Upper Midwest Lakes and Their Landscapes: 1800 to 2100

a proposal to the National Science Foundation
Division of Experimental Biology Long-Term Studies Program

from the
North Temperate Lakes
Long-Term Ecological Research Program

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PROJECT SUMMARY

Inland lakes are important features of the Upper Great Lakes region of North America. As collectors of water, solutes, and pollutants from overland or groundwater flow, as habitat for aquatic biota, and as attractors of human activities, lakes both affect and are affected by natural and human-induced changes in the regional landscape. The work proposed here will scale up the North Temperate Lakes Long-Term Ecological Research project to address the regional feedbacks that link lakes, landscapes, and human activity. Two primary objectives of the proposed research are to determine (1) whether and how dominant factors controlling lake ecosystems vary systematically as spatial scales expand from individual lakes, to watershed, to lake districts, to the Upper Great Lakes region, and temporal scales extend from years, to decades, to centuries; and (2) how natural and human-induced changes in the landscape have interacted with aquatic ecosystem structure and dynamics in the Upper Great Lakes Region over the past two centuries, and what changes can be expected over the next hundred years.

These objectives will be accomplished using several approaches. First, regional studies at a range of spatial scales will be used to determine large scale patterns and generality of smaller scale results. These studies will involve scientists and data from three other lake districts in the Upper Great Lakes region: the agricultural and urban catchments near Madison, Wisconsin; the Experimental Lakes Area of western Ontario; and the Dorset Research Area of eastern Ontario. Second, comprehensive site histories will be developed to evaluate past interactions between land use changes and inland lakes. These histories will include archived data and paleolimnological work coupled with detailed histories of land use in the lake districts. Finally, alternative scenarios for future land use-lake interactions will be developed and tested through cooperation of natural and social scientists. The work will be grounded in ecology, limnology, geology and water chemistry, but the context and feedbacks will be relevant to issues of conservation, economic development, sustainability, and ecosystem management.

The generality of key results from individual lake districts will be tested in other lake districts within the region. Specific issues for the next two years include the importance of landscape position in influencing lake dynamics, cyclic patterns of water clarity in lakes with simple fish communities, the utility of stable isotopes for assessing

water balances, and the potential impact of a generally warming climate on inland lakes. Models linking landscapes and lakes will also be developed. In the northern parts of the region major landscape changes have been associated with clearcutting of forests, subsequent regrowth, and increased development of seasonal and permanent houses on lake shorelines. Consequently, spatially explicit models linking water flow to lakes and biogeochemical cycling of forest ecosystems will be developed to determine potential impacts of various scenarios of changing climate and forestry practices on lakes. In the south, major changes have been transformation of savanna to agriculture and urban uses. Models linking surface flows to phosphorus input to lakes will be developed to test effects of alternative management scenarios.

Collectively, the understanding of landscape-lake-human interactions built by this study will be directly relevant to those making policies affecting the future of the Upper Great Lakes region.

PROJECT DESCRIPTION

Results From Prior NSF Support

Comparative Studies of a Suite of Lakes in Wisconsin

Grant #DEB9011660

The North Temperate Lakes Long-Term Ecological Research (NTL LTER) site, established in 1981, is currently in the fourth year of its third grant period. During the past 14 years we have designed and implemented a comprehensive study of seven lakes in the Northern Highland Lake District of Wisconsin and the surrounding landscape. As evidenced by the 105 peer-reviewed publications produced in the last five years, we have made significant advances in the understanding of lakes and their landscapes (Fig. 1). A complete publication list for our project is given in the bibliography.

Some of our most significant accomplishments in the past five years include:

Continuation of the collection and management of a high-quality, comprehensive, long-term data set on the physical, chemical, and biological properties and processes of the 7 lakes and the surrounding landscape (Magnuson and Bowser 1990).

Quantification of groundwater/lake interactions using stable isotopes and numerical modeling at individual lake and landscape scales (Krabbenhoft et al. 1990a,b, Bowser 1992, Kenoyer and Bowser 1992a,b, Anderson and Cheng 1993, Cheng and Anderson 1993, Krabbenhoft et al. 1994).

Identification of the roles of landscape position and spatial heterogeneity in explaining interannual variability of lake dynamics at local (Benson and Magnuson 1992) and landscape (Magnuson et al. 1990, 1991, Kratz et al. 1991a, Kratz et al. in press,) scales.

Assessment of how level of taxonomic aggregation of data influences ability to detect responses of lake ecosystems to stress (Frost et al. 1992, Carpenter et al. 1993, Kratz et al. 1994).

Development of approaches and protocols for using remote sensing to map land cover on a statewide basis for Wisconsin (Bolstad and Lillesand 1992a,b,c, Lillesand 1993a,b,).

Use of ice records on lakes as past and future climatic indicators (Robertson et al. 1992, Wynne and Lillesand 1992, Wynne and Lillesand 1993).

Identification and rough quantification of the role surface waters play as conduits for terrestrially fixed carbon to the atmosphere (Cole et al. in prep., Kratz and Bowser in prep.).

Elucidation of the dynamics of species richness and assemblage structure in inland lakes (McLain and Magnuson 1988, Tonn et al. 1990, Magnuson et al. in press).

In addition to direct scientific accomplishments, our LTER site has been highly successful in catalyzing interactions with other scientists. The potential for interacting with LTER researchers and the associated data bases has been a key factor in generating this interest. In the past five years alone more than 35 associated research projects, with total funding exceeding $12M, have been or are being conducted at the site. These projects are funded from a range of federal (NSF, EPA, DOE, USGS, USDA-SCS, NASA), state (Wisconsin DNR) and private (EPRI) sources.

We have also contributed significantly to education of students. Dozens of undergraduate students have been involved with research projects at Trout Lake and Madison. Graduate students have produced 10 MS and 5 Ph.D. theses related to LTER research in the past five years.

Relationship Between Past and Proposed Research

The research proposed here is designed to augment our existing LTER research. Requested funds will allow us to enhance work in each of our current major objectives (Box 1). We would increase our geographic scale to the Upper Great Lakes region and our disciplinary scope to include more policy-relevant research, providing a natural extension of our current LTER research.

Introduction

Small, inland lakes are a focal landform within the Upper Great Lakes region of North America. From the fertile, loess-capped soils of the north-central U.S. to the Precambrian outcrops of the Canadian shield, the thousands of inland lakes play a central role in regional hydrologic and biogeochemical cycles, in biological processes influencing the area's diversity of aquatic and terrestrial life, and in a wide range of human activities. Over the past two centuries, deforestation, fire suppression, agriculture, industrialization and urbanization have transformed landscapes within the regions and fundamentally altered the relationships of lakes to the regional biogeochemical matrix. Patterns of change in lakes and the surrounding landscape have been influenced by the availability of lakes for drinking water, irrigation, industry, transportation, fishing and recreation. For the next century and beyond, the quality of life and the economies of the region will depend upon the quality of the lakes.

We propose to scale up the North Temperate Lakes LTER (Magnuson and Bowser 1990) to address the regional feedbacks that link lakes, landscapes, and human activity. Until now, our efforts, including efforts at regionalization, have been largely limited to the Northern Highland Lake District of northern Wisconsin (Box 1). We propose to expand our current LTER project to develop comprehensive models of lake systems and land-lake interactions at local, watershed, landscape, and regional scales. Therefore, we will include three other lake districts within the Upper Great Lakes Biogeographic Region: (1) the agricultural and urban catchments near Madison, Wisconsin; (2) the Experimental Lakes Area of western Ontario; and (3) the Dorset Research Area of eastern Ontario. We also plan to strengthen our efforts in landscape ecology and ecosystem modeling, and propose to broaden our approach by developing links with the social sciences.

Box 1. Research Objectives of the Current North Temperate Lakes LTER.

(1) To perceive long-term trends in physical, chemical, and biological properties of lake ecosystems
(2) To understand the dynamics of internal and external processes affecting lake ecosystems
(3) To analyze the temporal responses of lake ecosystems to disturbance and stress
(4) To evaluate the interaction between spatial heterogeneity and temporal variability of lake ecosystems
(5) To expand our understanding of lake-ecosystem properties to a broader, regional context.

An advantage of expanding the spatial and temporal scales of our research is that it becomes possible to investigate a broader range of factors than is usually considered in evaluating controls of lake ecosystems (Magnuson et al. 1991). For example, at the expanded spatial scale of our proposed work, we anticipate differentiating land-use effects from other factors such as climate and geology that control the processes affecting lakes. This leads to the first of two overarching questions that will guide our program:

A. Do the dominant factors controlling inland lake ecosystems, and the predictability of their effects, vary systematically as spatial scales expand from individual lakes, to watersheds, to lake districts, to broader regions and temporal scales extend from years, to decades, to centuries?

For example, at the spatial scale of the Upper Great Lakes region, we hypothesize that it should be possible to determine effects that are driven by climate and atmospheric deposition. At the scale of particular lake districts, regions that are uniform geochemically and climatically, we anticipate the possibility of detecting changes associated with different land-use practices. For individual watersheds we expect to differentiate the effects of spatially distinct erosion and riparian vegetation. Finally, within separate lakes, we should be able to distinguish the effects of species recruitment events, invasions and extirpations or hydrologic forcing. Collectively across all scales, this suite of factors is determining the future of the world's lakes (Carpenter et al. 1994c).

Analogous scale dependencies are hypothesized as we expand the project's time scale. Over centuries, variance in lake processes is controlled largely by shifts in climate. At scales ranging from decades to centuries, temporal variability of lakes is primarily explained by shifts in land use, habitat change, species introductions, and fishery management policy. At shorter scales ranging from one to ten years, recruitment events, short climatic cycles and fluctuating weather patterns exert a major influence over lakes.

It is important to consider not only direct human effects on aquatic ecosystems but also the feedbacks that occur between human effects and continued human use. These feedbacks are evident in the observation that a better view of a lake makes the lake less attractive (Kitchell 1992). Lakes both affect and are affected by patterns of land use and economic development. Both natural and human-induced changes in the landscape must be considered along with the social and economic pressures associated with them in examining the full range of factors that control lakes. These considerations lead to our second overarching question.

B. How have natural and human-induced changes in the landscape interacted with aquatic ecosystem structure and dynamics in the Upper Great Lake Region over the past two centuries and what changes can be expected over the next hundred years?

Overall, our long-term goal is to develop the databases, models, analyses, and scientific theories necessary to predict the status and quality of lakes under alternative scenarios of natural and human-induced changes in the landscape. The knowledge base that we will develop about the interactions of lakes and humans from 1800 to the present, spanning urban to almost pristine watersheds, will be used to identify and anticipate the conditions of lakes as the regional landscape is transformed over the next century. Moreover, this knowledge base will be relevant to decision-makers who can influence the types of landscape transformations that will take place. Our program will continue to be grounded in ecology, limnology, geology and water chemistry, but the context and feedbacks will become more relevant to issues of conservation, economic development, sustainability and ecosystem management.

The vision introduced here will require a ten- to fifteen-year research program. This document seeks funding only for the first biennium. It will summarize our broader objectives and describe more specific goals for the next two years. We will use the few pages available to us to emphasize themes, ideas, and approaches. We point to the PI's 215 reviewed publications since 1990 as evidence of our capacity for rigorous research using state-of-the-art techniques, theory, and models.

Background and Approach

The central new objective of the augmented NTL-LTER is to analyze key processes and feedbacks of landscape-lake interaction over multiple temporal and spatial scales. We intend to develop predictive capabilities and test them by analyzing scenarios for the future of inland lakes and landscapes within the Upper Great Lakes region. Several approaches will be used to accomplish these objectives: **Regional Studies** at a range of discrete spatial scales to determine large scale patterns and generality of smaller scale results; **Site Histories** of system dynamics across a continuum of time scales to evaluate how past land-use changes have affected inland lakes; and a theoretical framework that brings in new disciplinary foci and leads to **Scenarios for the Future** useful as hypotheses to guide further work.

Although the spatial extent of our work encompasses landscapes that are largely terrestrial, we emphasize lakes as integrators of landscape processes and site histories (Fig. 2). Processes upland and upwind of lakes determine inputs of water, suspended solids and solutes. Hydrologic residence time is inversely related to rate of recovery of lake ecosystems following biogeochemical disturbances (Vollenweider 1976, Anderson and Bowser 1986, DeAngelis 1992, Cottingham and Carpenter in press). External forcing and internal dynamic interactions are expressed in outbreaks of exotic species, recruitment events, and irruptive blooms (Carpenter 1988, Harris 1989, Magnuson 1991, McLain 1991). The accumulating sediments archive surrogates and correlates of atmosphere-landscape-lake interactions and internal food web dynamics (Davis 1989, Hurley and Armstrong 1991, Kratz et al. 1991b, Kitchell and Carpenter 1993, Leavitt 1993). We focus on lakes as sensors and recorders of climate, human activity, landscape change, and ecosystem dynamics.

Spatial Scales: Regions, Districts, Watersheds, Lakes

This project involves four discrete spatial scales: the regional scale of the Upper Great Lakes province of North

America; selected lake districts; lake-watershed systems; and internal lake dynamics (Fig. 3). At the largest scale, we will use the comparative approach (Cole et al. 1991, Magnuson et al. 1991, Kratz et al. in press) across gradients of climate (e.g. evapotranspiration, ice duration), geological substrate and till thickness, watershed vegetation, cold- to warm-water biotas, and degree and nature of human influence. The lake districts differ in disturbance history and drivers of lake variability. These contrasts will allow us to assess the sensitivity and specificity of diverse ecological indicators (Frost et al. in press), and the extent to which results from one lake district apply to other lake districts in the region. We anticipate non-linear effects of interacting drivers at the regional scale. For example, the hydrologic budget of the northern part of the region is strongly influenced by vegetation, whereas the physical environment plays a greater role in controlling water balances in the southern part of the region where water stress is more important (Schlesinger 1991). If this hypothesis is correct, then changes in land use will have different effects on the hydrologic and geochemical cycling characteristics of lakes in the region.

While some of our data can be interpreted across a continuum of scales (e.g. climatology, geology, remote sensing), many crucial variates must be assessed at specific locations on the ground or water. We must therefore choose discrete spatial scales for intensive work. The four focal lake districts were chosen for the gradients among them as well as differences in drivers of lake variability and histories of disturbance. Most importantly, all four lake districts are sites of outstanding research programs of unusual longevity. In the past, researchers at these sites have shared ideas and data, and conducted some cross-site comparisons (Carpenter et al. 1991). We now propose to expand and intensify that collaboration. At the regional scale, we will take advantage of the comparable features of extant long-term data bases. At the sub-regional scale of Wisconsin, we will initiate new field programs designed for future integrative analyses and predictions of freshwater resources.

Temporal Scales: Site Histories and Predictions

Long-term databases collected at each of the lake districts are the centerpiece of this program (Fig. 4). We will also take advantage of coarse- (pre-settlement survey records) and fine-scale temporal land use records (Forest Inventory Analysis Plots), archived aerial photographs and satellite imagery (Lillesand 1993a), paleoecological data (e.g. Hurley and Armstrong 1991, Kratz et al. 1991b, Kitchell 1992, Carpenter and Kitchell 1993), and archived data sets of Birge and Juday and other past researchers (Kratz et al. 1987b, Kitchell 1992). These other sources of information are variable in detail and quality. In many cases, however, the older records have been intercalibrated with modern methods. Examples include land surveys (Curtis 1959), paleolimnology (Leavitt et al. 1989), and archived limnological data (Bowser 1986, Lathrop 1992). Such careful reconstructions will be used selectively to develop key aspects of the histories of our sites.

That the past is the key to the future is a central hypothesis of the entire LTER program. We will actively test this idea over the next 10-15 years. The databases will be used to calibrate models of selected processes and develop predictions under alternative scenarios. Predictions and scenarios thus become hypotheses for future work. Some of our models will be based on space-for-time substitution (Pickett 1989) or comparative analyses (Cole et al. 1991, Magnuson et al. 1991, Kratz et al. in press). An important class of questions addressed by these models is whether responses to disturbance in one watershed or lake district have predictive value in other systems. Other models will develop predictions from time series using the parameter-sparse, data-rich approaches of Walters (1986) and Scheffer (1994). Such models can be viewed as descriptions of structure (Jassby et al. 1990), hypothesis tests (Carpenter and Kitchell 1993, Rudstam et al. 1993), sources of testable predictions (Kitchell 1992, Scheffer 1994), or assessments of management scenarios, uncertainty and risk (Walters 1986, Carpenter et al. 1994a).

Scenarios of the Future

Scenarios of future land use change and lake management policy will be developed to guide our predictions and future research. Scenario development is analogous to hypothesis creation in that it must be guided by theory and seek informative contrasts. For example, predictions of lake eutrophication under contrasting scenarios of land use provide insights into how land can be allocated to meet human needs while preserving water quality (Peterjohn and Correll 1984, Soranno et al. in prep.). Or, predictions of groundwater discharge into lakes under various scenarios of climate and forestry practice can be used to assess optimal management plans in forest-lake landscapes (Running and Gower 1991, Cheng and Anderson 1992, in press).

Scenario development also requires us to interact with disciplines beyond the present core of NTL-LTER. Examples include sociology, economics, climatology, land use planning, landscape ecology, ecological modeling, fisheries management, and water quality management. These disciplines provide a crucial reference frame for relevant and informative scenarios.

In the first two years of the augmented program, we have planned for meetings and pilot projects to expand the disciplinary base of NTL-LTER. Initially, we will use two approaches with which we have experience. First, the methodology of Checkland (1981) will facilitate the finding of relevant ecological points of view, and bring stakeholders into a scientific investigation cognizant of important human effects. Allen's experiences with Checkland's methods will be crucial to our efforts (Allen and Hoekstra 1992). Second, the adaptive management modeling approach (Holling 1978, Walters 1986) will be used to engage diverse expertise on a central complex problem. This effort will build on Carpenter's experiences "modeling with managers" (Kitchell 1992). We are aware of the fact that our explorations will carry us beyond the limits of our own disciplinary expertise, and we will be adaptive in building collaborations and changing methodologies as the program evolves.

Specific Research Questions

In the previous sections, we presented two overarching questions and discussed our broad vision for an approach. Here, we use that framework to present a specific research agenda which will guide our activities. We present a mix of questions, ranging from those which are answerable within the two year funding period of this proposal, to others that will require concerted effort over the period of our next six-year LTER renewal.

The first overarching question is:

I. Do the dominant factors controlling inland lake ecosystems, and the predictability of their effects, vary systematically as the spatial scales expand from individual lakes, to watersheds, to lake districts, to broader regions and the temporal scales extend from years, to decades, to centuries?

We will approach this question by addressing three, complementary questions.

1) At what spatial and temporal scales, and for which types of limnological variables do lakes vary synchronously?

Lakes are affected by many driving variables, some acting locally, some at the watershed and landscape level, and some regionally. We expect the composite behavior of lakes over a large region to exhibit a complex mixture of local, intermediate, and regionwide patterns. By analyzing the spatial scales at which different limnological variables exhibit coherency (synchronous temporal variability, Magnuson et al. 1990), it is possible to determine the spatial scales at which various driving forces are most important. For example, if temperature and rainfall patterns have an important regional component on annual time scales, then we would expect water levels to increase regionwide in wet years, and decrease regionwide in dry years. We will use existing data from the four lake provinces to test for coherency both within each site and across sites in a diverse set of physical, chemical, and biological variables at local, lake district, and regional scales.

Analyzing for temporal coherence in inland lakes at scales up to the Upper Great Lakes region is an appropriate starting point in our regionalization efforts. Not only is it a powerful and conceptually straightforward approach, investigators at each of the four lake sites have an interest in this question and appropriate data. These efforts will allow us to work out data management protocols and electronic networking issues, while simultaneously building a cooperative interchange among investigators at the different lake districts and conducting a valuable analysis.

2) Over what spatial scales are landscape pattern (e.g. geologic landform and vegetation) and hydrology useful predictors of limnological processes and variables?

Although we expect that landforms close to a lake exert a greater influence than those farther way, it is unclear how, and at what scales, the spatial arrangement of vegetation, soils, and relief affects lakes. We propose to approach this problem by analyzing spatial "windows" of increasing distance around a waterbody of interest (Osborne and Wiley 1988, Soranno et al. in prep.). For each window we will assess land use, soils, and slopes. Then, by using statistical and modeling analyses that include the landscape pattern and direction of water flow estimated at these different scales, we can identify both which features of landscape pattern and at which scales these features are important in explaining the variability in limnological responses. Extrapolation of these results from local scales to landscape or regional scales will be based on a spatially explicit data base contained within a GIS. The GIS cover and hydrologic data already exist for the Northern Highland Lake District (Lillesand et al. 1989, Cheng 1994) and Lake Mendota's watershed (Soranno et al. in prep.). GIS data are in development for the entire state of Wisconsin (Lillesand 1993a).

Initially, we will focus on predicting dissolved organic carbon (DOC) concentrations in lakes in the Northern Highlands, and P loading in southern Wisconsin. DOC is a keystone variable in the north because of its links to landscape-level carbon budgets (Kling et al. 1991) and water clarity in lakes (Davies-Colley and Vant 1987, Koenings and Edmundson 1991). Similarly, in southern Wisconsin P loading is of central importance (Kitchell 1992, Cooke et al. 1993). Subsequently, we will use this approach to examine other variables, such as, inorganic carbon, silica, and nitrogen.

3) To what extent are results identified at a single lake district in the Upper Great Lakes Region valid for other lake districts within the region?

An important part of developing a regional understanding of lake ecosystems is knowing the degree to which results discovered at one site can be extrapolated to other sites within the region. We propose to test the generality of several results from the past 13 years of work at our LTER site by testing them with data from other lake districts. We will also use our data to test the robustness of results from other sites in the region.

Specifically, we propose to test the generality of local results in each of the following areas:

A. <u>Landscape position</u>. The position of a lake within the landscape scale hydrologic regime has been a predictor of average ionic chemistry as well as the annual variability of chemical variables in the Northern Highland Lake District (Kratz et al. 1991a). How important is landscape position as a structuring variable in other lake districts?

B. <u>Cyclic patterns in water clarity</u>. Crystal Lake, in northern Wisconsin, has exhibited two 5-year cycles in water clarity. These cycles are most likely caused by cycles in the population levels of yellow perch, the single dominant fish in the lake (Magnuson 1990). We will ask whether other lakes with such a simple fish community also exhibit cyclic behavior in water clarity (Carpenter and Leavitt 1991).

C. Hydrologic regime. We have found the hydrologic regime (water retention time, groundwater vs precipitation inputs, etc.) to be an important structuring factor in the Northern Highland Lake District (Krabbenhoft et. al, 1990a,b, 1994, Kratz et al. 1991a). In particular, we have found that concentrations of stable isotopes of oxygen and hydrogen have been useful in determining the relative contribution of different sources of water entering lakes. The four lake districts represent contrasts in such factors as duration of ice-free season, mean annual temperature, relative effects of direct runoff versus groundwater recharge, precipitation/potential evaporation, type of local vegetation, proximity to the North American Great Lakes, and variation in winter snowpack. We will test the utility of the stable isotope approach under these different conditions.

D. Climate change. Schindler (1990) found that increased temperatures during the past 20 years are linked to changes in various physical, chemical, and biological aspects of a small lake at ELA. We propose to join an effort initiated by scientists at ELA and Dorset to test the generality of that result by examining (Webster et al. 1990) and modeling (Hill and Magnuson 1990, McLain et al. in press) the dynamics of other lakes in the Upper Great Lakes Region.

The second overarching question is:

II. How have natural and human-induced changes in the landscape interacted with aquatic ecosystem structure and dynamics in the Upper Great Lakes Region over the past two centuries, and what changes can be expected in the next century?

To approach this question, we will use retrospective analyses to correlate records of land use change and limnological change (derived from long- term data and/or paleolimnological studies). These historical data will be used to calibrate models that link land use change to lake characteristics. The models will then be used to compare the limnological consequences of contrasting land use scenarios.

Specifically, we ask the following three questions:

1) How have past changes in the landscape affected lakes?

In the northern parts of the region, the major landscape changes have been associated with clearcutting of the forests, subsequent regrowth, and increased development of seasonal and permanent houses on lake shorelines. In the south, major changes have been transformation of savanna to agriculture and urban uses. To understand the impacts these changes have had on lakes we will construct comprehensive site histories of selected areas of the Northern Highland Lake District and the Madison lakes area. Site histories will be developed using a combination of approaches. We will use paleolimnological techniques to reconstruct past physical, chemical and biological conditions using pigments, microfossils of phytoplankton and zooplankton, charcoal, and fractions of sand, silt, and clay as proxies. Histories of landcover and land use will be derived from a variety of sources: a series of land use mapping efforts conducted beginning in the early 1800's, records of fires and logging activities maintained by natural resource agencies, and remote-sensing images. In combination, these two information sources will provide us with a powerful tool to relate past land use with lake condition.

2) What are present linkages between lakes and the surrounding landscape?

Northern Highland Lake District. The lakes of the Northern Highland Lake District are surrounded by a diverse landscape comprised of a mosaic of different soil types, landforms, and coniferous and deciduous forests of varying successional status. Because different vegetation and soil types have different rates of evapotranspiration, the vegetation and soils have a major influence on lakes through their effects on surface and groundwater hydrology. To better understand these terrestrial/aquatic interactions, we are currently developing a spatially explicit hydrologic model for the Northern Highland Lake District. This model links through the evapotranspiration term a groundwater model (MODFLOW, McDonald and Harbaugh 1988) with an added lake level fluctuation component (Cheng and Anderson 1992, Cheng 1994) to a terrestrial biogeochemical cycling model (FOREST-BGC, Running and Coughlan 1988, Running and Gower, 1991). The final output of the model includes the spatial and temporal distribution of groundwater and lake levels, and groundwater flow into lakes. The model can be tested using independent estimates of groundwater flow based on stable isotope techniques (Krabbenhoft et al. 1990a,b, 1994). The linked hydrologic model uses spatially explicit input data from a geographic information system (GIS) developed from existing geology and soils data and from remotely sensed land cover and productivity measures. In addition, we will develop a soil carbon and nitrogen cycling component of FOREST-BGC to simulate carbon and nitrogen mineralization, uptake, and leaching fluxes. Following validation, we plan to use the models to assess scenarios of global change, including both climate as well as land use, and to assess changes in chemical loading to lakes via groundwater.

An example of a specific application of this model is to determine the role surface waters play in landscape level carbon balances. Lakes act as conduits of terrestrially fixed carbon to the atmosphere (Kling et al. 1991, Cole et al., in prep., Kratz and Bowser in prep.). Groundwater is an important pathway for this carbon from the landscape to lakes. Having a linked forest cover-hydrologic model will allow us to determine how the role surface waters play in landscape-level carbon dynamics changes as a function of forest type and climate.

One of the steps in the development of this model is to examine the local influence of geologic landform on several key forest ecosystem attributes that drive the model, including vegetation cover, leaf area index (LAI) and aboveground net primary production (ANPP), and to examine if these attributes are scale-dependent. Such analyses are required to test our ability to scale up from plot level studies to larger areas. A nested combination of stratified random and gridded sampling schemes will be used to determine vegetation cover, LAI and ANPP in a 10 x 10 km cell. To determine if LAI, an important ecosystem attribute used to drive ecosystem C budget and land-surface models, is scale-dependent, we will compare estimates of LAI from satellite sensors with different levels of spatial resolution (grain), e.g. Landsat TM (30 x 30 m), MSS (80 x 80 m) and AVHRR (1 x 1 km). Three estimates of ANPP, using different scaling approaches (e.g. arithmetic average, forest ecosystem process model and production efficiency model for the 10 x 10 km cell) will be compared to determine if landscape estimates for important terrestrial ecosystem attributes are scale dependent for a heterogeneous landscape in northcentral Wisconsin.

<u>Agricultural and Urban Lakes</u>. The Madison area has the highest urbanization rate in Wisconsin; urban land area is expected to double in the next 40 years through conversion of agricultural land (Dane County Regional Planning Commission 1992). Our efforts will focus on the linkage of land use change and climate to loading of P, the nutrient that has the greatest impact on water quality in these lakes (Kitchell 1992).

We will quantify the effects of land use change and precipitation on P loading by developing and calibrating models. Informative contrasts for hypothesis testing and calibration will be obtained from: the historical record of land use and P loading (Watson et al. 1981, Lathrop 1992, Soranno et al. in prep.); differences between P loading in predominantly agricultural (Fish Lake, Lake Mendota) versus predominantly urban (Lakes Monona and Wingra) watersheds; and changes that occur during the time span of our studies. Important changes in P loading are hypothesized from the $30M Lake Mendota Priority Watershed Project (1996-2006), the largest nonpoint P load remediation ever undertaken in Wisconsin. Effects of such projects are rarely evaluated (National Research Council 1992). We have a unique opportunity to do that.

The modeling approach will build on extant models for the agro- urban lakes. P loading is modeled using approaches that differ in degree of spatial detail. The most richly detailed model, WINHUSLE, is a distributed parameter model that will be calibrated using state funds for the Mendota Priority project (Baun 1992). At a more general level, scenarios will be explored using an empirical model that accounts for spatial pattern using simple scaling and transport parameters (Soranno et al. in prep.). Loading models will be coupled to simple input-output models (Reckhow and Chapra 1983), empirical time series (Lathrop and Carpenter 1992a,b) and cross-sectional models (Reckhow 1993), and dynamic simulation models (Carpenter et al. 1992) to assess the implications of P load changes for lake ecosystem processes.

During the two year tenure of this proposal, we will complete modeling analyses for Lake Mendota of P loads in relation to land use changes from presettlement to the present, estimate P loads derived from a range of land use scenarios for the next century, and quantify past and future links of P load to blue-green algal blooms. In later years of the project, these analyses will be extended to the other southern Wisconsin lakes with contrasting land uses.

3) What are the limnological consequences of different scenarios of future land-use?

Humans impact lake ecosystems indirectly through changes in the landscape, and directly by altering food-web structure of individual lakes. We propose to address both types of impacts.

The interactions between socioeconomic and environmental factors as they affect landscape dynamics can be explored using a model that incorporates socioeconomic factors to drive land-use decisions and then simulates landscape change (Flamm and Turner in press (a,b), Wear et al. in prep.). Changes in the abundance and spatial distribution of land cover are modeled spatially by using transition probabilities conditional upon site attributes, such as soil type and percentage slope; land ownership; socioeconomic attributes, such as income and population density; locational features, such as distance to roads and market or service centers; land rents for various uses; and land use on adjacent parcels. The transition probabilities are estimated using logistic regression. The spatial data used to estimate the transition probabilities are integrated into a geographic information system (GIS) and linked directly with the simulation model. The effects of landscape change on selected environmental (e.g., persistence and abundance of native species, presence of exotic species, water quality) and resource supply (e.g., timber and real estate) variables are simulated. Alternative scenarios of land use can then be modeled to explore ecological and socioeconomic implications of land-use decisions or regulations (Wear et al. in prep.). In the agro- urban watersheds, we will emphasize surface flows of phosphorus to lakes (Soranno et al. in prep.). In the Northern Highlands, we will emphasize groundwater flows of carbon, major ions, and nutrients.

Fisheries exploitation and management affect lake ecosystems directly. The extent of exploitation is determined by a complex interaction of social, economic, ecological and management processes (Magnuson 1976). We propose to model fishery change by linking extant models of angler- fish interactions (Carpenter et al. 1994a, Johnson and Carpenter 1994) to models of lake food web dynamics and water quality (Carpenter et al. 1992, Carpenter and Kitchell 1993) and expanding the scale to multiple lakes on the landscape.

Project Organization And Management

Project organization and management will be integrated thoroughly with the existing management of our current LTER grant. Direction of NTL LTER is provided by Magnuson. The regional research program will be coordinated by an inter-site management team (Carpenter, Dillon, Hecky, Kratz, and Magnuson). Dillon (Dorset Research Centre) and Hecky (Experimental Lakes Area) have indicated that their research groups have a high level of interest in participating in the proposed research. NTL LTER is adding two new principal investigators, Carpenter and Turner, who will strengthen the project's modeling and landscape ecology expertise.

To address the expanded scope and integrative nature of the proposed research, we will form interdisciplinary synthesis groups in three primary areas: (1) land-water interactions, (2) human-lake interactions, and (3) regional analyses. Each team will consist of selected principal investigators, postdoctoral students, graduate students, and (when appropriate) representatives from resource management agencies (including the Wisconsin Department of Natural Resources, the Lac Du Flambeau Ojibwe Tribe, the Dane County Lakes and Watershed Commission) and social scientists at the University of Wisconsin-Madison from the Departments of Urban and Regional Planning, History, Geography, Rural Sociology, and Landscape Architecture and the Institute for Environmental Studies (Born, Cronon, Freudenburg, Heberlein, Jacobs, Niemann, Voss). These synthesis teams will be coordinated by a group of five core principal investigators and the data manager and by discussions at the monthly NTL LTER meetings.

The land-water interactions synthesis group will develop theory, databases, and models on the feedbacks between land use and lakes. The human-lake synthesis group will assess the feedbacks between lakes and humans and develop the land-use change scenarios studied by the land-water interactions group. The regional analyses synthesis group will assess coherency, predictability and scale questions using data from the Canadian sites and the Wisconsin lakes in the forested and agro-urban watersheds.

To expand the disciplinary scope of the project in addressing regional land use/lake feedbacks and developing future land use scenarios, early in project development we will hold a planning workshop on the University of Wisconsin-Madison campus with the resource managers and social scientists who will be working with the synthesis teams. There will also be a planning workshop held at the Experimental Lakes Area early in the first year of the project for 4-5 representatives from Wisconsin and each of the two Canadian sites. Participants from all sites will also continue this interaction at national meetings. Most of the research interactions, however, will use the existing computer networks. Email, data exchange, and manuscript development will occur over the Internet. Our research group at NTL LTER is already experienced in this mode of operation.

The regional analyses and the development of a knowledge base of land use change will require coordination among multiple research centers and agencies and the linkage of databases for which these groups are custodians. These efforts will bring increased challenges to data management, including development of data sharing policies, data exchange formats, aggregation of inter-site data, remote data access, intercalibration, quality assurance and metadata requirements. Data management and remote sensing staff will be part of the organizing meetings with the Canadian sites and resource management agencies. Our site and the associated research centers will bring considerable existing data management resources to the expanded research agenda. The Canadian research centers, Experimental Lakes Area and Dorset Research Centre, are currently planning to integrate some of their data into multi-site databases. Further facilitating our regional efforts is the fact that these sites and NTL LTER all plan to use the same relational database technology, Oracle RDBMS.

Our scientific efforts will benefit from direct ties to a broadly-based range of resource management decision makers. Carpenter, a principal investigator on the proposed research, is directly involved with ongoing research projects on the Madison lakes and is a member of the Executive Committee for the Lake Mendota Priority Watershed Project. The Environmental Remote Sensing Center, under the direction of NTL LTER principal investigator Lillesand, is providing the remote sensing and GIS support to ongoing development of regional land use databases under the WISCLAND and Gap Analysis Programs and will provide direct links to the large and diverse group of cooperating land management institutions involved in these programs.

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