of arthropods, plant and animal pathogens, and plants is a seemingly inevitable consequence of increasing international trade. Although invasions by non-native invasive species started with the European colonization of North America, they have increased at a high, linear rate since 1900 in concert with the boom of immigration and the burgeoning of international trade over the past century (Liebhold et al. 1995, Office of Technology Assessment 1993, Sailer 1983).

The risk of introduction of forest insects and pathogens has been exacerbated in recent years by the increasing intercontinental movement of wood in various forms. An obvious source of risk is the movement of forest products, major components of international trade that typically move from less developed to more developed nations. Less obvious is the extensive movement of shipping crates fabricated from raw wood. Such crates are a ready pathway for the introduction of wood-boring insects. Examples are the recent introductions of the pine shoot beetle and the Asian longhorned beetle, which arrived into the United States through shipping (Haack et al. 1997, Liebhold et al. 1995). Recent introductions of the Asian gypsy moth on both coasts of North America have been attributed to the insects hitchhiking on cargo (Liebhold et al. 1995).

Non-native tree-feeding insects are of great concern for forest ecosystems in the DRB. Many of the most destructive forest pests introduced into North America inhabit the region. Examples include Dutch elm disease, chestnut blight, gypsy moth, and most recently, hemlock woolly adelgid. Two major shipping ports, New York City and Philadelphia, near the DRB are a continuous source of potential new introductions.

Although most introduced insects and diseases do not become pests, the many foreign species that have become serious pests of forests in the Eastern United States show evidence that these forests are vulnerable to insects and pathogens from other continents. Their vulnerability may be high because native tree species have not evolved physiological resistance to exotic invaders and because forest habitats often do not harbor effective natural enemies of those invaders (DeBach 1974, Liebhold et al. 1995). In addition, ongoing global climate

change may contribute to the ability of non-native species to establish, spread, and harm host trees (Williams et al. 2000). The most extreme effect of non-native invasive species on forests is catastrophic tree death. Fortunately, such a dramatic effect is caused by only a few invaders, most notably pathogens such as chestnut blight and Dutch elm disease. However, invasive pests have profoundly affected forest ecosystems in the DRB and elsewhere on the east coast of the United States as they virtually exterminated populations of dominant tree species over wide areas.

A common form of damage inflicted by invasive insects, defoliation, does not usually result in the immediate death of a tree. However, repeated defoliation can kill a tree as its effects accumulate over several seasons. Defoliation exerts both direct and indirect effects on tree physiology that may alter forest ecosystem processes. Direct effects of heavy defoliation include drastically reduced photosynthesis and transpiration, which may limit tree growth, nutrient flow, and accumulation of reserves. Indirect effects result from the presence of the defoliating insects and can include the buildup of frass and dead insects, which may alter streamwater quality and the quality and availability of nutrients for tree growth and other ecosystem processes.

Over the long term, non-native invasive species that kill trees will change the species composition of forests and in doing so may alter other aspects of forest habitats. For example, exchanging overstory species in a riparian habitat through selective mortality induced by a non-native invasive species can alter water quality in the stream below. In the DRB, hemlock stands are known to help sustain cool stream temperatures, and this cooling determines the composition of stream communities of macroinvertebrates and fish (Evans et al. 1996). As these stands are killed by the hemlock woolly adelgid and replaced by stands of deciduous hardwoods, stream communities in the DRB are altered (Evans et al. 1996).

## **5.2 Non-native Pests of Current Concern**

Three insect species are of special concern in the DRB because they are currently or potentially very damaging to forests in the watershed. The gypsy moth was introduced into the United States well over 100 years ago and first appeared in the DRB around 1940, and the hemlock woolly adelgid was first noticed in the DRB in the 1970s. The Asian longhorned beetle is not known to be established in the basin, but it does attack forest types prevalent there and has entered North America through the port of New York City. These species are in widely different taxonomic groups, have diverse modes of feeding, do not overlap in the tree species they attack, and differ in the information available about their biology and ecology. Hence, they provide a case study of how forests vulnerable to historical, recent, and potential non-native pests can be identified and monitored.

### **5.2.1 Gypsy Moth**

The gypsy moth was accidentally introduced into North America near Boston in the late 1860s. Although it is not highly mobile and has only one generation per year, the gypsy moth spread steadily south and west in the United States and advanced through the DRB region in the 1950s and 1960s. The forests in the region are the types very susceptible to the gypsy moth (Fig. 5.1A), and it continues to threaten to forests in the region. The gypsy moth is an outbreak species and, once established in an area, it exhibits dramatic regionwide population explosions about every 10 years. Destructive outbreaks occurred in the early 1970s and early 1980s, and some areas have been defoliated five to nine times in the last

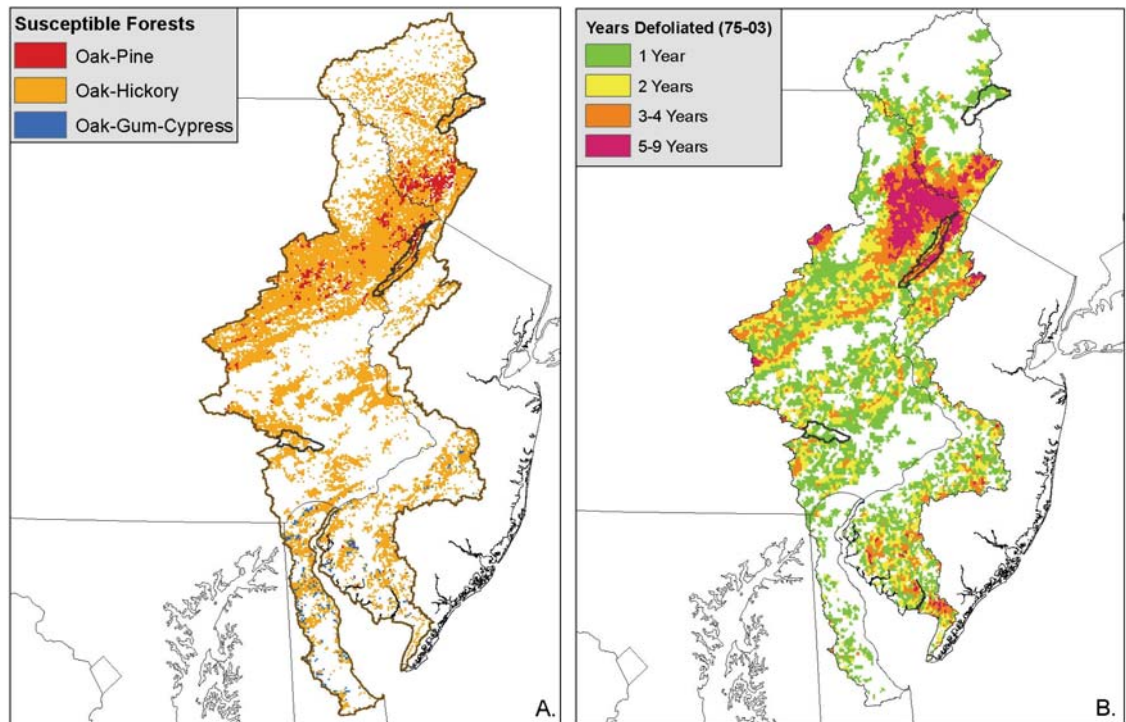


Figure 5.1. The gypsy moth and its host forests in the Delaware River Basin. A) Distribution of susceptible forest-type groups (Zhu and Evans 1994). B) Historical frequency of defoliation by gypsy moth over the years 1975 to 2003 (<http://www.fs.fed.us/ne/morgantown/4557/gmoth/atlas/#defoliation>).

28 years (Fig. 5.1 B). After 10 to 20 years of light and localized defoliation, populations are currently on the upswing in the DRB. During outbreaks, gypsy moth caterpillars defoliate trees extensively during their growth period from April through June (Leonard 1981). With repeated defoliation over the typical 3- to 4-year duration of an outbreak, many trees may be weakened and die (Davidson et al. 1999). The gypsy moth prefers to feed on oak species, but outbreak populations feed on many diverse species, including conifers (Houston 1974). Forests in the oak-hickory and oak-pine forest type groups are most vulnerable to gypsy moth, and they are prevalent throughout the Delaware River Watershed (Fig. 5.1A). Computer simulation studies have suggested that continued gypsy moth outbreaks will reduce the proportions of oak species significantly in eastern forests in the coming centuries (Byrne et al. 1987).

### 5.2.2 Hemlock Woolly Adelgid

The hemlock woolly adelgid was first found in the Eastern States, in Virginia, in 1951 (specimen record in Smithsonian Institution's National Collection) and likely came from Japan (McClure 1996). Like the gypsy moth, the hemlock woolly adelgid is not very mobile. However, because it has two generations per year and few natural enemies, it has spread rapidly and now occurs from North Carolina to Massachusetts (Souto and Shields 2000). It was found in the lower DRB in the 1970s and likely moved north, up the watershed, entering the Delaware Water Gap IMRA in the early 1990s; the adelgid was first found in the Neversink River Watershed in 2003 and may have moved westward to there from the Hudson River Valley (Fig. 5.2).

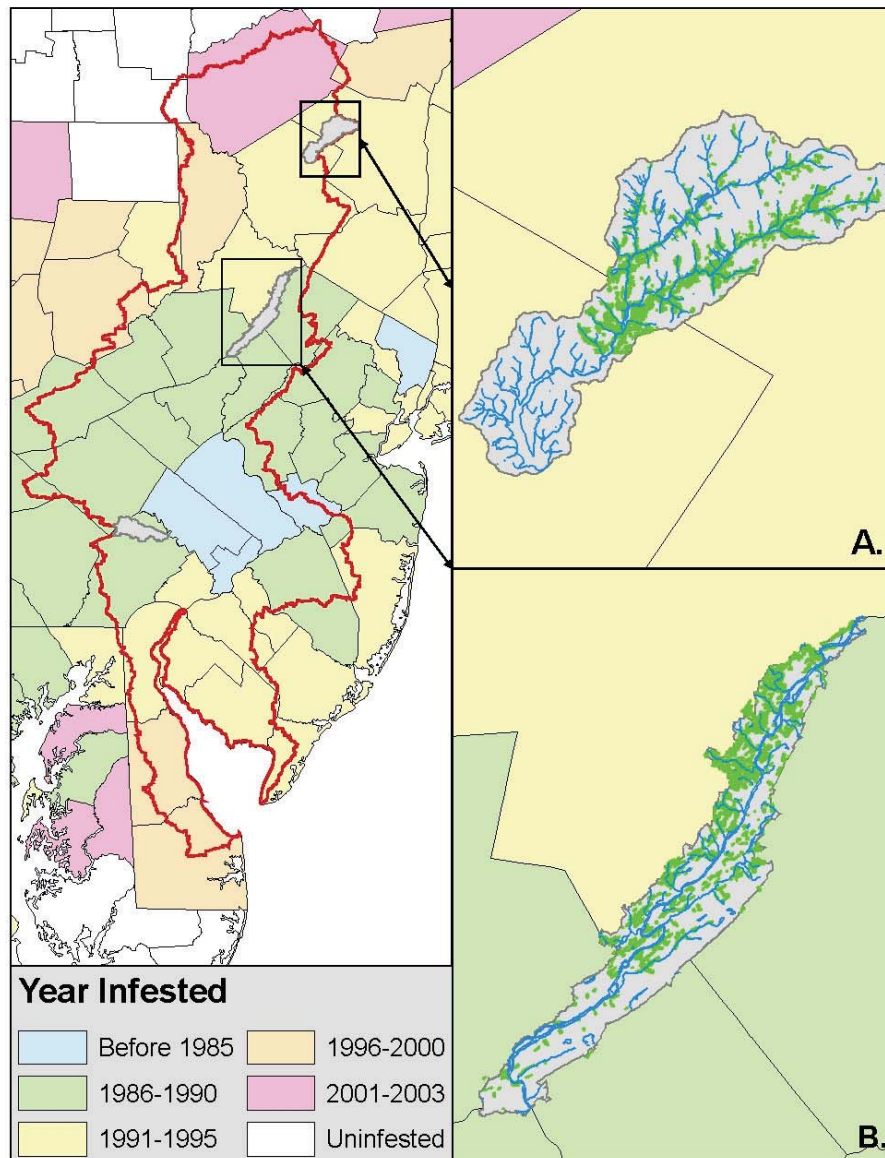


Figure 5.2.—History of hemlock woolly adelgid invasion of the Delaware River Basin ([http://www.na.fs.fed.us/fhp/hwa/distribution\\_maps.shtm](http://www.na.fs.fed.us/fhp/hwa/distribution_maps.shtm)). A) Hemlock stands in the Neversink IMRA. B) Hemlock stands in the Delaware Water Gap IMRA.

Because of the adelgid's small size and generally sessile nature, its infestation is much less obvious than the ravages of an outbreak defoliator. It is a piercing and sucking insect that feeds on storage cells within the needle tissue. Feeding presumably weakens a tree, and the outward sign of this stress is needle drop. As populations build, extensive needle loss can overcome an individual tree and kill it in as few as 4 years (McClure 1991). Noticeable tree damage resulting from hemlock woolly adelgid infestation takes several years, but once apparent, damage to trees is visible throughout the year.

The insect has the potential to dramatically reduce the prevalence of hemlock forests in the Eastern United States. The loss of hemlock cover in riparian areas will have serious consequences for wildlife habitats, stream communities, and recreational values in the region.

### 5.2.3 Asian Longhorned Beetle

The Asian longhorned beetle was introduced from China into the New York and Chicago metropolitan areas about 1990. Infested street trees were first discovered in 1996 and 1998 in the respective urban areas. Since the discovery, a program of rapid removal of infested trees, intensive monitoring, and rigorous quarantine has been imposed that appears to have contained known populations of the Asian longhorned beetle. The beetle could become a serious pest in the DRB should it be discovered in a new location or escape the quarantine around New York City. The Asian longhorned beetle has only one generation per year, but successive generations continue to reproduce on individual trees. Damage is caused by the feeding of larvae, which first bore tunnels under the bark and then deep into the tree heartwood. When fully developed, the adults emerge from the tree by boring 1-cm-diameter holes in branches, trunk, and exposed roots. After several successive generations of the beetle, trees are weakened and may die. The Asian longhorned beetle has a wide host range that includes maple, poplar, willow, birch, elm, ash, horse chestnut, and locust. The maple-beech-birch forest type is likely to contain the most preferred hosts of the Asian longhorned beetle (Fig. 5.3). Maple-beech-birch forests are prevalent throughout the DRB, particularly in the

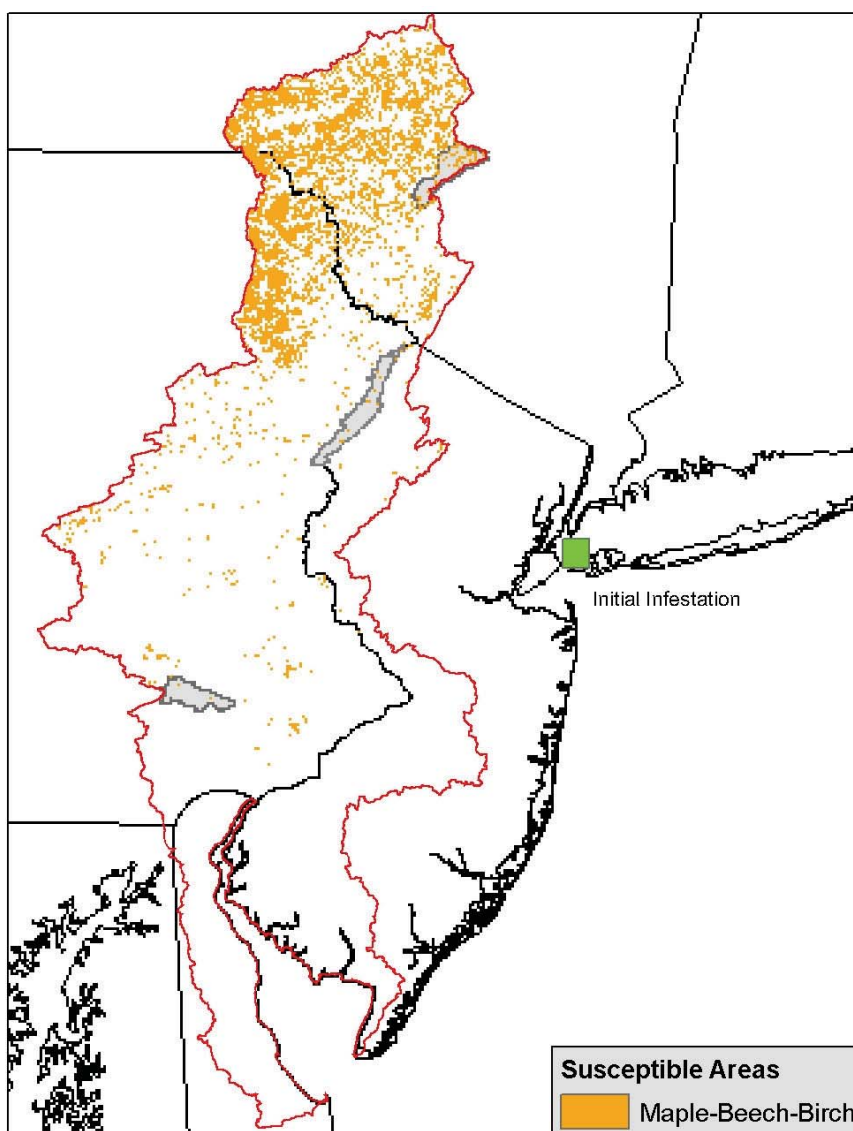


Figure 5.3.—Potential host forests of the Asian longhorned beetle in the Delaware River Basin (Zhu and Evans 1994).

### **5.3 Existing Monitoring Programs and Regional Assessment Capability**

Catskill Mountains that contain the northern basin boundary. Because sugar maple, with its colorful fall foliage and its sap production, is an important component of these forests both ecologically and economically, escape of the beetle from quarantine and associated sugar maple mortality could seriously jeopardize the maple syrup and tourist industries in local rural economies. The nearest quarantined area, in Brooklyn, is only 60 km from maple-beech-birch forests in the central DRB.

Existing gypsy moth programs are an example of current large-scale monitoring of the status and effects of non-native invasive species. These programs are usually conducted by State agencies on State and privately owned land. The U.S. Forest Service (USFS) conducts parallel programs for federally owned lands and provides advice and support to the States. Gypsy moth monitoring programs typically consist of defoliation monitoring using aerial sketch mapping of areas with visible defoliation (usually >30 percent canopy defoliation) in June and July. In the fall, ground surveys count egg masses to assess where populations of gypsy moth may be sufficiently high to cause defoliation the next year. The objective of such monitoring programs is to determine where to apply pesticides to prevent further defoliation during an outbreak. The relationship between defoliation and population size is often not verified for specific forest types or regions. Other aspects of pest damage or environmental impact are not usually monitored, and physiographic, chemical, or climatic conditions that might influence defoliation intensity are not documented.

Like the gypsy moth monitoring program, the program for the hemlock woolly adelgid is currently a cooperative one among State agencies and the USFS; however, it also includes the National Park Service (NPS) at the Delaware Water Gap NRA (DEWA). Several types of remotely sensed information have been investigated for developing tools to assess the degree of adelgid infestation and hemlock decline (Pontius 2004, Royle and Lathrop 2002). The State of Pennsylvania, the USFS, and the NPS monitor permanent plots to help document tree health decline in the host trees over time. Sampling at these permanent plots occurs in stages. First, the overall health of an infested tree is evaluated using the Forest Inventory and Analysis (FIA) crown rating system. Second, counts are made on marked branches to estimate numbers of terminals that are infested by the adelgid and those that produce new growth. Over time this monitoring program gives a quantitative estimate of the effects of the hemlock woolly adelgid on its host. As with gypsy moth monitoring programs, however, other aspects of pest damage and environmental impact are usually not monitored, and physiological, chemical, or climatic conditions that might influence damage intensity are not documented.

Because the Asian longhorned beetle was not known to be established in the DRB during CEMRI, all monitoring for this pest is carried out in the context of a quarantine program conducted by the USDA Animal and Plant Health Inspection Service. Monitoring involves visual searches of individual trees for adult beetles and evidence of oviposition sites and adult exit holes at ground level (using binoculars) and in the tree canopy (using bucket trucks).

In addition to these pest-specific studies, tree damage is recorded at FIA plots for all trees larger than 5 inches diameter at breast height (d.b.h.). These damage assessments, however, are typically limited to visual examination of bole defects, crown density, and foliar

discoloration; they are not linked to pest population densities or even to pest presence-absence surveys. As a result, existing forest monitoring programs can provide a snapshot of pest impact when the plot is sampled, but only if the crews can be certain about the source of the damage and only if damage to trees is visible.

Existing monitoring programs have several inadequacies. Aerial surveys for defoliators like the gypsy moth record only the presence or absence of damage and provide no estimates of the sizes of populations causing the defoliation. Also, monitoring may be inconsistent from year to year because the focus is on outbreak periods, and monitoring is often discontinued to save money between outbreaks. However, when accumulated and plotted over space and time, aerial surveys can provide a picture of the historical trend of an outbreak.

At the opposite extreme, the current monitoring program for the hemlock woolly adelgid provides information on the interaction of the pest and its host at the tree and small plot levels, but not on the spatial distribution of the pest on a large scale. Anecdotal information on presence or absence of the adelgid at the county level is the only spatial monitoring currently done by State and Federal agencies. Ironically, some of the most detailed spatial information about non-native invasive species may exist for quarantine pests such as the Asian longhorned beetle, which are intensively monitored over small areas in conjunction with eradication efforts.

Due in large part to the weak links between spatially extensive pest monitoring and plot-level studies of pest effects for most invasive pest species, our ability to analyze linkages between environmental conditions and pest outbreaks is limited.

#### **5.4 Information Available in the Delaware River Basin**

For the CEMRI, we developed tighter links between large-scale spatial information and plot-level process studies. Rather than acquire new data by establishing a complex set of plots that would be expensive to maintain, we used information from existing sources for the analysis. Digitized spatial information (GIS layers) on forest composition and physiographic features (including soil, climate, slope, elevation, streams, roads, etc.) was available for both the DRB and the surrounding region. Existing spatial information providing an initial estimate of the regional extent of the three non-native forest pests had been assembled into a uniform database.

The Pennsylvania Department of Conservation and Natural Resources has digitized sketch maps of gypsy moth defoliation that date back more than 30 years. New Jersey also has sketch maps for a similar time period, but most have not been digitized. For this study, we digitized more than 500 defoliation maps to obtain a history of New Jersey gypsy moth defoliation. Spatial records of gypsy moth defoliation in New York are not available.

A history of damage resulting from hemlock woolly adelgid infestation before the CEMRI was developed for the DRB using Landsat Thematic Mapper images (Bonneau et al. 1999, Royle and Lathrop 1997). Leaf-off, cloud-free, and snow-free images from 1984 (before adelgid infestation), 1998, and 2001 were used for this purpose. By comparing the later images with the 1984 image, we identified changes in hemlock foliage in 30-m pixels over the entire region. We verified these remotely sensed images with tree health data acquired

**Table 5.1.—Key variables and analyses for assessing invasive pest status, trends, and impacts in the Delaware River Basin, by monitoring tier**

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|                                                                                                                    |
|--------------------------------------------------------------------------------------------------------------------|
| Tier 1: Intensive sites                                                                                            |
| Relationship between pest distribution and pre-infestation forest condition (hemlock woolly adelgid- only)         |
| Relationship between pest distribution and soil condition (HWA only)                                               |
| Effect of pest infestation on soil water and surface water quality/ quantity (HWA only at Delaware Water Gap IMRA) |
| Relationship between pest distribution and climate measures (HWA only)                                             |
| <br>Tier 3: Regional surveys                                                                                       |
| Pest population extent and degree of infestation (HWA only)                                                        |
| Forest health assessment- pre and post infestation                                                                 |
| Geography of infestation: rate of spread (HWA only)                                                                |
| <br>Tier 4: Remote sensing and mapping                                                                             |
| Forest type (from Landsat Thematic Mapper)                                                                         |
| Air photo assessment of forest health parameters such as defoliation (from color infrared aerial photographs)      |
| Deposition from generated maps                                                                                     |
| Climate measures from generated maps                                                                               |

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at FIA phase 3 plots on the ground. Before this study, ground monitoring of the adelgid in the DRB was limited to 14 pairs of plots within the DEWA. Each of the plots consists of 10 hemlock trees whose health was evaluated annually by using the FIA crown rating guide and by determining the percentage of terminals that were infested with the adelgid and that were producing new growth. This method was also used in other areas of Pennsylvania and in West Virginia. Examination of these data, and the investigator's experience in establishing similar monitoring plots in the DRB, indicated this type of plot-level monitoring was extremely expensive relative to the usefulness of the data obtained.

For the Asian longhorned beetle, investigators identified those areas in the DRB that would most likely incur damage should this insect disperse to the region and become established. Existing spatial data on the distribution of forest types were used for this purpose.

## 5.5 The CEMRI Monitoring Program for Non-Native Invasive Species

Consistent and extensive monitoring of regional pest populations, extent, and damage over time, combined with indepth process-level research at intensive study sites, was needed to begin to address ecosystem effects of invasive pests at large scales. The CEMRI study attempted to accomplish this by enhancing data collection within the hemlock intensive monitoring sites at DEWA, simplifying regional sampling methods, developing forest vulnerability maps, and linking physical and chemical environmental data with data on pest infestation. Table 5.1 presents an idealized summary of the key research and monitoring components needed for a regional and interdisciplinary assessment of the extent and impacts of invasive forest pests, as well as the CEMRI strategy for addressing these research and monitoring components.

### 5.5.1 Intensive Site Research and Monitoring (Tier 1)

The process-level information collected at the field plots was primarily derived from intensive studies of areas currently being affected by the hemlock woolly adelgid. Available funding limited intensive site analysis for the Asian longhorned beetle, which has not invaded

the DRB to date, and the gypsy moth, for which several intensive-site studies have been completed (Townsend et al. 2004).

Paired hemlock and hardwood research stands had already been established in the DEWA by the NPS, and represented a gradient of exposure from heavy adelgid infestation in the southern portions of the park to lighter infestation in the north. Research teams from the NPS and the USFS collaborated on monitoring forest and soil conditions and adelgid status in these research stands, and the USGS and the State University of New York College of Environmental Sciences and Forestry (SUNY-ESF) collected water samples monthly from April to October from streams draining watersheds that contain the paired plots. Soil solution chemistry data below uninfested hemlock stands (USGS) and hemlock stands girdled to simulate adelgid effects (SUNY-ESF) were collected in the USGS research watersheds within the Neversink River Basin. Forest and soil measurements were consistent with FIA protocols, and stream samples were analyzed for several constituents including base cations, nutrients, pH, acid neutralizing capacity, and dissolved organic carbon (DOC).

### **5.5.2 Regional Survey Monitoring (Tier 3)**

Simple methods developed at the IMRAs for monitoring adelgid distribution and abundance were integrated into the FIA sampling protocols as part of the CEMRI project. These protocols fill a gap in existing monitoring programs by making it possible to survey a spatially extensive set of plots for non-native invasive species and thereby facilitating continuous sampling in the DRB between and during outbreaks. The data collected provided continuous information on adelgid occurrence, as well as hemlock health and related damage in the upper DRB.

Because the hemlock wooly adelgid is not visible from the air until defoliation is well underway, a truly detailed assessment of the regional extent of its infestations required a separate ground survey focused on the small areas where the host tree species are present. The USFS's Forest Health Protection (FHP) network uses such a targeted survey approach to track the effects of invasive species on specific forest types. Collaborating with the State programs that carry out the FHP monitoring plan and enhancing that survey where gaps in data collection were observed were critical components of Tier 3 monitoring for this issue-based assessment.

Links between water quality and pest infestation at a larger scale were initially explored through an infestation-gradient study spanning the region between the Neversink in the Catskills and the DEWA in the Pocono Mountains, but the patchiness of hemlock stands rendered regional surface water effects undetectable through simple streamwater sampling techniques. The highest rates of infestation were observed in the southern part of the gradient, whereas the adelgid had been detected on only one tree in the Neversink IMRA. Methods of soil solution monitoring that could be used on a regional gradient were therefore tested in the later part of the CEMRI monitoring period, so detection of potential chemical effects on surface waters could be assessed on a hemlock stand scale, and could be used to draw maps of potential effects.

### **5.5.3 Remote Sensing and Inventory Monitoring (Tier 4)**

The hemlock woolly adelgid and its effects are not visible from aerial photography until damage is so severe that many trees have already died. Techniques based on changes in spectral characteristics therefore needed to be developed to use remote sensing for detecting adelgid infestation. During the CEMRI, the USFS used separate funding to investigate the use of hyperspectral imagery for detecting hemlock mortality and decline (Pontius 2004; Pontius et al. 2005a,b; Pontius et al., in press). The resulting methodology was applied to the Catskill Mountain region; it is now being correlated with soil, soil solution, and stream chemistry collected by the USGS to draw regional maps of adelgid infestation and determine the factors controlling rates of hemlock decline and the biogeochemical responses in the ecosystem. This collaborative field program extended beyond the period of the original CEMRI, but it will contribute significantly to the CEMRI objectives.

### **5.5.4 Modeling of Pest Infestation and Damage to Ecosystems**

The goal of the CEMRI pest assessment was to develop maps of current infestation and forest vulnerability to the respective pests and to develop methods for assessing water quality responses to current pest conditions. The CEMRI tested methods that rely on a combination of remotely sensed imagery, field data, and historical datasets of pest damage. Based on regional maps of vulnerability to the hemlock woolly adelgid and gypsy moth, forest stands across the DRB could be selected for future study and assigned to discrete health classes. Maps of damage could then be analyzed along with maps of other environmental factors (climate variability, soil fertility, and forest sensitivity to pests, etc.) in the study region. These maps could then be used in models that, when fully developed, could predict the rate and vectors of pest infestation based on specific climate scenarios. Funding and the current state-of-the-science were limited at the initiation of the CEMRI on linkages between pest infestation and environmental parameters and on the effect of pest damage and forest change on long-term water quality. Development of models for tracking pest infestation and damage was therefore not completed during this study.

### **5.5.5 Interpretation of the Integrated Dataset for Resource Managers**

Forest vulnerability maps will be available for planning the mitigation of pest impacts as well as for assessing potential effects on surface water quality. For example, the map of hemlock health may be used to develop a map of expected water quality changes resulting from adelgid activity. Using information from the surveys and IMRAs on the relationship between hemlock health and soil solution or streamwater quality, a map of streams in the DRB that are vulnerable to water quality changes resulting from adelgid outbreaks could be developed. Such a product would help meet one of the overall goals of the CEMRI project—to bridge the gap in monitoring efforts among Federal agencies responsible for environmental monitoring.

In summary, soil chemistry and water quality studies conducted by the USGS, assessment of pest infestation at FIA monitoring points, and ancillary data from National Oceanic and Atmospheric Administration (NOAA) weather stations, as well as data from other ancillary monitoring networks within the region, were used to develop strategies for collaborative monitoring of the causes, extent, and consequences of forest pest infestation and to form an initial regional assessment of the environmental parameters associated with pest outbreaks and the resulting effects of those outbreaks on environmental quality. This work provided the first truly integrated effort to monitor the distribution and abundance of pest populations, as well as their effects on surface-water quality.

5.6 Preliminary Results

The USFS expanded the extent and intensity of its surveys of the hemlock wooly adelgid and integrated that survey data with aerial photo mapping of adelgid infestation by Rutgers University (Fig. 5.4). Intensive integrated monitoring of forest conditions, adelgid infestation, and soil and stream chemistry was established through collaboration among the NPS, USFS, USGS, and SUNY-ESF. Correlations between pest infestation and changes in stream chemistry were indicated during the short period of the CEMRI assessment (Fig. 5.5), and methods for integrated tracking of the effects of pest outbreaks on forest soil and stream biogeochemistry were developed and tested. Continued research in the Catskill Mountains involves testing the accuracy of remote sensing imagery for detecting adelgid outbreaks and biogeochemical responses.

Figure 5.4.—Map of the intensity of damage from the hemlock wooly adelgid in the Delaware Water Gap area, derived from remote sensing data (Pontius et al. 2005).

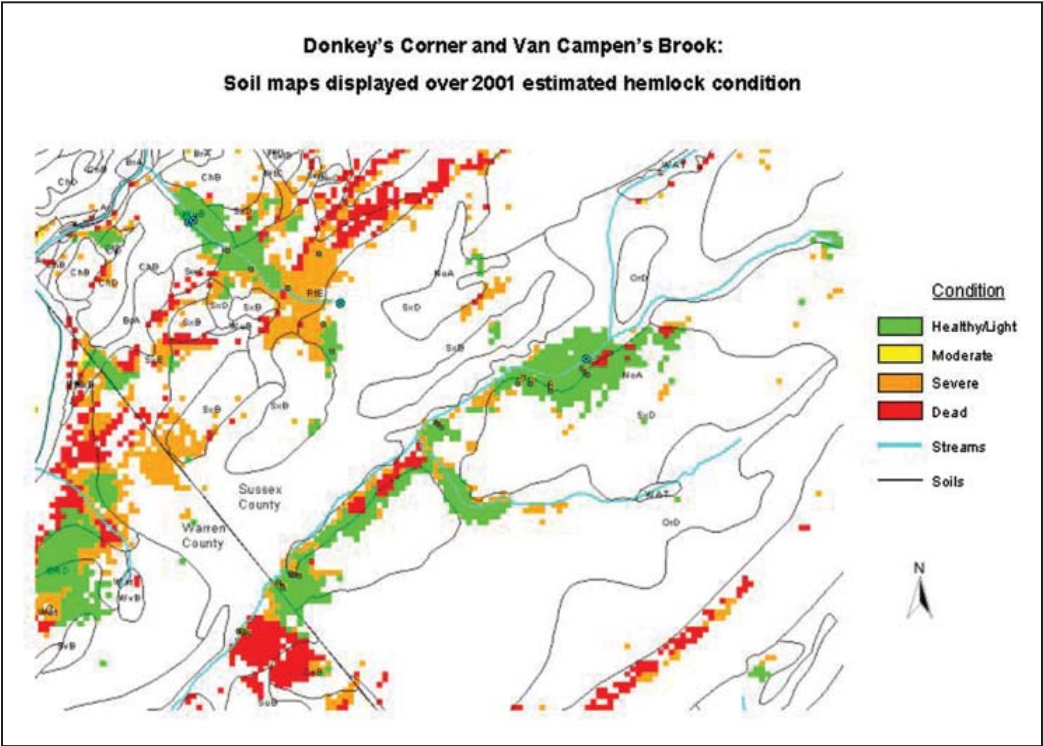
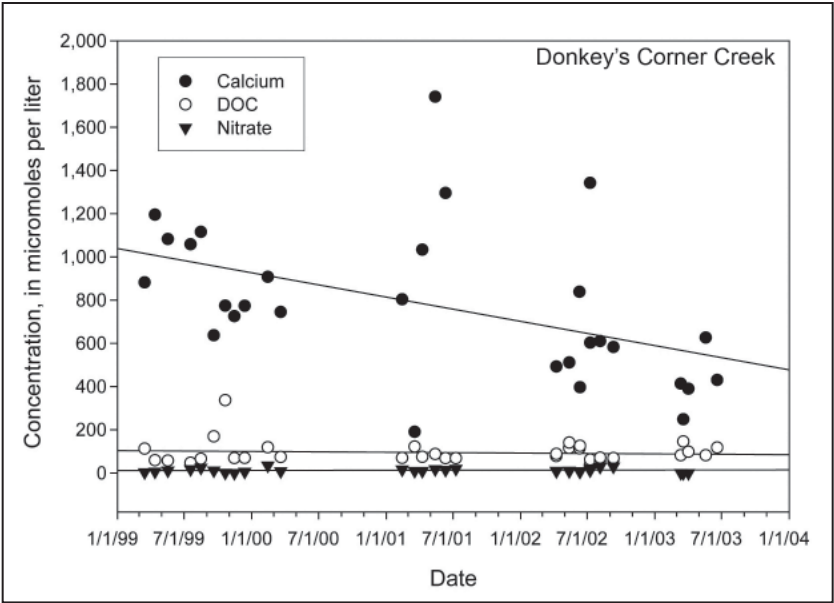


Figure 5.5.—Decrease in stream calcium concentration in a stream draining a forest stand with 80 percent hemlock wooly adelgid infestation, Delaware Water Gap National Recreation Area.



## 6.0 MONITORING RECOVERY FROM CALCIUM DEPLETION AND NITROGEN SATURATION

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Atmospheric emissions from industrial processes in the early part of the 20th century resulted in acidic deposition in the Northeastern U.S., a phenomenon known as “acid rain.” Acid rain has been implicated in acidification of sensitive waterways, nitrate enrichment of surface waters, and fish population declines in poorly buffered mountain streams (Baldigo and Lawrence 2000, Murdoch et al. 1998). Scientists are also discovering that acid rain has had additional lasting and negative effects on soil and stream chemistry and that these chemical changes may slow tree growth (Hallett et al. 2006). The goals of this research and monitoring development project were to:

- Develop relationships between soil and foliar calcium (Ca), soil and stream Ca, forest nitrogen (N) saturation, and tree productivity at intensive monitoring and research areas (IMRAs) to quantify and verify the impact of Ca depletion on forest growth
- Develop methods for regional monitoring of forest and stream recovery from acidification, Ca depletion, and other stressors
- Develop methods for early detection of forest and ecosystem stress due to factors such as Ca depletion

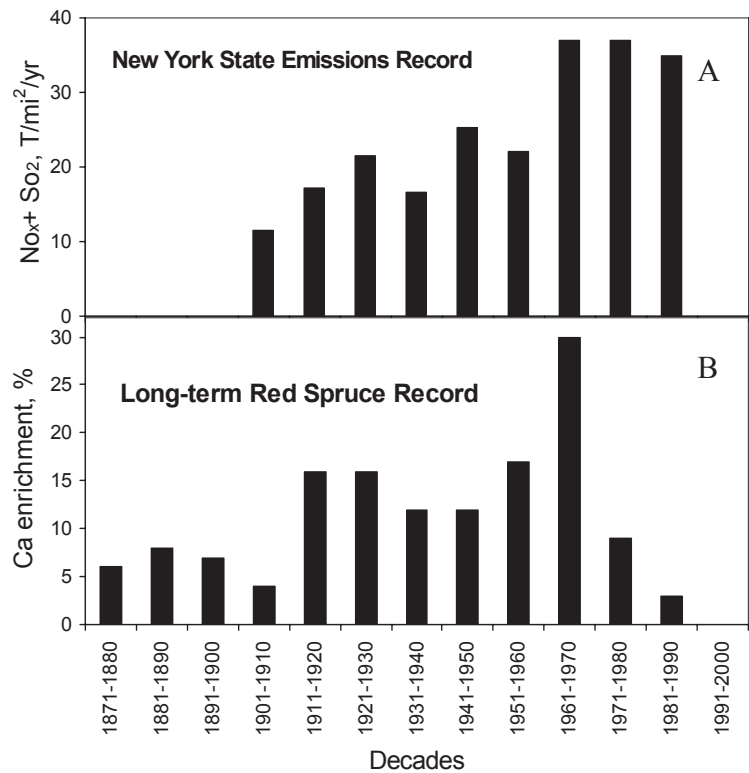
### 6.1 Background

Calcium is the fifth most abundant element in trees, after hydrogen (H), carbon (C), oxygen (O), and nitrogen (N). It occurs as part of the structure of wood, regulates acidity, and signals changes in various biological functions (McLaughlin and Wimmer 1999). For wood to form, a steady supply of Ca is needed.

Trees obtain Ca via their roots as they grow through forest soils. These soils have a topmost forest floor layer, derived from decaying leaves, branches, roots, and dead trees, and an underlying layer of mineral soil, derived from rock of varying mineral composition. Calcium and other essential elements in the forest floor are the result of decades of organic cycling as trees grow, shed, die, and decay, during which time some Ca is leached from the soil into streams where it is needed to support aquatic life. Some Ca is added back to the system from atmospheric deposition and weathering of the underlying minerals. In most cases the amount of Ca available to trees remains relatively constant because removal processes are offset by replacement processes. However, if a major disturbance occurs, the system can be disrupted and net losses can occur, reducing the amount of Ca available for tree uptake. The disturbances are various: major fires, heavy harvesting operations, or changes in the input of inorganic acidity brought about by industrialization in the 20th century.

The latter form of disruption of the organic cycling of Ca is of particular concern for the Northeastern United States, where the Delaware River Basin (DRB) is located. Oxides of sulfur (S) and N, emitted during industrial processes, can react with water to form strong inorganic acids, which are the basis of acidic deposition. Emission of sulfur and nitrogen oxides increased from the beginning of the century until 1970, when the Clean Air Act was

Figure 6.1.—Dendrochemical marker of calcium mobilization and coincident change in emissions of oxides of sulfur and nitrogen. A) Combined emissions of sulfur dioxide and nitrogen oxides for the State of New York from 1901 to 1990. B) Percent frequency of calcium enrichment by decade. For example, the frequency of calcium enrichment between 1961 and 1970 relative to the preceding decade (1951-1960) was 30 percent across all sample trees.



passed (Fig. 6.1A). Since 1970, emissions have not increased further, but have remained historically high. Since 1990 there has been about a 40-percent reduction in deposition of sulfur oxides, but little change in deposition of nitrogen oxides (Driscoll et al. 2001).

In some regions, N deposition has exceeded the biological demand for N in forested watersheds, leading to a buildup of N in the soil and the leaching of N from the watershed to surface waters (Aber et al. 1989). This phenomenon, referred to in the literature as “nitrogen saturation,” appears to be occurring in parts of the northern DRB, where acidification of soil water and surface water by nitric acid has been evident (Murdoch and Stoddard 1992).

When deposited from the atmosphere, inorganic acids such as nitric acid remove Ca from where it is bound on decaying organic matter to make it soluble, or mobile. Mobile Ca is then absorbed by roots for use by the tree. Initially, the increase in mobile Ca helps trees to grow. However, this inorganic acidity can also mobilize aluminum (Al). When this occurs, Al does two things: it binds very tightly to soil particles, thereby displacing Ca from the soil, and it blocks the uptake of Ca by tree roots (Fig. 6.2). Forest soils can become depleted of Ca to the point where some tree species have Ca deficiency, which reduces growth. Prolonged growth suppression of mature trees can lead to mortality from a variety of causes.

## 6.2 Relationships Between Soil Calcium Depletion and Tree Growth

The problem of Al-induced Ca deficiency syndrome (Shortle and Smith 1988) and Ca loss from the forest floor (Lawrence et al. 1995) has been extensively studied in spruce forests to the north of the DRB (Lawrence et al. 2000, Shortle et al. 2000). In this research, chemical data from tree cores (dendrochemistry) were used to infer changes in soil chemistry in the past. Growth ring patterns (dendrochronology) were used to infer tree response to changing soil conditions and climate variables.

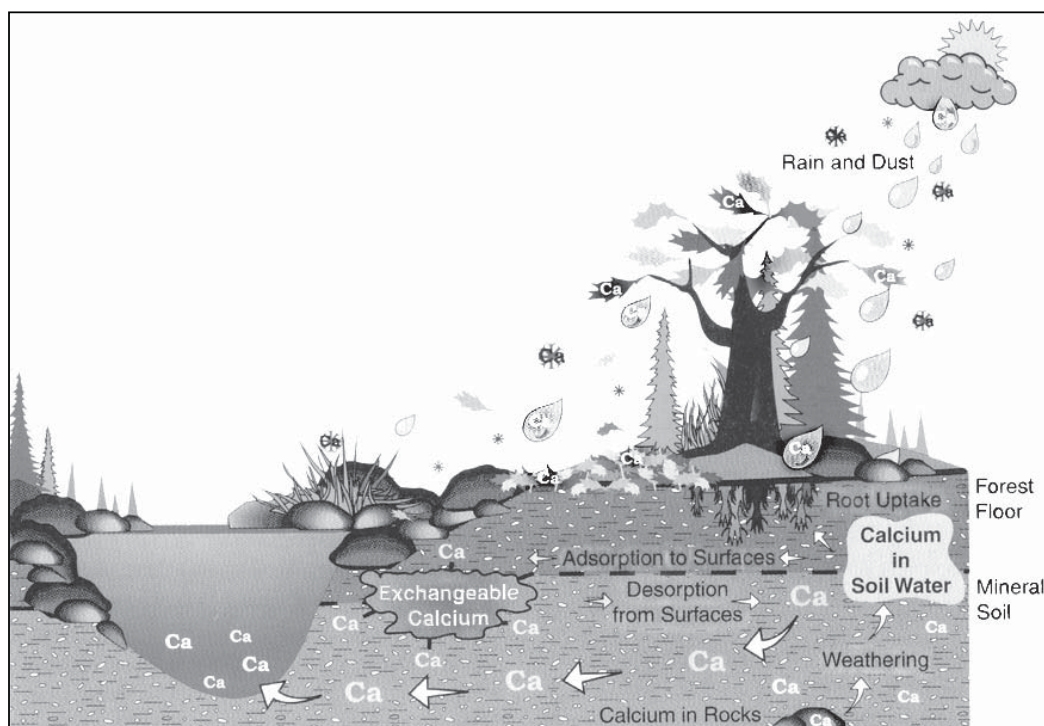


Figure 6.2.—Calcium cycle in a forest ecosystem. Inputs to the pool of available calcium in the soil result from weathering of rocks, atmospheric deposition, and litterfall. Outputs from this pool result from root uptake and leaching out of the soil. From Lawrence and Huntington (1998).

Calcium depletion from soil appears as Ca enrichment in wood because mobilization of Ca by inorganic acids increases the availability of Ca for root uptake as well as leaching. When we look at a 12-decade record in spruce (Fig. 6.1B), the 4 decades from 1871 to 1910 had a mean Ca enrichment (Ca concentration in a tree core formed in a particular decade, relative to the previous decade) frequency of 6 percent, which more than doubled in the 5 decades of 1911-1960 and doubled again in 1961-1970 before returning to 6 percent in 1971-1990. This pattern indicates a period of low soil Ca depletion and low wood enrichment followed by six decades of disruption, in which depletion and enrichment became more common after acidic deposition increased and reached a maximum in 1961-1970. After 1970, the pattern indicates a return to low depletion and low enrichment because much of the bound Ca in soil was replaced by Al as soil became acidified by acid rain. A buildup of Al on organic storage sites in the forest floor tends to block Ca uptake by the tree. Analysis of forest floor material indicated that bound Ca levels are related to bound Al levels, not to bound H levels as expected if only natural organic acidity was mobilizing Ca. These patterns are consistent with the concept that Ca storage and uptake before 1911 were governed primarily by organic acidity of trees and associated organisms, but that after a long period of elevated inputs of inorganic acidity, mobilized Al became a limiting factor in the Ca cycling of spruce forests.

Does this pattern exist in sugar maple and other species in the DRB? Does the tree ring record indicate growth reductions following Ca depletion? Did the growth relationship to climate variables change after Ca depletion? These questions were addressed by coring trees and analyzing dated tree ring tissue at the Neversink IMRA.

### **6.3 Early Detection of Stress Using Foliar Indicators**

Early detection of changes in soil chemistry and resulting changes in physiological and biochemical processes in trees, before the appearance of visual symptoms, can point to geographic areas needing special attention and can enable the early abatement of emerging forest health problems. The relationship of altered soil chemistry to foliar biochemical indicators has been studied in spruce forests (Minocha et al. 1997) and in field experiments with maple, pine, and oak (Minocha et al. 2000). One group of indicators showing special promise for early detection of increasing environmental stress in trees are nitrogenous compounds, such as polyamines and amino acids.

Putrescine (a polyamine) has been shown to increase in foliar samples of healthy spruce under conditions of increasing Al and decreasing Ca in soil (Fig. 6.3). When Ca was experimentally added to deficient soils, the health of sugar maples was restored and foliar putrescine levels were reduced (Figure 6.3A,B). Additions of nitrate to stands of pine, maple, and oak at Harvard Forest to simulate the effect of increased nitrate inputs by acid rain resulted in decreased soil Ca and increased foliar putrescine (Fig. 6.3 C,D). It appears that foliar polyamine analysis, coupled with inorganic analysis of soil and foliage, indicates that altered soil chemistry produces stress in trees before symptoms of declining health appear.

Polyamines like putrescine are not specific indicators of a particular kind of stress, such as Ca depletion, which makes them very useful for detecting a broad range of environmental stress. To determine the cause of the stress detected, other analyses of soil and foliage are needed. Arginine, an amino acid, appears to be a specific indicator of high N input which can be a serious tree health problem in Ca-depleted soils.

### **6.4 Existing Monitoring Programs and Regional Assessment Capability**

Federal and State monitoring programs operating within the DRB collect data on individual components of the forest ecosystem that are important to a regional Ca-depletion assessment. Information about air quality, surface water quality and quantity, and forest growth has been collected by the U.S. Environmental Protection Agency (EPA), the U.S. Geological Survey (USGS), the U.S. Forest Service (USFS), and State agencies. A brief summary of the existing databases used to assess the N-saturation and Ca-depletion issues follows.

#### **6.4.1 Soil Chemistry**

Information on soil chemistry is routinely collected at the Forest Inventory and Analysis (FIA) phase 3 plots, which are randomly and sparsely scattered through the DRB (as well as other regions of the U.S.), and USGS researchers collect soil chemistry information associated with their individual research projects in the Neversink IMRA. The resulting dataset on soil chemistry and condition, however, is inadequate for generating accurate maps of soil chemistry within the IMRAs or the upper DRB.

#### **6.4.2 Forest Condition**

Research on foliar chemistry and biochemical indicators of tree stress is developing promising tools for tracking forest condition, but foliar measurements have not yet been implemented as part of routine monitoring in state or national forest-monitoring programs. Foliar N and Ca data have been collected at a few scattered research sites in the DRB, but the number of points represented is inadequate for developing a map of regional condition. Remote sensing products from MODIS were used to estimate forest net primary production (NPP) in the DRB, by parameterizing the interpretive models for eastern forest species (Pan et al. 2006). Remote sensing of foliar Ca was in the development stages during the Delaware CEMRI.

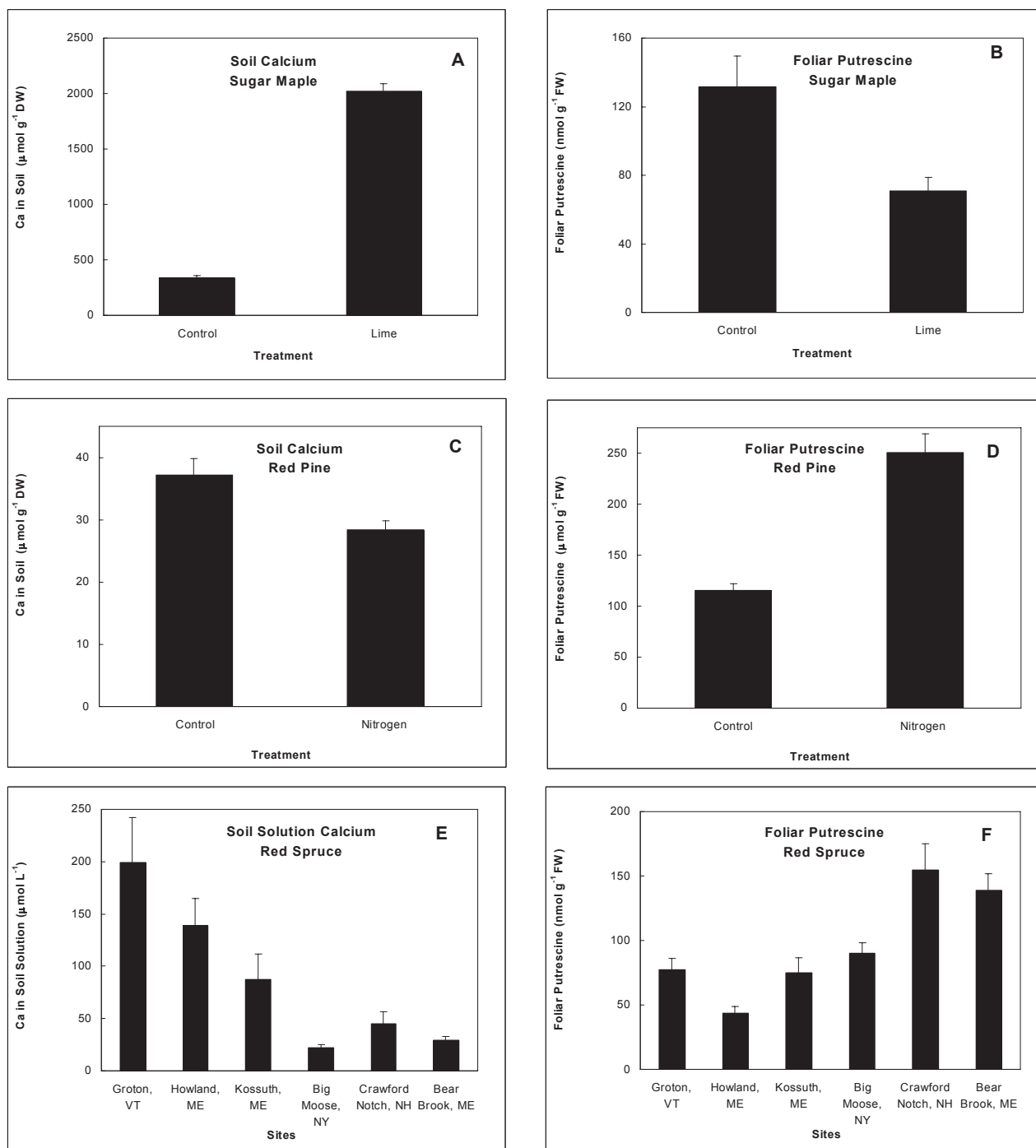


Figure 6.3.—Inverse correlation between foliar stress indicators (putrescine) and calcium in soil in three different tree species under different growth conditions. A-B) Impact of liming treatment on exchangeable calcium in sugar maple stands on the Allegheny Plateau, PA. Data for putrescine are mean  $\pm$  SE ( $n=100$ ) and for soil ( $n=16$ ). C-D) Effects of chronic nitrogen addition (as ammonium nitrate) on exchangeable calcium in organic soil and foliar putrescine in red pine trees at Harvard Forest, MA. Data for putrescine are mean  $\pm$  SE ( $n=100$ ) and for soil ( $n=18$ ). E-F) Calcium in soil solution of organic soil and foliar putrescine in red spruce trees growing at six sites across the Northeastern U.S. Putrescine data are mean  $\pm$  SE ( $n=40$  except for Kossuth, ME, and Big Moose, NY, for which  $n=20$ ) and soil data are mean  $\pm$  SE ( $n=12$ ).

#### **6.4.3 Water Quality**

Water quality monitoring funded by EPA is primarily conducted through State monitoring programs and is focused on areas of human disturbance and associated pollution runoff. The EPA has collected scattered data in the upper DRB on streams draining forested watersheds as part of its Ecological Monitoring and Assessment program (EMAP), but that sampling occurred over a limited time and had an insufficient density to provide estimates of Ca concentrations in streams draining undeveloped landscapes in the DRB. State water quality monitoring in the basin includes some sampling of forested watersheds as indicators of background conditions for assessing the effects of human disturbance. The New Jersey Department of Environmental Protection (DEP) recently established a 73-site network of ecoregion reference stations that is generating data primarily on invertebrate populations and habitat conditions. The New York City DEP monitoring program in the Catskills includes several streams draining forested watersheds. Of the few streams sampled that have drainage areas measuring less than 25 km<sup>2</sup> in the northern DRB (i.e., first- or second-order drainages), reported Ca + magnesium (Mg) concentrations range from 0.8 to 20 mg/L, and nitrate concentrations range from 0 to 4 mg/L (0 to 64 uEq/L: Ward Hickman, NAWQA program 2001, written communication). Forest and soil condition measurements are not systematically tied to these stream monitoring networks, and the stream samples are typically collected at base flow when root-bearing soils are not hydrologically connected with streams. The association of streamwater quality with forest and soil condition could not be assessed with pre-CEMRI data.

#### **6.4.4 Deposition**

The National Atmospheric Deposition program (NADP) and State deposition chemistry monitoring stations either within or near the DRB have been used in models to create regional maps of deposition in the Northeastern United States. The accuracy of those maps for specific subregions of the DRB is uncertain, but the general pattern of N deposition can be used with reasonable confidence.

#### **6.4.5 Summary of Gaps in Current Data Collection**

The greatest gap in current monitoring systems is the lack of a multiresource monitoring effort, particularly surveys of soils and surface waters, needed to understand the interrelated nature of atmospheric deposition, soil and stream Ca status, and tree growth. The lack of these data on a regional scale precludes all but the most simplistic regional assessments of Ca depletion or N saturation at this time.

**Table 6.1.—Key variables and analyses for assessing forest recovery from calcium depletion and nitrogen saturation**

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|                                                                                            |
|--------------------------------------------------------------------------------------------|
| Tier 1: Intensive sites                                                                    |
| Relationships between foliar and soil nitrogen and calcium (Neversink IMRA only)           |
| Relationships between tree growth (net primary production-NPP ) and soil/ foliar chemistry |
| Relationships between soil N and Ca, forest NPP, and water quality (Neversink IMRA only)   |
| Relationship between forest stress factors and soil chemistry                              |
| <br>                                                                                       |
| Tiers 2 and 3: Gradient sites and regional surveys                                         |
| Forest NPP and crown condition                                                             |
| Soil chemistry                                                                             |
| Soil physical parameters                                                                   |
| <br>                                                                                       |
| Tier 4: Remote sensing and mapping                                                         |
| Atmospheric deposition: N and Ca                                                           |
| Remote sensing of foliar chemistry: foliar N and foliar Ca                                 |
| Forest type, species classification                                                        |
| Remote sensing of forest productivity (from MODIS satellite)                               |

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## **6.5 The CEMRI Monitoring and Assessment Approach for Nitrogen Saturation and Calcium Depletion**

### **6.5.1 Intensive Site Research (Tier 1)**

A summary of the key research and monitoring components needed for a regional assessment of the extent and effects of N saturation and Ca depletion is presented in Table 6.1. A brief description of the current information base for a regional assessment is provided below.

The relationship between soil chemistry and tree stress, and the development of indicators that reveal disturbance of that relationship, was the focus of IMRA activity related to Ca depletion and N saturation in forested watersheds. Specific process-level questions that were addressed included the following:

- What are the thresholds of Ca availability in soil below which NPP is decreased and trees show stress characteristics?
- Is there a spatial or elevational gradient of Ca depletion and associated tree stress that can be related to deposition rates and soil fertility?
- How does Ca depletion affect tree growth (leaf area, root area, survivorship, and reproduction), C sequestration, nutrient uptake, and adjacent aquatic ecosystems?
- What combination of soil characteristics, deposition rates, and forest conditions results in nitrate leaching from forest soils?
- What indicators of Ca-depletion stress on an ecosystem can be used to assess the regional extent of the N-saturation and Ca-depletion issues?

Based on this list of questions, foliar chemistry, growth and dendrochemical history, wood polyamine content, soil chemistry, and drainage water quality were the primary components of the ecosystem measured as indicators of Ca and N stress at the IMRAs.

One goal of this research was to determine whether Ca depletion and retarded tree growth are related in Appalachian Plateau hardwoods and to assess whether stream Ca concentrations are an indicator of forest nutrient status. These were tested at the IMRAs

by applying dendrochronological and dendrochemical techniques and integrating those data with soil chemistry and streamwater quality data in the same landscapes (Table 6.1). Relationships between changing soil Ca and tree response determined at the Tier 1 study sites were applied across a region using the combination of data describing atmospheric deposition, soil condition, tree species, and tree health available from Tier 3 regional surveys. To further assess the relative importance of these potential controls on current tree growth at the regional scale, repeat measurements of growth over a 3-year period at selected plots in the IMRAs and randomly located within the broader basin were used to confirm growth patterns.

Research by the USFS was also conducted at the Neversink IMRA to develop methods for detecting stress using foliar polyamine content in trees exposed to Ca depletion before visible signs of stress appear. Foliar samples were collected from plots where soil Ca status and tree growth rates are known with certainty. Results from these intensive sites were then applied across the region to determine if they could be correlated with remote sampling of foliage by near-infrared spectrometry. In previously published data from Harvard Forest, a high correlation was seen between putrescine level and foliar N numbers obtained by near-infrared spectroscopy (Minocha et al. 2000). Collection of foliage from mature trees was difficult to incorporate into extensive plot sampling, because of the time-dependent nature of the sampling technique.

#### **6.5.2 Gradient Surveys (Tier 2)**

Regionally extensive data collection for addressing the N-saturation and Ca-depletion issues incorporated measurement of forest, soil, and water conditions as well as deposition volume and chemistry. Gradient surveys relating soil, stream, and foliar Ca were conducted within or near the DRB before the Delaware CEMRI and proved adequate for relating the intensive site research results to the regional probability-based survey. Foliar C and N, soil chemistry, NPP, and nearby stream chemistry were also computed for 16 regional plots distributed throughout the Appalachian Plateau of the upper DRB, and for 10 plots within each of the IMRAs (for a total of 30 IMRA plots) representing a range of soil Ca and forest types. All plots were integrated in the broader FIA plot grid for the United States and were thus easily scalable to survey data collected at the FIA plots within the basin.

#### **6.5.3 Regional Probability Surveys (Tier 3)**

Regional probability surveys were linked to the IMRA intensive datasets through measurement of these same components on a less intensive but more widely distributed scale. Some measurements, such as polyamine content in wood, were still at the experimental stage and were not available for use in broad surveys. Forest condition assessments relied on data from the USFS FIA plot networks. Data on current NPP, canopy condition, species distribution, presence/absence of key pests, and historical information on forest growth were used where available. To make inferences about soil Ca status and tree growth at the regional scale, monitoring methods were developed to enable the regional mapping of soil Ca status. Soil samples collected from the O horizon and two depths in the B horizon at each phase 2 and phase 3 FIA plot within the Appalachian Plateau portion of the DRB were analyzed for soil Ca and other related constituents.

Because large-scale soil monitoring is extremely time consuming and costly to implement, one goal of the research at the IMRAs was to compare soil chemistry from each plot to

nearby stream chemistry. If water chemistry and soil chemistry were found to be closely linked, then water samples could be used to infer soil chemistry. A stream survey is preferable to a soil survey for implementation as an extensive monitoring program for soil Ca status because stream samples are simpler and faster to collect, less costly to process, and integrate the chemical signal of large areas of the upper soil. To develop these regional soil/water relationships, streamwater samples were collected by the USGS district research and monitoring program at the nearest first-order stream to the FIA plots where soils have been collected. First-order stream chemistry, especially during periods of high flow when the flowpath of water through the watershed is through the shallow soil, can serve as an integrator of soil condition and can thus reveal where N is leaching from soils and Ca depletion in soils is starting to affect runoff water quality. A survey of first-order streamwater quality that was linked to survey measurements of NPP, foliar chemistry, soil chemistry, and forest condition (crown density, pest presence/absence, etc.) provided the major parameters needed for the first comprehensive regional assessment of Ca depletion in the study area.

Data from this experimental survey linking terrestrial and aquatic information were also compared with data from the USGS National Water Quality Assessment program (NAWQA) stream gradient survey and fixed-site monitoring networks, thus allowing an assessment of the downstream extent of forest soil-stream chemistry relationships and the relative importance of forest soil conditions to downstream water quality.

#### **6.5.4 Remote Sensing and Maps from Fixed-Point Measurements (Tier 4)**

Several coverages of spatially extensive data were developed for the region with existing or developing methodologies to address the N-saturation and Ca-depletion issue. Critical coverages that could be derived from interpolable fixed-point measurements and remote sensing imagery include

- Topography and hypsography
- Air temperature and precipitation maps
- Deposition rates of Ca, N, and other related constituents
- Forest species, species distribution and fragmentation (derived from Landsat imagery)
- Foliar C, N, and Ca, and forest NPP (derived from MODIS and AVIRIS imagery where available within the basin or from the FIA plot data)

The intensification of the FIA network within the DRB provided an unprecedented opportunity for large-scale validation of remote sensing tools, including MODIS for forest biomass and NPP, and Landsat-TM for characterizing patterns of forest fragmentation and land use. Indicators of Ca depletion and N saturation in forests from remote sensing data were in the development stage during the Delaware CEMRI.

New experimental methods for determining foliar N and Ca from remote sensing were concurrently being developed by researchers at the University of New Hampshire and the USFS research laboratory in Durham, New Hampshire. The methods being tested used AVIRIS imagery, which was available for the northern Catskill Mountain region of the DRB (Hallett et al. 2006). Maps of forest species derived from the USFS FIA plot data, and NPP from remote sensing interpretation were also developed for a thorough regional Ca-depletion

monitoring program. Maps of deposition rates were generated through modeling of data from the several deposition monitoring stations in the DRB by researchers at Pennsylvania State University (James Lynch, 2003, written communication). This development of a linked deposition, aquatic forest, and soil chemistry database for the upper DRB should improve our ability to infer and model large-scale patterns of forest recovery from acid deposition.

These combined measurements provide the first regional database in the United States that integrates forest condition, soil condition, and associated surface water quality. Determining regions within the DRB where N saturation and associated Ca depletion are most acute will allow resource managers to plan forest harvest and development in those areas in ways that limit the further degradation of the ecosystem.

#### **6.5.5 Modeling**

Models that specifically address the extent of Ca depletion for a given region, or the likelihood of Ca depletion occurring in a specific watershed, were still in their development stages during the Delaware CEMRI and were further developed as part of the initiative. The PnET-II and PnET-BGC models are designed to determine the extent of, and potential for, development of N saturation and Ca depletion, respectively, for specific instrumented watersheds. The CEMRI provided a spatially and temporally integrated dataset that was used to develop and verify those models on a regional scale and to test the use of the models in support of a regional or national monitoring strategy.

### **6.6 Preliminary Results**

Collaborative research between USGS and USFS research laboratories revealed important biogeochemical correlations among foliar chemistry, tree stress indicators, and both stream and soil Ca concentrations in the Neversink IMRA (Murdoch et al. 2003) (Fig. 6.4). A significant addition to our understanding of soil Ca's influence on forest condition, made possible through the CEMRI strategy, was concurrent mapping of forest condition, soil chemistry, and first-order stream chemistry for the northern half of the DRB (the area underlain by the Appalachian Plateau). These maps, when compared with regional nitrate deposition maps, indicate a common pattern of low soil Ca concentrations and low stream acid neutralizing capacity in the western Pocono Mountains and the eastern Catskill Mountains, the areas of the basin hardest hit by acidic deposition (Fig. 6.5). The CEMRI effort therefore created the first regional picture of soil Ca depletion and its relation to acidic deposition and stream acidification through integrating and augmenting existing USGS and USFS programs.



## 7.0 MONITORING THE STATUS AND IMPACTS OF FOREST FRAGMENTATION AND URBANIZATION

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*Rachel Riemann, Karen Riva-Murray, and Peter S. Murdoch*

The geographic expansion of urban and suburban development and the influx of residential and recreational development into previously forested areas are growing concerns for natural resource managers. This project sought to:

- Identify and characterize urbanization and forest fragmentation over large areas with the detail and accuracy required for studies of wildlife habitat, plant composition, and water quality
- Identify potential effects of urbanization and fragmentation on water quality
- Develop appropriate methods for achieving the first two objectives, with a focus on:
  - o Identifying ways of describing and quantifying urbanization and forest fragmentation that are scale- and issue-appropriate, reasonably accurate, consistent over time, and relevant to management.
  - o Identifying measures of and standards for accuracy assessment

### 7.1 Background

Development intrusion has been shown to increase edge conditions and reduce forest interior habitat, which can change the habitability of the forest for particular wildlife or plant species. Enough development may even create isolated islands of this previously continuous forest habitat, affecting the long-term survivability of such species and biodiversity of the system as a whole. Contributing to the effects of forest fragmentation, urbanization increases the proximity of forest land to human disturbances and land uses such as roads, industrial sites, and residential areas, and changes the landscape context in which a forest or stream occurs. This frequently increases contact between humans and forests and streams, changes the local hydrology, alters the types of forest management that can be used, facilitates the invasion of exotic species and increases exposure to chemical pollutants. Changes in the type, density, and distribution of developed land uses within the surrounding area have the potential to change the physical and biochemical characteristics of terrestrial and aquatic ecosystems and to alter many of the ecological processes at work.

### 7.2 Measurement of Urbanization and Fragmentation

Urbanization is the process of increasing urban (vs. agricultural) development and includes the loss of forest land to developed land uses. Forest fragmentation in this study was considered to be the spatial breakup of forest land by developed land uses and is described by its distribution and configuration with respect to other land uses. Context, another important descriptive factor, is defined as the land use composition and pattern of the area surrounding a point, stream, or patch of forest of interest. Proximity is a measure of the distance between forest or stream to the nearest developed land use of any type. Together, these types of measures describe landscape characteristics of interest for their potential impact on forest and hydrologic systems.

A number of methods and indicators have been used for assessing urbanization and forest fragmentation. These include, but are not limited to, quantification of patch size and shape, edge, interior area, land use composition, forest isolation, human use, landscape pattern, and parameters describing landscape texture and the degree of connectivity. Different

parameters of landscape structure have more or less relevance to specific issues of interest because of their correlation with observed changes in those areas. For example, parameters of fragmentation, proximity, and context that have been shown to be important to forest management are the size of the forested patch and its distance to the nearest road, residential, or urban area—factors that affect both treatment constraints and the economic viability of forest industry on that patch (e.g., Barlow et al. 1998, Cooksey 2000, Wear et al. 1999). On the other hand, parameters of fragmentation observed to be important to water quality are land use composition of the watershed; length of stream bounded by agriculture, forest, and residential; and percent of impervious surfaces in the watershed—factors that affect flow and flow variability, biogeochemical cycles, macroinvertebrates, and sedimentation (e.g., Hunsaker et al. 1992, McMahon and Cuffney 2000, Richards and Host 1994, Wear et al. 1998). Parameters observed to be important to changes in forest composition are total size of forest patch, amount of edge, distance from edge, distance to nearest road or developed land use, an index of human development or human use, or a measure of human, deer, or road density in the area—all factors that have the potential to affect regeneration, differential species survival, and the number of exotics or invasives introduced (e.g., Airola and Buchholz 1984, Heckscher et al. 2000, Saunders et al. 1991, Zipperer and Pouyat 1995).

Scale is another important factor in the study of the effects of human development on forest and hydrologic systems. For example, effects on water chemistry and quality may be local (affected by streamside land use), regional (affected by the land use composition and configuration of the entire watershed), or perhaps broader if contaminants are airborne. Effects of forest fragmentation on forest composition may be local (invasive species from neighboring land uses) or local and regional (human recreation pressure). Fragmentation measures at multiple scales will thus likely be important until the relative magnitude and thresholds of these effects are better understood.

### **7.3 Existing Monitoring and Regional Assessment Capability**

Before this study, efforts to monitor fragmentation focused on developing methods to quantify it using remotely sensed imagery. Two existing programs in this region were a) the sample point interpretations of 1:40,000 aerial photography at FIA phase 1 points (Riemann and Tillman 1999) (Fig. 7.1) and b) statistics generated from Landsat Thematic Mapper (TM)-derived land use/land cover classifications (Riitters et al. 2000) (Fig. 7.2). Other efforts such as point or area interpretation from 1:40,000 aerial photography at FIA plot locations (Collins 1995, Rudis 1995) did not provide regional maps of these variables, but did provide fragmentation or context statistics for those point locations and areas large enough to contain a sufficient number of plots (Fig. 7.3). Other efforts improved small area estimates by increasing the sampling intensity of these photointerpretation points with subsequent tradeoffs in cost or number of variables collected (Azuma et al. 1999). Still other efforts used related and already available information such as roads or road density to describe and quantify human impact in an area (Fig. 7.4).

These monitoring strategies, while providing us with a relative picture of how fragmented an area is in comparison with other areas within the region, often gave us little information about the impact of fragmentation on ecosystem health because the measures being monitored were not yet linked to studies of impacts on forest or water quality, or the thresholds of impact were not well understood. Similarly, techniques had not yet been

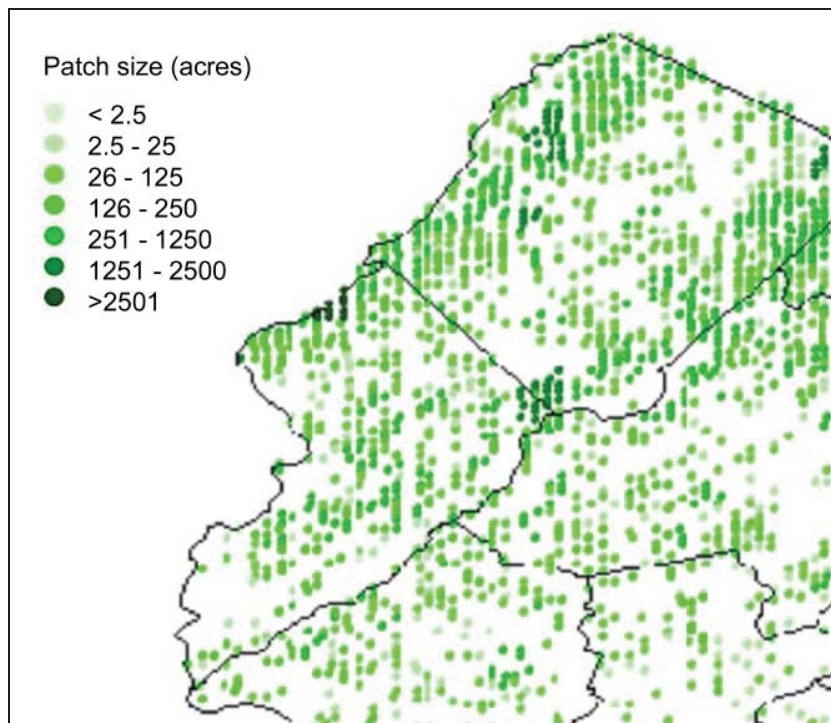


Figure 7.1.—Point-sample interpretation from high resolution imager—example of forest patch sizes in northern New Jersey.

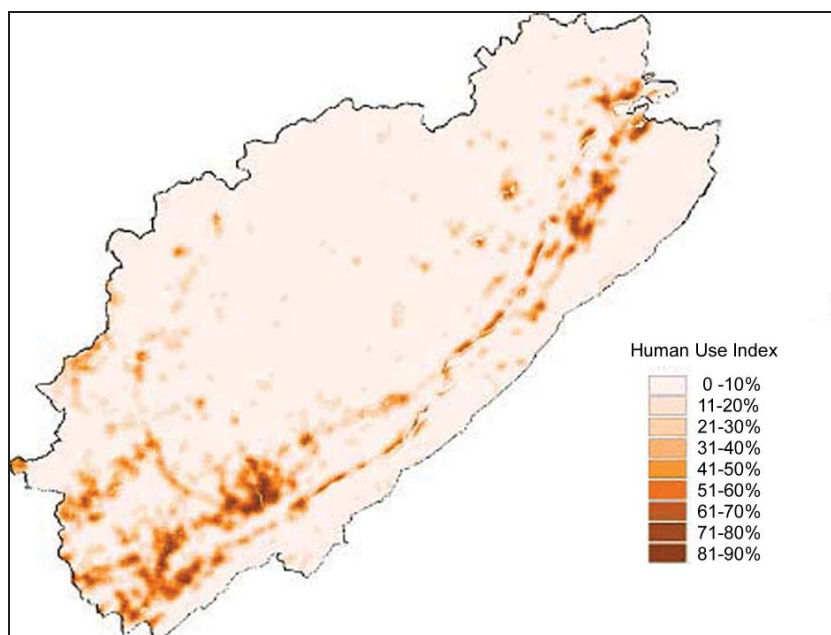


Figure 7.2.—Calculation of a human-use index from a TM-derived land use-land cover map using a 27x27 cell window—example from the Delaware Water Gap IMRA tributary watersheds. Human-use index is the proportion of agriculture plus developed land cover types in the window and is a measure of general land use pressure by humans. From: Riitters et al. (2000).

Figure 7.3.—An illustration of area-sample interpretation around FIA plots—example from the Delaware Water Gap IMRA tributary watersheds.

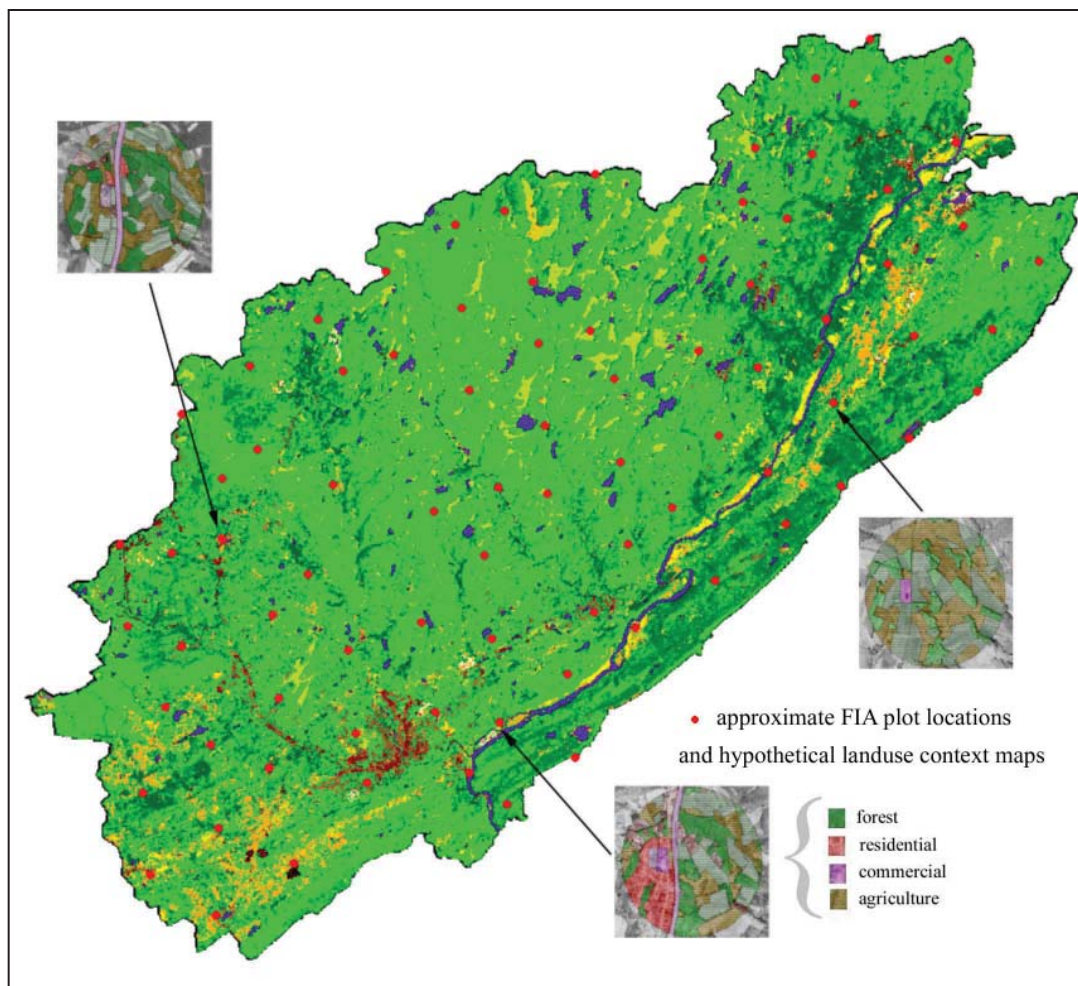
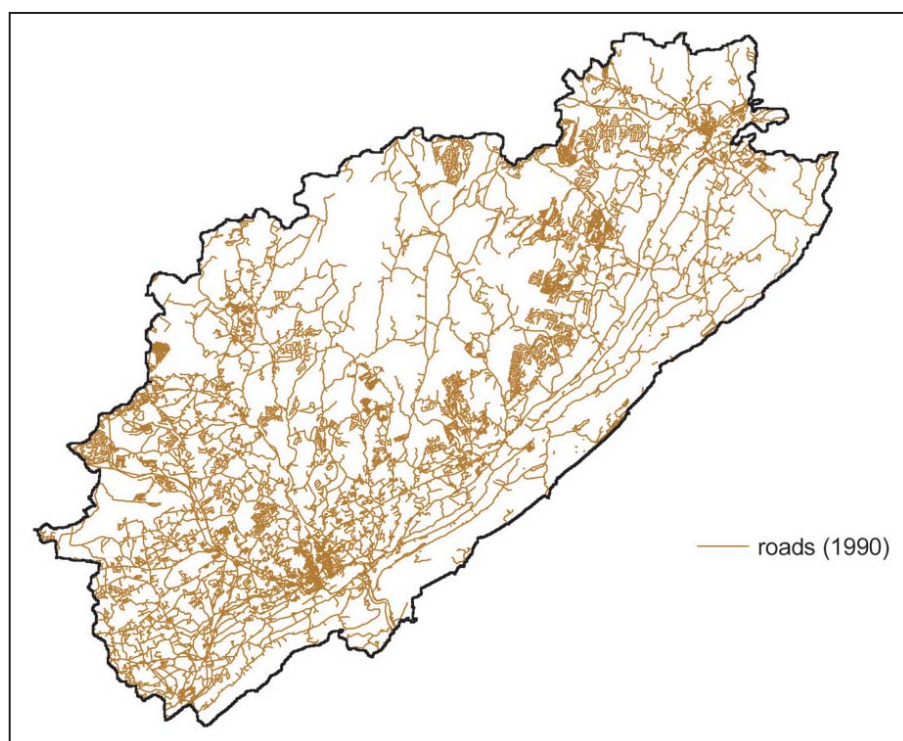


Figure 7.4.—Human impact described by local road density—example from the Delaware Water Gap (IMRA) tributary watersheds.



established for accurately monitoring those measures that research had found were linked to changes in the forest ecosystem. Some of the data collected at FIA plot locations in other regions have the potential to tell us more about these impacts on forest ecosystem characteristics through the linking of fragmentation data to forest inventory data. However, the FIA data alone lack the information either to create maps of the results allowing spatial analysis of the situation or to link the fragmentation data with locations not coincident with the original plot locations.

#### **7.4 Limitations of Existing Monitoring Programs**

Although the monitoring by existing independent programs was useful in providing maps of regional characteristics or relating data collected at individual plot locations, each of the existing monitoring programs has limitations for developing regional assessments of fragmentation and its effects on aquatic ecosystems. Manual photointerpretation is too time-consuming for large areas except through probability-based point or area samples, which means no continuous data are available from which to summarize information for locations lacking interpreted aerial photography or for variables or scales not originally interpreted. There is also a lower limit to the area for which statistics can be accurately calculated. On the other hand, measures calculated from TM-derived fine-resolution land use/land cover datasets, while available over broad areas, are not necessarily consistent with reality at plot or stream locations on the ground and are highly dependent upon the accuracy of the original classification (e.g., Wickham et al. 1997). These classification datasets are rarely, if ever, checked for accuracy of the spatial distribution or configuration of classes or for the accuracy of land use composition data over the small areas frequently of interest with forest fragmentation. In addition, the types of areas of particular interest in fragmentation studies include those in which residential land uses are occurring in previously forested land and those areas that have a lot of edges between different land uses—both of these have traditionally been difficult areas for TM-derived datasets to classify accurately.

Methods for providing maps of forest fragmentation and landscape context used in previous studies were based on imagery and data readily available over large areas, such as the 1992 National Landscape Characterization Dataset (NLCD'92). It was not known for what variables or to what extent these data could be scaled down to provide information relevant to individual streams, point locations such as FIA plots, or intensive research areas for which we have detailed forest and water measurement data. Similarly, where there were particular variables or parameters significantly related to changes in water quality, methods were needed to project that high-resolution information to a region—by relating it to the fragmentation and context information available over large areas, by improving the classification or resolution of what is available so that it is more strongly related, or by area-sample or point-sample interpretation of high-resolution imagery.

Many researchers and natural resource managers have observed that increasing development and other human influence on forested landscapes can harm forest ecosystems, and several parameters have been identified as indicators. Yet frequently we have only an elementary or local understanding of specifically how fragmentation, changes in forest context, and increasing proximity of forest to developed land uses are related to changes in water quality, aquatic habitat, forest composition and structure, incidence of invasive pests, and changes in forest chemistry. Although we can measure urbanization and forest fragmentation in several

different ways, and we have identified many potential impacts of these conditions on forest ecosystems, there is no clearly articulated body of knowledge relating scales and measures of fragmentation with specific types, degrees, and thresholds of changes in terrestrial and aquatic resources—details that are important if we are to make management decisions to address these changes. In addition, the links between currently monitored fragmentation measures, the scale at which forest fragmentation is measured, and the impacts of fragmentation on forest characteristics and ecosystem processes are tenuous at best. As a result, it is difficult to scale up the fine-scale factors to regional levels or to be sure the lower resolution information is accurate enough to address the process-level questions. The goal of the Delaware CEMRI was to develop a collaborative ground-based monitoring program that would significantly improve our ground-truthing capabilities for remote sensing interpretations of the DRB and improve the accuracy of those interpretations.

Coordination between Federal natural resource agencies, State and local regulators, and research units was also very weak before the Delaware CEMRI, limiting the connection between those monitoring forest fragmentation and those involved in regional surveys and process-level studies of water quality, invasive pests, multiple stressors on forests, and other issues of interest to resource managers. The result was fragmentation statistics and maps that were not necessarily relevant to managers, planners, policymakers, or researchers working with those issues. This situation occurred because those making the maps did not know which measures were actually indicators of potential changes, did not know which thresholds were important, did not know the level of accuracy sufficient for process-level studies, and provided measures of sufficient complexity to make it difficult to hypothesize the source cause(s) and thus determine and influence the relevant parameters through policy and management. During the Delaware CEMRI, the National Water Quality Assessment (NAWQA) program was assessing the effect of urbanization on water quality in the DRB using a gradient-based survey approach. Land use interpretations in the watersheds being studied were based on Landsat imagery without sufficient consideration of its applicability and accuracy and did not include detailed fragmentation statistics. Detailed analysis of fragmentation in the NAWQA watersheds as part of the Delaware CEMRI significantly increased their capability for the effects of urbanization and fragmentation.

Finally, there were no standard protocols for classifying most remotely sensed imagery into land use-land cover classes to evaluate forest fragmentation. As a result, significant differences exist between available datasets because of different minimum mapping units, classification methods, and class definitions. The consequences were frequently substantial differences in the calculation of urbanization and forest fragmentation around fine-scaled features (Fig. 7.5).

Without the benefit of integrated regional monitoring linked with intensive site-level research, and the benefit of improved linkage between natural resource agencies specializing in forests and water, our understanding of the status and impacts of urbanization and forest fragmentation as well as the links between fragmentation and terrestrial and aquatic characteristics were based on best guesses about the factors that drive fragmentation and its effects. A comprehensive effort combining new monitoring technologies and techniques being applied by existing programs with up-to-date, accurate land use and land cover datasets, as well as other sources of information about the impacts of fragmentation from intensive study sites, was required to develop an effective monitoring protocol.

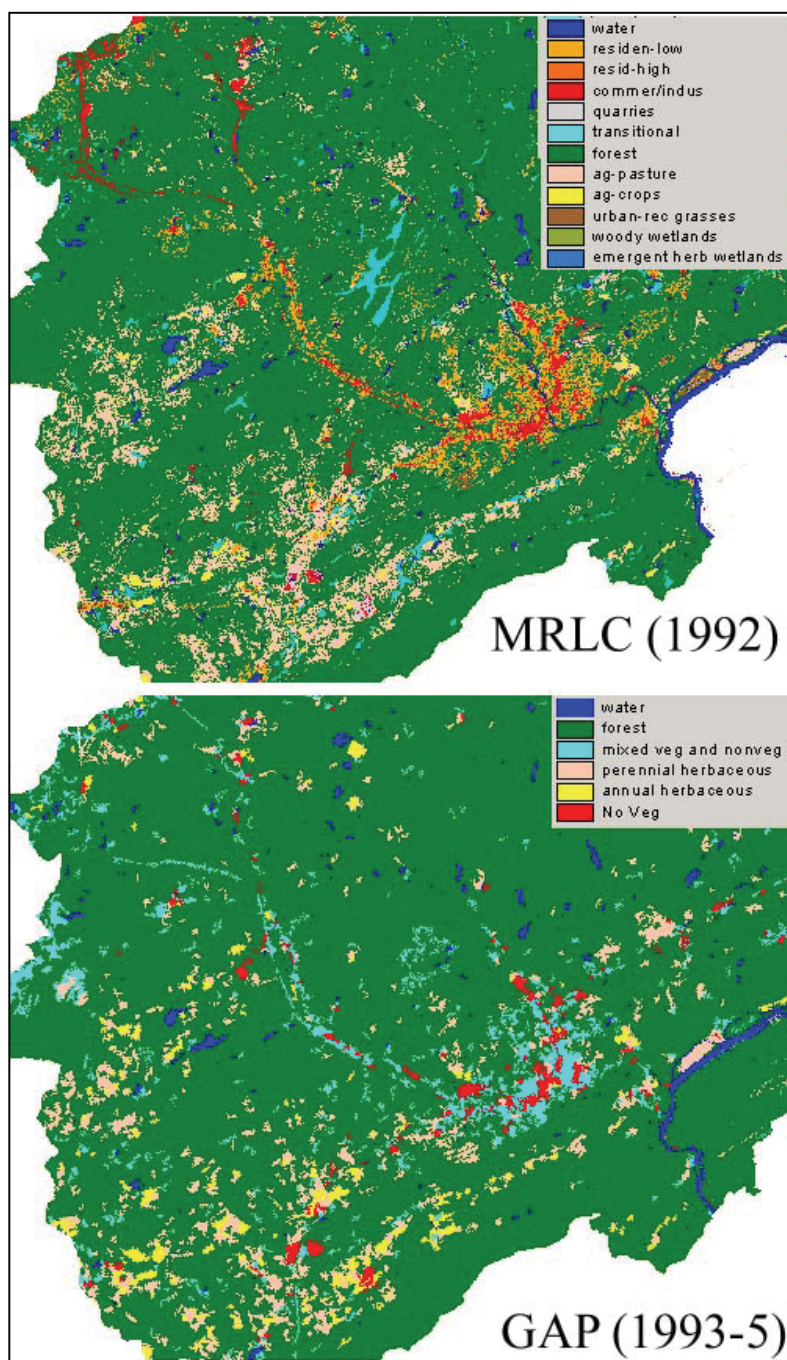


Figure 7.5.—Two land cover-land use maps for the Delaware Water Gap IMRA, both derived from TM imagery but classified by two different sources. These differences in land cover-land use classifications would affect summaries of fragmentation and landscape composition.

## 7.5 The CEMRI Program for Monitoring the Status and Impact of Forest Fragmentation

A summary of the components of an effective research and monitoring plan to address the status and impacts of forest fragmentation is presented in Table 7.1. The knowledge gathered during this research was applicable to all tiers of the framework. The French Creek and Delaware Gap IMRAs were chosen in part because residential development has been occurring rapidly outside the park and the greater Philadelphia area, and there is concern that development might affect water quality (Fig. 7.6).

**Table 7.1.—Key variables and analyses for assessing the status and trends of forest fragmentation**

Tier 1: Intensive sites

Relationships between land use type and temporal fluctuations in water quality/quantity

Relationships between development, forest condition, and temporal fluctuations in water quality/quantity

Tiers 2 and 3: Gradient sites and regional surveys

Relationships between landscape characteristics and water quality/ quantity

Relationships between land use type and sediment

Relationships between forest patch size/context and water quality/ quantity

Relationships between measures of urbanization and fragmentation and water quality/ quantity

Define exports (especially nitrogen and sulfur, maybe phosphorus, potassium K, other) from different development, logging, etc. scenarios

Water quantity and quality, and sediment

Flora and fauna surveys

Tier 4: Remote sensing and mapping

Atmospheric deposition

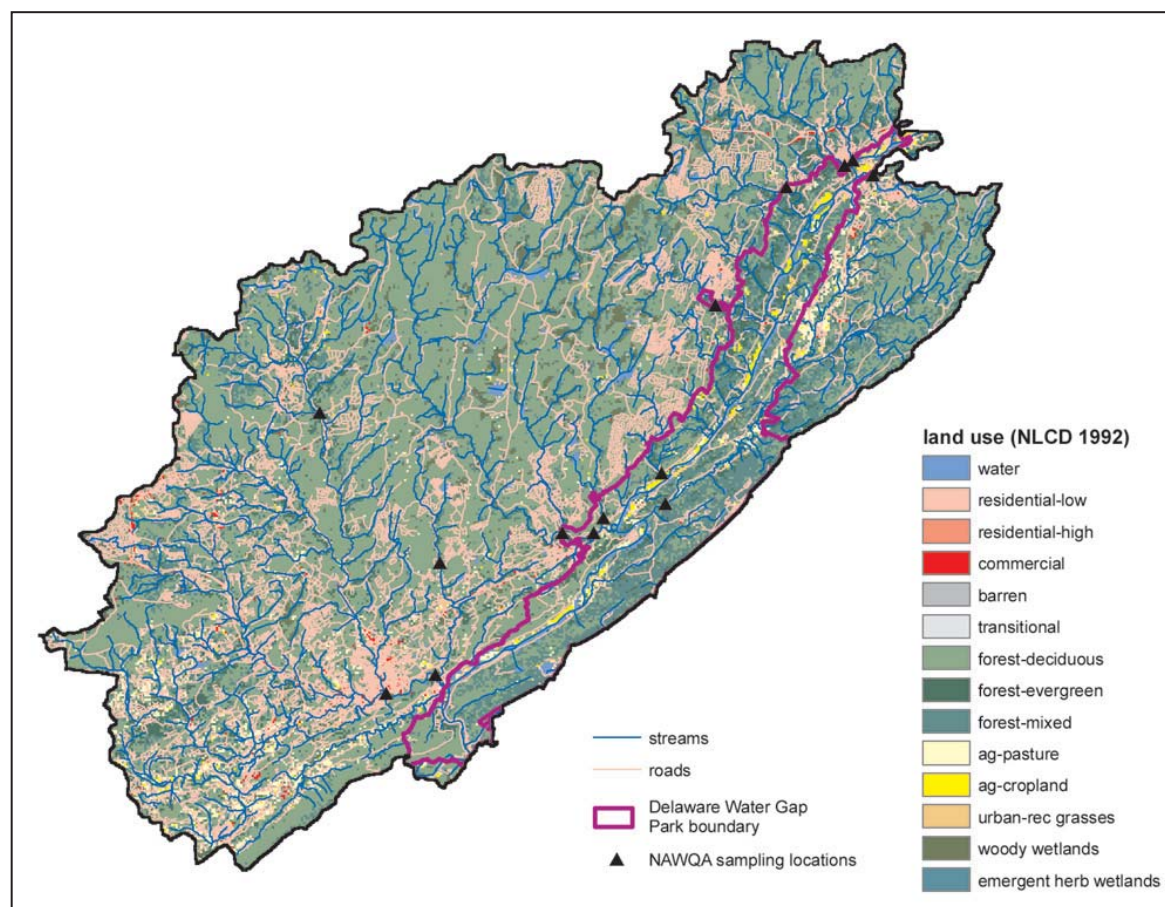


Figure 7.6.—Map of streams, development, park boundary, and NAWQA sampling points within the area.

### **7.5.1 Intensive Site Research and Monitoring (Tier 1)**

Joint research activities among the participating agencies were established within each IMRA, but were focused on the tributary watersheds draining through the Delaware Gap NRA where development surrounding the park has become the most pressing environmental issue. A joint USGS-National Park Service (NPS) project to characterize the water quality of the tributary streams at the boundary of Federal and private lands was established in the second year of the Delaware CEMRI. Stream samples were collected approximately monthly except during the winter and analyzed for major ions, pesticides, and indicators of suburban runoff (boron, bromide, chloride, caffeine) (Fig. 7.6). These sampling points defined the watersheds for which the USFS developed land use, land cover, and fragmentation data from high-resolution aerial photography. Intensified ground-based sampling of forest condition was established within three of these watersheds representing high, medium, and low degrees of development, and the USGS established stormwater sampling for a 1-year period on the two of these watersheds that represent the highest and lowest development intensity. Stormwater samples were analyzed for nitrate, chloride, sulfate, boron, and dissolved and total organic carbon.

Intensification for the forest fragmentation issue in the other IMRAs was limited. Stormwater sampling was established as part of the Delaware CEMRI, and habitat and invertebrate assessments were conducted by the NAWQA program at the mouth of the main river draining each area. A USGS streamgauge provided multiple years of 15-minute flow records at each monitoring station. These data, and the intensified network of FIA forest plots established within each IMRA, served as a ground-truthing database for the aerial photointerpretation, and the intensive streamwater data provided a temporal context within which the gradient study of fragmentation-water quality relationships described below could be assessed.

### **7.5.2 Gradient-based Data Collection Network (Tier 2)**

The NAWQA program established measurement stations at selected sites along a gradient of development intensity, where water and sediment sampling and habitat assessment have occurred during the past 3 years over a range of seasons and flow conditions. The effects of forest fragmentation and human development context on the water chemistry, sedimentation, aquatic habitat and aquatic wildlife populations of streams draining these watersheds were analyzed through a combination of field data collected by collaborating programs and modeling techniques. To pull together this information on the impacts of forest fragmentation, we used gradient surveys established by the NAWQA program in the summer of 2001, the NPS monitoring activities in the DEWA, USGS district research and monitoring activities associated with the CEMRI in the summer of 2002, detailed photointerpreted data on fragmentation, and regression modeling. Datasets of fragmentation indicator variables were developed for each of the selected study watersheds, and correlations were established between those indicators and aquatic chemistry, flora, and fauna.

### **7.5.3 Regional Survey Monitoring (Tier 3)**

Terrestrial ecosystem effects of forest fragmentation were investigated using the forest composition, structure, and condition measurements currently collected on FIA plots. Selected phase 3 plots were visited by a USFS research botanist, and additional data were collected on exotic and invasive species using two different detection methods. The results of these studies were linked to the landscape-scale variables of recreation, forest fragmentation, and urban gradients to allow the development of recommendations for how to collect exotic species information on FIA plots.

Probability-based stream surveys were conducted within each of the IMRAs and for the Catskill Mountain region of the upper DRB as part of the Delaware CEMRI. The data collected were used to create cumulative frequency curves for selected chemical constituents known to increase in river water with increased suburbanization. The surveys thus allowed investigators to assess what portion of the population of stream reaches within the IMRAs were represented by the intensive monitoring stations.

#### **7.5.4 Remote Sensing and Mapping (Tier 4)**

One of the first products of the CEMRI research on forest fragmentation and its effects was a map of land use and land cover using classification most appropriate for summarizing and calculating indices of fragmentation and context, and using a scale most appropriate for describing fragmentation in the DRB. Several data sources were examined: 1) high-resolution imagery (in this case 1:24,000 color infrared or 1:40,000 panchromatic digital aerial photography), 2) 30-m TM imagery from Landsat 7 (both in-house and existing land use/land cover classifications), and 3) a combination of TM and higher resolution satellite imagery. In the photointerpretation of the high-resolution imagery, additional land cover information was interpreted and attributed to each urban polygon. Data generated from the high-resolution imagery was used to help accurately assess and iteratively classify the TM-derived classifications if necessary.

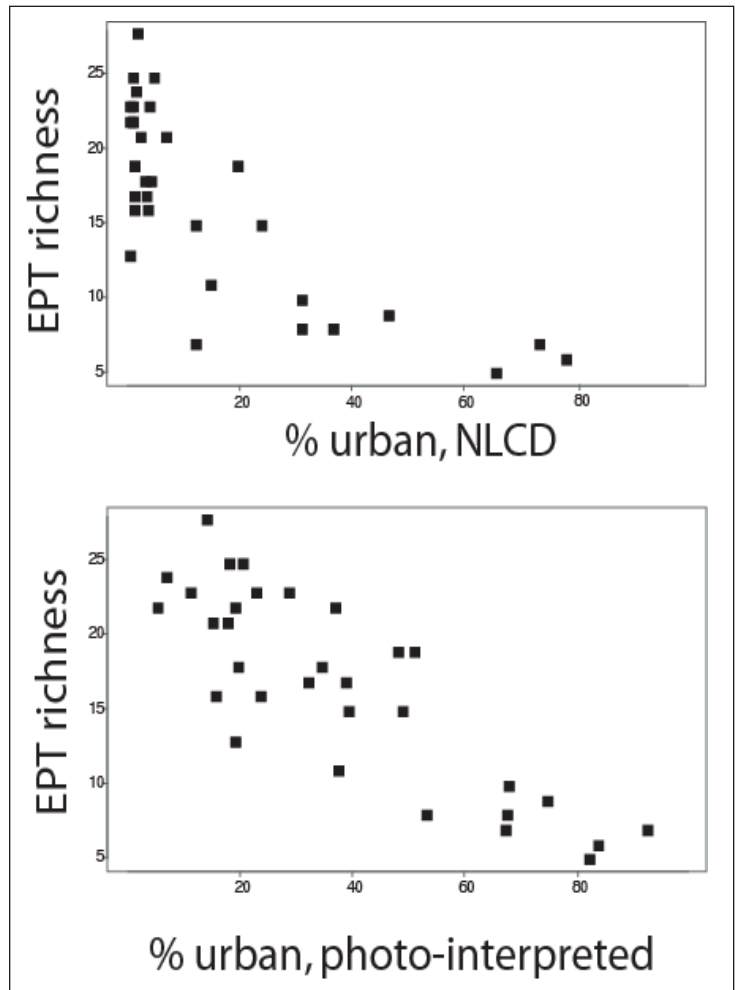
From this manually photointerpreted or digitally classified information, we summarized and calculated a variety of urbanization and fragmentation measures, focusing on those that have particular relevance to water quality as well as those suspected of being of general relevance to changes in forest composition, structure, health, wildlife habitat/use, invasive pests, forest chemistry, and multiple stressors.

Data from other sources, such as the USGS National Hydrologic Database (NHD) and TIGER/Line roads database were also used in this analysis. Statistics were calculated for local areas (e.g., around plots, research sites, and streams), sub-watersheds and watersheds. Emphasis was placed on those indicators that describe real differences in the landscape and that are less sensitive to small differences in manual and automatic interpretation that may unavoidably occur during any classification conducted at two different times. In addition, both point-sample and area-sample approaches were simulated using the data from the manual interpretation of digital aerial photography to determine what intensity of sampling would be necessary to generate accurate summary information for watersheds, by either of these two methods, for those measures that are poorly captured by the TM-derived data sources. Final interpretations of remote imagery were mapped to overlay on the USGS National Hydrologic Dataset of hydrology and a linked digital elevation model for topography.

#### **7.6 Preliminary Results**

Analysis of macroinvertebrate and stream chemistry data along with forest fragmentation and landscape composition data from interpretation of color infrared aerial photography showed a much stronger correlation between declining water quality and increasing urbanization and forest fragmentation than was possible using land use data derived from satellite remote sensing, even at relatively low levels of disturbance (Fig. 7.7)(Murdoch et al. 2003). The remote sensing data source had a large influence on the response pattern observed, especially at lower levels of disturbance, which was due partly to an underestimation of residential and

Figure 7.7.—Patterns of correlation between an indicator of water quality (EPT richness) and two different remote sensing datasets: National Land Cover Data (NLCD) from the Landsat Thematic Mapper, and color infrared aerial photography.



other urban-developed land uses in areas of high tree cover in the TM-derived data source. The correction of the more widely available satellite land use/land cover data by overlaying road density information, and correction of the widely available percent impervious information by incorporating road density, holds promise for broader scale studies of forest fragmentation and urbanization in similar settings. The collaboration of two existing monitoring programs provided significantly improved and refined understanding of the effects of changing land cover on stream-water quality.

This study helped determine to what extent current TM-derived land use/land cover classifications are sufficient for quantifying parameters of forest fragmentation, and whether the addition of more sophisticated classification techniques or higher resolution satellite imagery increases the spatial and class accuracy of the TM-derived classes sufficiently to improve ability to provide information on fragmentation, context, and proximity to fine-scale features such as streams, vernal ponds, FIA plots, and IMRA sites. This study established guidelines on what TM classification protocols or requirements can be suggested to improve the ability of TM-derived datasets to provide such fragmentation and context information, in terms of both the spatial resolution of the imagery and the classification resolution and class types. Finally, because manual interpretation of high-resolution imagery is necessary for some important indicators, this study established some guidelines concerning what sampling intensities are necessary to effectively capture that information.

## 8.0 INTEGRATING THE EFFECT OF TERRESTRIAL ECOSYSTEM HEALTH AND LAND USE ON THE HYDROLOGY, HABITAT, AND WATER QUALITY OF THE DELAWARE RIVER AND ESTUARY

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*Peter S. Murdoch, John L. Hom, Yude Pan, and Jeffrey M. Fischer*

To complete the collaborative monitoring study of forested landscapes within the DRB, the data collected for each of the issues described in previous sections must be used to improve our regional perspective on the cumulative effect of different disturbances on overall ecosystem health. This section describes two modeling activities used as integrating tools for the CEMRI database and a validation system that used nested river monitoring stations.

### 8.1 Background

One limitation of regional surveys is that we simply cannot afford to measure every possible variable at every site. Part of the justification for monitoring at fixed sites is that it provides the opportunity to measure a wider variety and complexity of variables (e.g., measurements of ecosystem processes and their driving variables). However, if the measurements are made at only a few fixed sites, there will be insufficient information to determine their regional significance and distribution. Remote sensing products provide a wall-to-wall spectral image of a region, but those spectral data are of limited use without rigorous ground-truthing of our interpretations of the spectral signals.

The key to the integration of field data collected at varied temporal and spatial scales is the development of correlative or process-based models from intensively studied areas and the application of those models at the regional scale where only sparse datasets are typically available. The only requirement is that the data necessary to run the models be available (or obtainable) from the intensive sites and from regional surveys or other regional sources (e.g., mappable fixed-site data, remotely sensed imagery). Sometimes this requirement may lead to simplification through calibration of the models to the more readily available data. A key characteristic of the proposed framework for collaborative monitoring is that it allows the iterative improvement and modification of multiscale models. This process can confirm the linkages between cause and effect on a regional scale and can be used to predict and evaluate regional environmental problems.

The mass balance paradigm (typically applied to watershed input-output chemical budgets) provides a second mechanism for scaling up information developed at the index areas to larger regions. This, too, is integration across space. In the nested watershed approach, large basin monitoring stations include smaller watershed sampling locations within their drainage boundaries. Exports from these smaller watersheds and information on within-watershed aquatic and terrestrial characteristics can then be used in transport models to predict chemical exports at the larger watershed station downstream, as data from the large basins can be used to create estimates of inputs to downstream water bodies (e.g., estuaries, Great Lakes, and coastal zones). The same conceptual approach has been used for scaling up process and trends information on air quality to broad regions, given secondary stratification along source and pollutant concentration gradients (CENR 1997). Statistical modeling and mass balance methods can be used in nested basins to measure the effect of specific upstream regions or land use types on the ecosystem health and water quality at larger river stations downstream

(Alexander et al. 2000). Both the regionally distributed and nested watershed approaches to integrating environmental information will be tested as part of the DRB CEMRI.

Process-based forest ecosystem models, such as PnET and the Terrestrial Ecosystem Model (TEM), can provide a way to integrate monitoring and research data collected at a range of scales for addressing issues such as the effects of nitrogen (N) deposition and land use changes on forest productivity, forest health, and surface water quality. The objective of the CEMRI modeling effort was to improve our ability to integrate monitoring information across resources and scales for assessing the extent and causes of environmental change in forested and partially forested landscapes. To do so, the model outputs for net primary production (NPP), biomass, carbon (C), water yield, and water quality must therefore be scalable from the plot level to the regional watershed.

As part of its overall mission, the U.S. Geologic Survey (USGS) National Water Quality Assessment (NAWQA) program seeks to quantify the effects of land use and land use change on the quality of water and biota in the Nation's river and estuary systems (Gilliom et al. 1995). The NAWQA program has been supporting development of the SPARROW (Spatially Referenced Regressions on Watershed attributes) model as a tool to relate in-stream water quality measurements to spatially referenced characteristics of watersheds, including contaminant sources and factors influencing terrestrial and stream transport using a nested index watershed approach (i.e., subwatersheds with a specific dominant land use; Alexander et al. 2000, Smith and Alexander 2000). Initial versions of the SPARROW model were designed to estimate exports for regions encompassing multiple large watersheds. Refinement of the SPARROW model to provide export estimates for single large or medium watersheds requires the availability of detailed export and land use data for multiple locations within a single river basin.

Efforts to assess the effects of land uses and proposed land use changes can be significantly improved by developing and applying a consistent geospatial database that links the water quality information in State and Federal databases with point and spatial information (e.g., vegetation, land use, diversions). The NAWQA program used the data-rich environment of the DRB CEMRI to improve the SPARROW model (Chepiga et al. 2002).

## **8.2 Model Descriptions and Regional Assessment Capability**

Two models will be tested as the primary tools for integrating forested landscape data in the DRB: the SPARROW model developed by the USGS, and the PnET model developed by the University of New Hampshire and the USFS. The current status of these two models and their limitations is described below.

### **8.2.1 The SPARROW Model**

The SPARROW model was used as a tool for cross-linking data from different programs collecting environmental data within the basin. The model can link process data from small-scale watershed studies with monitoring data from large-scale river sites. It used an empirical model to evaluate the CEMRI data collected on a watershed-wide basis in forested and partially forested landscapes, and it linked that modeled export to estimates developed by the NAWQA program for urban and agricultural landscapes. In this way, the model created overall estimates of watershed export of chemical constituents within the DRB. The model output was then compared to measured export values computed at USGS monitoring stations nested within the DRB (Chepiga et al. 2002).

The SPARROW model has been used at a national level to relate land use patterns to water quality indicators by identifying land use or climate factors that influence water quality (Alexander et al. 2000). The model provides a statistically valid approach for examining factors that affect transport and losses of nutrients both overland and in-stream. The model is not used for temporal analyses, but rather provides a detailed snapshot of water quality processes. Although the national model provides a valid approach for assessing non-point source impacts, it has several limitations that restrict its usefulness on a regional or local level.

The national SPARROW model uses the RF1 (River Reach File Version 1) river reach file with a scale of approximately 1:500,000, which limits the model to watersheds of about 60 mi<sup>2</sup> or larger. Recently modeled estimates of N export from rivers draining into the Chesapeake Bay have shown that smaller watersheds have higher in-stream losses of nutrients than are predicted by the model (Preston and Brakebill 1999). For the CEMRI, SPARROW was refined to include more accurate stream delineation in smaller watersheds (20 mi<sup>2</sup> or less). Inclusion of smaller watersheds allowed data from many research sites to be used and facilitated the use of the model as a tool for integrating data from small-scale watershed-process studies with data from larger watershed monitoring stations. Having more data available for input to the model increased the statistical validity of model results for the larger watershed. The main problem with the national modeling approach is that the existing RF3 (1:100,000 scale) reach coverage does not offer sufficient detail at the regional scale and does not have flow or travel times associated with each stream segment (J. Fisher, U.S. Geological survey, oral communication 2002). Thus, smaller scale stream segment data had to be independently generated. The National Hydrography Dataset (NHD) developed by the USGS for the DRB as part of the collaborative effort provided the detail needed. The NHD is a 1:24,000 river reach dataset with full GIS capability (USGS 1999). This NHD for the Delaware was compiled and referenced to a 30-m digital elevation model (DEM) and to a 10-m DEM in selected portions of the watershed.

To date, the SPARROW model has shown that land-to-water delivery losses of nutrients are significant. The processes responsible for these losses, however, are uncertain. Some of this loss is storage and transport in ground water systems (Chepiga et al. 2002). It is expected, and recent studies have suggested, that on local and regional scales topography and soil types are important factors in transport processes (Wolock 1999). In addition, the distance of a particular land use from a stream channel or point of measurement influences transport and attenuation processes. By combining land use, soils, topography, and distance in a GIS-based weighting scheme, it is possible to determine what factors control overland transport of specific chemical constituents. Including these factors in a regional SPARROW application facilitated a more rigorous exploration of land-to-water processes.

**8.2.2 The PnET Model** Ecosystem process modeling for the DRB was derived from a combination of the CEMRI database and existing work based on climate change scenarios and N deposition on forested regions of the mid-Atlantic and Chesapeake River Basin (Hom et al. 1998, Pan et al. 1999) using the PnET family of models. The PnET model is a process-based ecosystem model that uses spatially referenced information on vegetation, climate and soil to make estimates of important variables of forest ecosystems such as C storage, NPP, water yield, and N leaching loss. The PnET model has several variants—PnET-II, PnET-CN, PnET-BGC, and PnET-

Day—for different simulation needs and scales (Aber et al. 1992, 1993, 1995, 1997b; Aber and Driscoll 1997a). The model is validated for NPP and water yield predictions at locations within the Northeastern U.S. (Ollinger et al. 1998). In addition to general input information, the model also requires data on N deposition, ozone ( $O_3$ ), and atmospheric carbon dioxide ( $CO_2$ ) to examine the impact of changing atmospheric chemistry on forest ecosystems.

The PnET-II model includes a spatially explicit modeling capability. We used PnET-II together with the GFDL-30 and UKMO global climate model scenarios to predict the effects of climate and a doubling of atmospheric  $CO_2$  on NPP and water yield for the mid-Atlantic region. Initial model results showed an overestimate of NPP, primarily in the deciduous species when compared to NPP estimates developed from FIA data. Water holding capacity (WHC) was a sensitive parameter in this application of the PnET-II model, but water yield predictions validated well with surface runoff maps under contemporary scenarios using the WHC for the 0- to 50-cm soil depth (Kern 1995, Krug et al. 1988).

PnET-CN incorporates coupled C and N cycling into the model. Using PnET-CN, we predicted the role of forests in watershed N retention to be 86 percent in the Chesapeake Bay Watershed, with an average leaching loss of  $1.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$  (Pan et al. 1999). PnET-CN was modified to simulate regional NPP in the mid-Atlantic region (Pan et al. 2004). Spatially referenced forest types, monthly minimum and maximum temperature, monthly precipitation, monthly solar radiation (PAR), and soil WHC are regular input data layers for the GIS version of the model.

PnET-BGC is a recent incarnation of the PnET model developed by researchers at Syracuse University to simulate biogeochemical transformations of water as it moves through vegetation, soil, and stream environments in forested watersheds as a result of varying natural condition, land use change, and deposition input scenarios (Gbondo-Tugbawa et al. 2001). The PnET-BGC model simulates both abiotic and biotic processes, and model output integrates the effects of disturbance on the biogeochemistry of both the terrestrial and aquatic systems. Perhaps most importantly for the CEMRI, the PnET-BGC model expands the PnET capability to include simulation of abiotic and biotic processes that influence base cation mobility and transport, and thus could be a tool for assessing the regional extent of soil calcium (Ca) depletion. This version of PnET, like the others, is designed to predict ecosystem change in small research watersheds, but could be enhanced to provide output useful for making regional assessments of cation depletion.

### **8.3 The CEMRI Program for Integrating Data Across Spatial Scales Through Modeling**

The combination of the empirical SPARROW model and the process-based PnET models provided a powerful and complementary modeling support system for a regional collaborative monitoring program in forested landscapes. Programming these models to provide meaningful results at the scale of the DRB, or the mostly forested northern subbasin that drains the Appalachian Plateau, required a scaling down of existing capabilities for the SPARROW model and a scaling up of the modeling capabilities of the PnET-CN model. These contrasting requirements allow the CEMRI to address the technical issues involved in moving up and down from the scale of data collection to the scale of interest. A brief description of the model application for the CEMRI is provided below.

## 8.4 Application of the SPARROW Model to Address Regional Nutrient Transfer

The SPARROW model as currently designed was used to explore factors that affect nutrient transport in the DRB. Major refinements developed for the model to make it more useful at a regional level include the following:

- An improved stream network coverage (1:24,000) so watersheds smaller than 60 mi<sup>2</sup> can be incorporated
- Topographic and distance weighting factors for different land uses to simulate more realistic watershed processes
- An Access database for data preprocessing and manipulation
- Detailed land use and ecosystem condition data from the integrated monitoring network of the CEMRI

SPARROW modeling was used in the DRB to:

- Integrate data at different scales from various agencies as part of the CEMRI effort
- Assess the influence of landscape condition (e.g., fragmentation, infestation by pests, reduced forest health, acid deposition) on downstream water quality and water yield

### 8.4.1 Approach

SPARROW modeling was a major part of the NAWQA contribution to the CEMRI effort. USGS personnel on the Delaware NAWQA study developed the datasets and ran the model. Development of slope and distance weighting factors was coordinated with ongoing efforts in the USGS New Jersey District office. Acquisition of datasets from other agencies was coordinated through the NAWQA/CEMRI effort. Work was conducted in four phases:

- 1) Development of regional datasets and conducting regional analysis using national model output
- 2) Development of smaller scale stream network and distance/slope weighting factors for the DRB model
- 3) Incorporation of NAWQA, CEMRI, and other agency data into the model for regional analysis
- 4) Comparison of the results of the SPARROW modeling to measured export at selected USGS monitoring stations within the DRB

The initial step in this process was to extract data from the national SPARROW model that are pertinent to the DRB and to develop a model for the DRB on that initial national-scale data. The main datasets needed for developing the model included the following:

- 1) Stream networks at an appropriate scale
- 2) Delivery factors (e.g., temperature, precipitation, land use, soil permeability, slope/distance weighting factors)
- 3) Point-source discharges
- 4) Non-point-source loads (e.g., agricultural and atmospheric deposition, land use)
- 5) Stream nutrient loads based on data collected by various agencies and the CEMRI surveys
- 6) Soil chemical characteristics identified in the CEMRI surveys

7) Incorporation of USDA-STATSGO maps of soil condition and chemistry for the assessment watersheds

For the model to be successful, smaller scale river-reach data were independently generated. The National Mapping Division (NMD) of the USGS provided the first regional version of the NHD to support CEMRI. The NHD is a vector format GIS database providing 1:24,000 stream reach coverage. This database was linked to a 30-m DEM coverage for the river basin and a 10-m DEM for selected IMRAs to provide the base map for other GIS coverages developed as part of the CEMRI. Flow and travel times for each stream segment were estimated using ArcGrid. The improved coverage allows use of data from basins about 15 mi<sup>2</sup> or larger. To the extent possible, this work was coordinated with USGS personnel working on the Chesapeake and New England SPARROW models.

Many of the basic datasets were available (e.g., temperature and precipitation) and were retrieved as part of the Delaware NAWQA project. However, some datasets needed to be developed. In particular, the soils and land use data were combined with the DEM data to determine distance and slope weighting factors for the various land uses, which is a straightforward, stepwise, but time-consuming procedure in ArcGrid. Stream-load data were calculated using the software package Estimator. Other datasets that would improve the precision of the model were developed through the CEMRI process where possible. For instance, the atmospheric-loading data for each assessment watershed were developed in cooperation with the USFS PnET modeling effort described later in this section.

Updated land use and point-source maps were obtained through the CEMRI because these inputs tend to change so rapidly. The USGS-NMD provided a 1997 land use map for the DRB as part of the collaborative effort. Recent MODIS maps were reclassified by the USGS and the USFS for linking to data from FIA plots within the basin. Land use maps were also obtained from local agencies. Point-source data were obtained from the Delaware River Basin Commission and various State agencies. Other agencies providing data to the SPARROW model included the following:

- 1) Pennsylvania Department of Environmental Protection
- 2) New York State Department of Environmental Conservation
- 3) New Jersey Department of Environmental Protection
- 4) Delaware Department of Natural Resources and Environmental Control
- 5) New York City Department of Environmental Protection
- 6) US Army Corps of Engineers
- 7) USGS Pennsylvania District
- 8) USGS New York District
- 9) USGS New Jersey District
- 10) U.S. Forest Service
- 11) USDA Natural Resources Conservation Service
- 12) USEPA Environmental Monitoring and Assessment program

#### **8.4.2 Anticipated Products and Benefits from SPARROW Modeling**

Development of a method for expanding RF1 and RF3 stream coverages to smaller watersheds and calculating flows and travel times was a significant contribution of national interest. Likewise, adding the slope and distance weighting factors to the SPARROW model helped define what land-to-water processes were important in transporting or retarding the movement of various chemical constituents. The CEMRI SPARROW modeling provided a more complete analysis of the NAWQA nutrient data. When combined with the additional data provided through the CEMRI effort, the SPARROW model improved our understanding of watershed processes that affect the transport and distribution of many chemical constituents of concern. Development of land use and distance/slope weighting factors improved our ability to predict the effects of future land use changes on water quality (Chepiga et al. 2002, Stolte et al. 2003).

### **8.5. Application of the PnET Model to Address Regional Nutrient Transfer**

#### **8.5.1. Approach**

The PnET model was applied to individual watersheds as part of the research to address the C- cycling, N-saturation, and Ca-depletion issues described above. In addition, the PnET-CN model was enhanced to assess combined effects of the different issues studied on regional ecosystem and water quality conditions. Several improvements to the potential output from the PnET suite of models were possible through the collaborative data collection strategy for the Delaware CEMRI. Parameters such as species-specific foliar N, commonly estimated using allometric equations for a given forest type, became available at the IMRAs for model development (Pan et al. 2004). Through funding provided by NASA, the USFS and the USGS reclassified MODIS imagery to define 10 forest types for the region where only 5 categories were previously defined, and they made those classifications consistent with the classification system for the FIA program (Pan et al. 2006). Detailed mapping of forest types in the Catskills by the Institute of Ecosystem Studies provided further detail for model parameterization in the Neversink IMRA (Driese et al. 2004). Research on soil fertility and its effects on tree health and productivity at the IMRAs further refined the PnET models for predicting changes in NPP. Regional extrapolation of the model output developed for the IMRAs was expedited by regional survey data from the FIA and regional stream surveys: soil C:N ratios, for example, are important to modeling forest C cycling but are typically not known on a regional scale. Streamwater quality data verified PnET estimates of stream chemistry at both the intensive site (NAWQA and IMRA stream monitoring stations) and the regional scale (NAWQA-and CEMRI-sponsored stream surveys) (Murdoch et al. 2003).

An enhanced version of PnET-CN incorporates N deposition GIS data directly, instead of having to interpolate from point measurements. A new 10-year averaged wet-deposition map with 250- m resolution developed by Pennsylvania State University replaced the single-year estimates currently used for deposition load parameters in the model (J. Lynch, Pennsylvania State University, written communication 2003).

To establish an effective long-term strategy for monitoring regional changes in forested landscapes, cost-effective methods for monitoring at IMRAs, survey, and remote sensing/fixed-site mappable data tiers must be defined. Detailed remote sensing data such as AVIRIS are becoming available for small areas of the U.S. but are currently costly and probably not a realistic option for areas outside the IMRAs. Less detailed information, such as that provided by MODIS and Landsat, is more readily available for the entire United States. Reclassifying the MODIS imagery for forested landscapes of the DRB increases the interpretive value

of the MODIS data, as does the systematic ground-truthing offered by the CEMRI for remotely sensed products.

The overlap of the MODIS, Landsat, high-resolution aerial photography, and AVIRIS imagery in the Neversink IMRA, combined with the detailed ground-based monitoring established there, allowed the CEMRI to test strategies for integrating the remote sensing programs to develop a national strategy for collecting high resolution, detailed data at IMRAs or areas of special concern, and nesting those datasets within broader, lower resolution coverages. The modeling of nutrient export, Ca depletion, C flux, and changes in NPP using the PnET models formed the necessary structure for linking the ground-based and remotely sensed data into a coherent monitoring and assessment plan.

### **8.5.2 Products and Benefits from PnET Modeling**

Several products and benefits, such as the following, have come or are being developed from the PnET models as part of the CEMRI strategy.

- Use of process-based spatial models to improve the capability of integrating monitoring information across resources and scales (Pan et al. 2004)
- Expansion of the PnET model's ability to incorporate regional stresses, such as Ca-depletion effects, on forests in and near intensive monitoring sites in the Delaware Basin (Stolte et al. 2003)
- Development of a "bottom-up" modeling method that directly incorporated the FIA and IMRA data for more precisely conceptualizing ecosystem processes (Murdoch et al. 2003)
- Testing of model validation methods by comparing the results from the integrated modeling to estimates of forest condition using FIA databases from the USFS and water chemistry analysis from USGS stream monitoring stations; these databases provided independent validation of model outputs (Murdoch et al. 2003)
- Parameterization of the PnET model for estimating forested landscape export of water quality parameters and providing a direct input to the SPARROW model to improve estimates of chemical exports to large rivers (in process)
- Intercomparisons among field measurements, models, and remote sensing products (MODIS) to combine observations from ground inventories, remote sensing satellites, and synthesis via process-based ecosystem models; the intercomparisons provided useful insight for developing scaling strategies in carbon research (Pan et al. 2006)
- Region wide comparison of PnET-CN process modeling with an empirical model, SPARROW, for N leaching and water yield in forested regions using standardized inputs generated from the DRB CEMRI (in process)

### **8.6 Validation of Model Results Through Existing Monitoring of Water Quality**

The monitoring stations along the main stem and tributaries of the Delaware River described above serve as nested IMRAs where detailed information on episodic and seasonal variability in stream load can be calculated. These river monitoring stations are being operated by the USGS in cooperation with State environmental monitoring programs, and represent a major contribution to regional environmental monitoring by State agencies (Fischer et al. 2004). Several States also conduct regional probability-based surveys of water quality, aquatic biology, and habitat condition in streams and rivers (Olson et al. 1999). These surveys,

designed through collaboration with EMAP, provide a regional map of aquatic ecosystem conditions. The existing surveys and river monitoring stations provided separate probability-based and nested-watershed estimates of water quality that further validated data for model results developed by the CEMRI multi-tiered monitoring approach. As part of the CEMRI, probability-based surveys and nested-site monitoring were supplemented to provide adequate regional data for validating the SPARROW and PnET modeling efforts in the upper DRB.

Throughout the nation, parallel monitoring programs are creating databases that, if integrated, would greatly increase our understanding of terrestrial-aquatic interactions. An exercise such as the CEMRI that addresses regional issues related to creating comparable load estimates in the DRB served as a model for developing common protocols or data-comparability systems nationwide.

### 8.7 Preliminary Results

Modeling forest biogeochemistry with the PnET-CN model showed how N leaching from forests is responsive to levels of N deposition, and indicated high levels of N leaching from forested landscapes to streams in the upper DRB (Fig. 8.1). The pattern of N deposition matched the soil Ca and stream acid neutralizing capacity maps generated by the CEMRI surveys, with the greatest amount of N leaching to streams in the western Pocono and eastern Catskill Mountains (Fig. 6.5) (Murdoch et al. 2003).

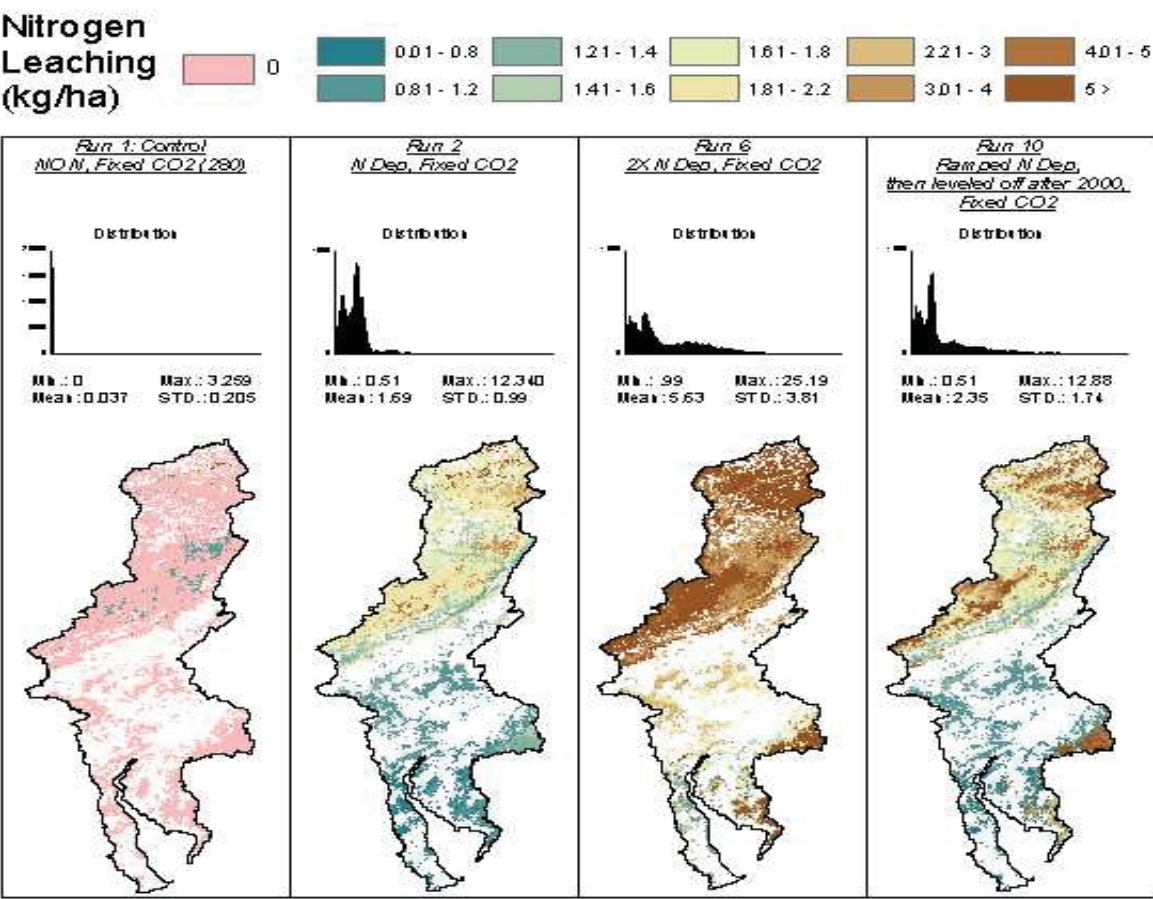


Figure 8.1.—Effects of scenarios of nitrogen deposition on nitrogen leaching as shown by the PnET-CN model. Compared with the control that shows almost no nitrogen leaching with no nitrogen deposition (Run1), nitrogen leaching at current deposition rates is about 2 kg per hectare (Runs 2 and 10) and significantly large with doubled current nitrogen deposition (Run 6).

## 9.0 CONCLUSIONS

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The Delaware River Basin (DRB) CEMRI effort described in this document points to several opportunities for national and regional collaboration strategies that could greatly improve the interpretive power of our environmental monitoring programs. Linking water quality data from deterministically selected, frequently sampled monitoring stations with regional survey data embeds the intensively sampled stations in a regional context and thus allows interpretations not possible if the data are collected in isolation. Likewise, linking terrestrial data on forest and soil conditions with data on surface water quality at local and regional scales has long been advocated by researchers but yet to be achieved in any systematic manner in the United States.

The Delaware CEMRI did not supply all the answers about effectively linking every one of the Nation's major environmental monitoring programs into a broad national database. Key programs that would logically be part of that national strategy did not participate in the DRB pilot test of the monitoring framework; some gaps in data collection and scientific analytical capacity were not filled by existing programs. However, the DRB CEMRI did provide a fairly comprehensive test of the framework concept for forested landscapes and sufficient evidence of the potential for collaborative monitoring strategies to justify an expansion of the concept to other regions of the United States. Resource managers need integrated whole-system assessments of environmental issues to develop effective management policy. They also need to understand how resources are linked to one another, and they must have access to information about how trends in one resource might be linked to trends in other resources. No one environmental monitoring program can afford to provide that comprehensive information: only through scientifically rigorous collaborations among programs will the needs of resource managers be met.

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The U.S. Forest Service, the U.S. Geological Survey, and the National Park Service formed the Collaborative Environmental Monitoring and Research Initiative (CEMRI) to test strategies for integrated environmental monitoring among the agencies. The initiative combined monitoring and research efforts of the participating Federal programs to evaluate health and sustainability of forest and freshwater aquatic systems in the Delaware River Basin (DRB). Forest ecosystem health issues addressed by the CEMRI effort include urbanization and forest fragmentation, productivity and carbon sequestration, nitrogen saturation and calcium depletion, vulnerability to exotic insects, and effects of interactions among these factors. Ongoing monitoring programs were enhanced with supplemental sampling locations and measurements, and models were developed or modified to associate intensive process-level information with extensive landscape-scale information from satellite, aerial, and ground monitoring systems. This paper discusses development of the CEMRI in the DRB and methods to address environmental issues across multiple spatial and temporal scales.

**KEY WORDS:** Environmental monitoring, forest fragmentation, carbon sequestration, nitrogen saturation, calcium depletion

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