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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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 mi2 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 mi2 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 kg ha^{-1} 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 mi2 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 mi2 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).

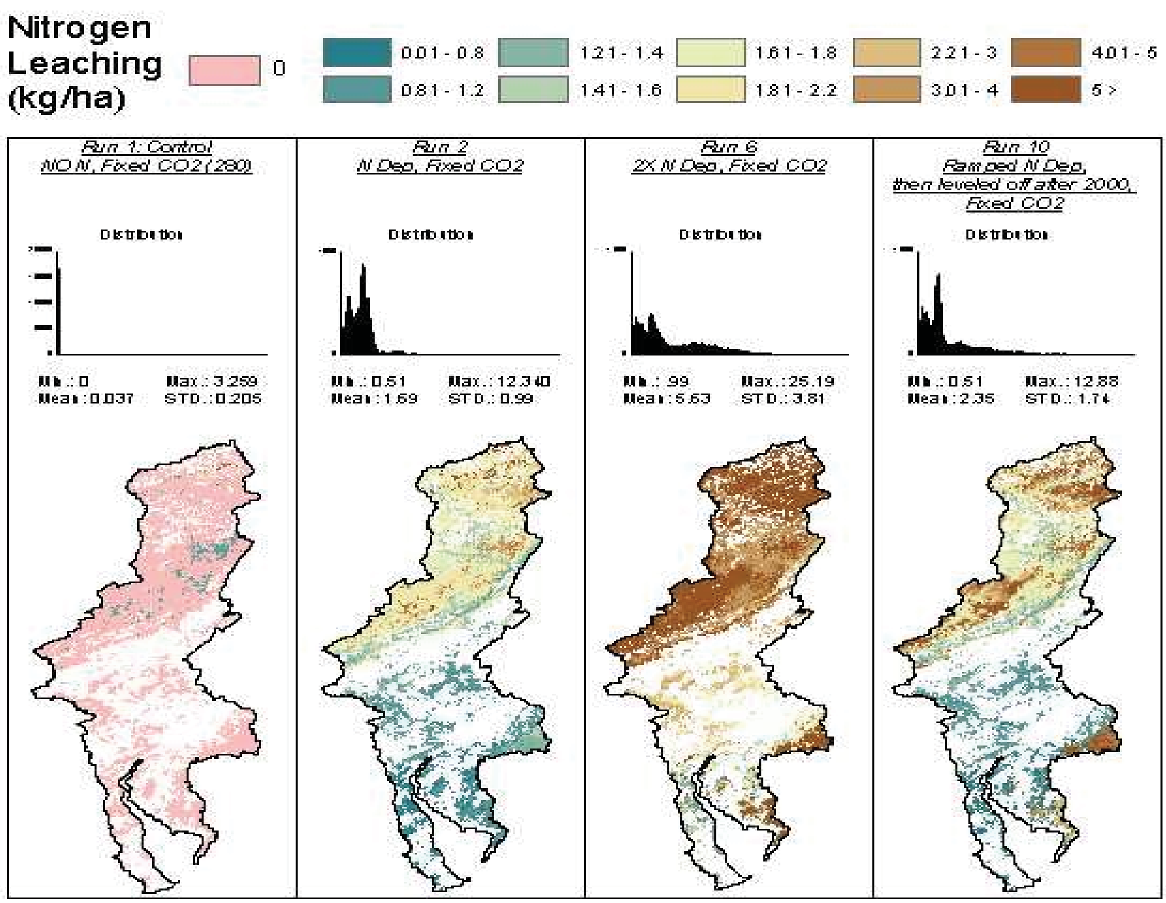

Figure 8.1.—Effects of scenarios of nitrogen deposition on nitrogen leaching as shown by the PnET-CN model. Compared with the control that shows almost no nitrogen leaching with no nitrogen deposition (Run1), nitrogen leaching at current deposition rates is about 2 kg per hectare (Runs 2 and 10) and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