

Project Summary

LTER: Comparative Study of a Suite of Lakes in Wisconsin

Freshwaters are ecologically important and socially valued elements of landscapes and a nexus of hydrological, biogeochemical, biotic, and human social interactions. The North Temperate Lakes (NTL) Long-Term Ecological Research Program aims to understand change in lake districts in relation to relevant abiotic, biotic, and human processes. Our overarching research question is “**How do climate, social-ecological interactions, land use and cover, and ecological processes act in concert to shape the history, status, and future of lake districts?**” We address this question through research in two regions in Wisconsin, the Northern Highland and Yahara lake districts. We have four interrelated themes:

- A. **Perception of Long-Term Change:** How and why have lake districts changed, and how will they change in the future?
- B. **Climate Forcing of Change:** What are the major ecological and social responses of lake districts to climate change?
- C. **Interacting Drivers, Scales of Space and Time, and Regional Change:** How do multiple interacting drivers affect regional change in lake districts at multiple scales?
- D. **Ecosystem Services: Past, Present and Future:** What are the magnitudes, interactions, and potential future flows of ecosystem services in lake districts?

We focus on four of the most important drivers of change: climate, land use and cover, nutrient mobilization, and invasive species. We examine ecological and social patterns and processes at five major spatial scales: individual land parcels, a lake and its watershed, a lake district, between the two NTL lake districts, and among diverse long-term research sites including NTL. Temporally, we consider scales from centuries to minutes. We measure responses of hydrologic, hydrodynamic, biogeochemical, biotic and social systems. In addition, forecasts of freshwater ecosystem services provide a framework for organizing our understanding of regional change. Considered collectively, the long-term observations, comparisons, experimental manipulations, and diverse modeling and statistical tools for synthesis of data that we employ offer a powerful approach for understanding change. Our interdisciplinary team includes expertise in biogeochemistry, climatology, ecology (landscape, ecosystem, community and population), economics, education and outreach, hydrodynamics, hydrology, information management, microbiology, and rural sociology.

We expect our research to produce new synthetic understandings of the causes and consequences of ecological and social-ecological change in lake districts. We will sustain a 33-year database of regional change and provide scientific information and understanding relevant to decisions of individuals and institutions concerned with the future of our region and the welfare of its residents. Results of our research are integrated in K-12, undergraduate, graduate, and continuing education, and our studies provide scientific information to individuals, non-governmental organizations, local, state and federal agencies, and global assessments.

Section 1. Results from Prior Support
Comparative Studies of a Suite of Lakes in Wisconsin
Grant DEB-0217533, Funding (2002-2008) = \$6,720,000

Since the start of North Temperate Lakes Long-Term Ecological Research (NTL-LTER) program in 1981, we have been conducting a regional, long-term comparative study of two lake-rich regions: the Northern Highland Lake District (NHL) and the Yahara Lake District (YLD). We have increased our understanding of long-term dynamics of lakes at spatial scales ranging from small sites within lakes, to whole lakes and their watersheds, to lake districts and to the northern hemisphere. We published 280 journal articles, books, or book chapters during the last six years (2002-2007 and in press; Fig. 1). A complete publication list is in the Supplementary Documentation.

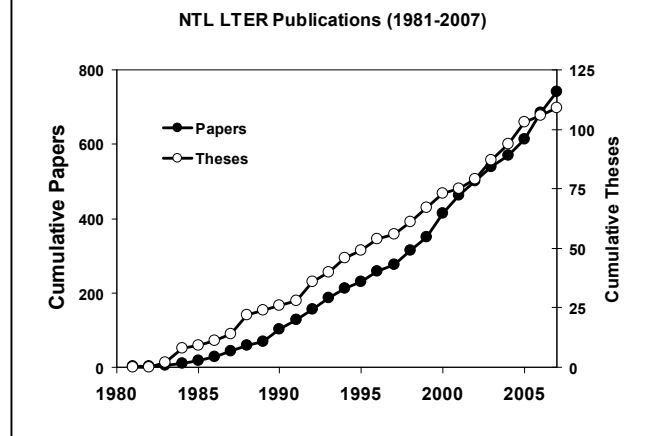
Here we briefly describe selected research accomplishments of the past 6 years, organized by the main research topics of our 2002 proposal. We then summarize our activities in intersite science, information management, and outreach and education. Details and additional examples can be found at <http://lter.limnology.wisc.edu/findings.html> and in our publications.

Perception of Long-Term Change

In addition to our continued collection, management, and analysis of a comprehensive series of core datasets, we produced two major synthesis products. First, our site synthesis volume *Long-Term Dynamics of Lakes in the Landscape: Long-Term Ecological Research on North Temperate Lakes* was published in 2006 (Magnuson, Kratz, and Benson 2006) with 38 contributing authors. The book, which summarized the first 20 years of our NTL program, has been well received by reviewers (review comments and book summary at <http://lter.limnology.wisc.edu/ntlbook.html>).

Second, we compared regional changes in the NHL and YLD in a synthesis paper in *BioScience* (Carpenter et al. 2007). In the NHL, housing density increased around the shoreline of many lakes and in urban centers. In the YLD, farmland was converted to residential and commercial uses. Changes in human activity and land use and cover were associated with changes in the lakes. Biogeochemical and hydrologic modifications were extensive in the YLD. Biotic change was extensive in both regions. Important invasive species include common carp

Fig. 1. Cumulative publications vs. year for the NTL LTER project, 1981 to present. Publications in press are counted as 2007. All papers were either fully funded by NTL or jointly funded by NTL and other sources. Popular articles are not included. Publication numbers are likely underestimated because we do not learn of every paper that uses our publicly-available data.

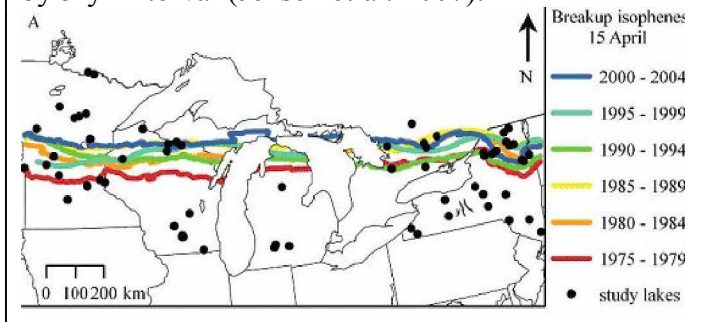


and Eurasian water milfoil in the YLD, and rusty crayfish and rainbow smelt in the NHLD. Eurasian water milfoil has invaded some NHLD lakes. These invasions were associated with secondary extirpations of native species in both regions, leading in some cases to deterioration in sport fisheries.

Understanding Temporal Variability

Ice-on and ice-off data from lakes distributed around the Northern Hemisphere continue to provide our longest and most widespread observational time series. New investigations showed that temporal coherence of ice-off dates decreased with distance between lakes for lakes within the Great Lakes region of North America (Magnuson et al. 2005) and for lakes throughout the northern hemisphere (Magnuson et al. 2004). An analysis of the climatic determinants of lake ice phenology trends across the Great Lakes region showed that contour lines connecting lakes that thaw on 15 April (isophenes) have marched northward at an average rate of 3.8 kilometers per year from 1975 to 2004. This trend is nearly in step with the northward movement of temperature contours and totals almost 100 km over 25 years (Jensen et al. 2007; Fig. 2).

Fig. 2. The 15 April ice breakup isophenes averaged by 5-yr interval (Jensen et al. 2007).



Long-term studies and meta-analysis have demonstrated negative impacts of invasive rainbow smelt on walleye recruitment (Mercado-Silva et al. 2007) and of rusty crayfish on zoobenthos (McCarthy et al. 2006). We also developed models forecasting invasive species spread on landscapes, focusing on invasions and impact of rainbow smelt (Mercado-Silva et al. 2006).

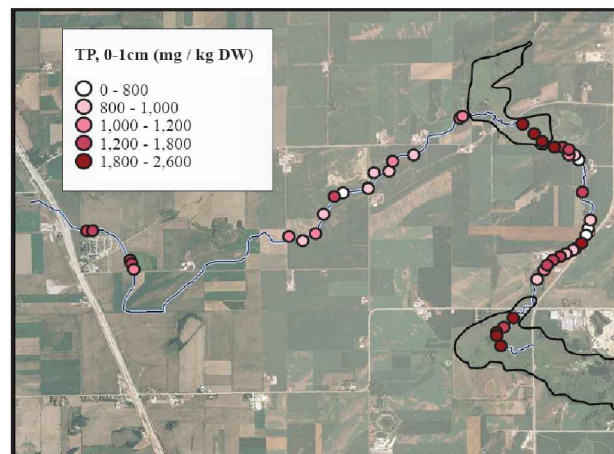
Experimental removal of invasive rusty crayfish and rainbow smelt from Sparkling Lake started in 2002 and is ongoing. Removal has produced more than tenfold declines in both invaders, and populations of some native taxa have rebounded (Hein et al. 2006, 2007). Feedbacks have the potential to maintain the ecosystem in a predator-dominated state with reduced abundance of invaders (Roth et al. 2007b).

Molecular analyses of bacterial community composition (BCC) reveal that regular physical and biological events, such as water-column mixing and planktonic grazer population dynamics, can trigger dramatic change in BCC. These patterns of change were repeated in different lakes and years despite major differences in BCC (Yannarell et al. 2003, Graham et al. 2004, Kent et al. 2004, Shade et al. 2007). Bacterial and phytoplankton community dynamics were remarkably coherent among a set of six bog lakes, suggesting that seasonal drivers are responsible for synchronizing community change during the ice-free season (Kent et al. 2007).

Spatial Dependencies and Long-Term Change

Hydrologic and biogeochemical linkages of landscape elements (e.g., uplands, wetlands, streams, lakes) organize many spatial dynamics in lake districts. Groundwater flowpaths are often highly focused (Lowry et al. 2007), and adjacent paths can differ greatly in origin, age, and chemistry (Pint et al. 2003, Walker et al. 2003, Masbruch 2005, Dripps et al. 2006). Variation in both flowpath composition and landscape elements contribute to distinct biogeochemical and ecological characteristics of surface waters (Hunt et al. 2006). Analyses have focused on organic carbon on the NHLD (Cardille et al. 2004, 2007) and phosphorus (P) in the YLD (Fig. 3), where wetlands and streams are sites of P storage and significant sources of dissolved reactive P during base-flow periods (Hoffman et al. in review).

Fig. 3. Storage of total phosphorus (TP) in channel and wetland areas of Dorn Creek, one of the major tributaries to Lake Mendota. Wetland boundaries are outlined in black.



Housing and development represent an important social-ecological interaction in both study regions. Development density in the NHLD increased 4.6-fold between 1940 and 2000 (Hammer et al. 2004), and this development has been concentrated around lakeshores (Carpenter et al. 2007). Lewis and Provencher (in preparation) took the analysis further by evaluating the factors determining shoreline development from 1974 to 1998. In the YLD, new development is a major source of P erosion to streams and lakes, yet political activity of lakeshore property owners helps motivate policies to mitigate eutrophication (Carpenter et al. 2006). NTL scientists are employing valuation methods to understand the economic values related to policies for managing shorelines and ecological conditions of lakes and have shown that restrictive zoning regulations increase values of lakeshore properties (Papenfus and Provencher in preparation).

Thresholds and Regime Shifts

We developed a theoretical framework for regime shifts (Carpenter 2003) to explore thresholds and big changes, especially in eutrophication and food web dynamics. Phosphorus load thresholds for eutrophication were quantified using 30 years of P budgets and used in ecological-economic analyses of policies for mitigating eutrophication (Ludwig et al. 2003). Leading indicators of regime shifts were investigated using eutrophication as a case study (Carpenter and Brock 2006) and extended to more general cases of ecosystem services (Brock and Carpenter 2006).

Studies of biotic regime shifts included the whole-lake manipulation of coarse woody habitat in Little Rock and Camp Lakes (Sass et al. 2006). Removal of wood led to declines in largemouth

bass growth rates and the virtual elimination of their prey, yellow perch, highlighting the important role of woody habitat in mediating predator-prey interactions in lake ecosystems (Sass et al. 2006, Roth et al. 2007b). In Lake Wingra, a carp exclosure experiment has produced major improvements in water clarity, though it appears that invasive Eurasian watermilfoil is responding to the increase in light.

Disease plays a role in some lake regime shifts. Chytrid fungal infections affect the population dynamics of *Daphnia*, a keystone grazer of phytoplankton (Johnson et al. 2006a) and make *Daphnia* more vulnerable to fish predation (Johnson et al. 2006b).

Forecasting Long-Term Change

We developed qualitative scenarios of long-term regional change in the NHLD (Peterson et al. 2003) and the Lake Wingra watershed of the YLD (Biggs et al. 2007) and made progress toward quantitative projections of regional change over decadal time scales. In the NHLD, effects of climate and land use change on water and organic carbon dynamics were analyzed using a regional model of 7588 lakes and their watersheds (Vano et al. 2006, Cardille et al. 2004, 2007). In the YLD, long-term quantitative projections focused on effects of climate and land-cover change on flows of water and P in the Lake Mendota watershed and consequences for eutrophication (Carpenter 2005, Collins et al. in prep.).

Intersite Science

NTL scientists have been leaders in cross-site science, both within and outside the LTER network. The Global Lake Ecological Observatory Network (GLEON; gleon.org), led by NTL scientists, is a grassroots network of lake scientists, engineers, and information technology experts who use instrumented platforms on lakes to assess high-frequency dynamics (Porter et al. 2005, Kratz et al. 2006, Tilak et al. in press). Scientists from more than 12 countries spanning Asia, the Americas, Europe, and the Middle East participate in GLEON. The information technology being developed for GLEON is directly applicable to NSF's large environmental observation programs such as NEON and WATERS.

We lead comparative research with two other north temperate lake districts (the Experimental Lakes Area and Dorset Environmental Science Centre in Ontario) to evaluate the predictability of lake physics, chemistry and biology along a natural gradient of groundwater influence. We regularly lead and participate in cross-site workshops, including ones on environmental sensors (Porter et al. 2005), species-time relationships (Adler et al. 2005, White et al. 2006), the relationship between disturbance and variance (Fraterrigo et al. in review), and ecosystem services (Kinzig et al. in prep.). We also participated in a comparative analysis of coupled human and natural systems involving sites from several continents (Liu et al. 2007).

NTL scientists were active in LTER Network leadership and development of the decadal science plan or ISSE (see Section 3, Project Management). We are committed to cross-site science and expect this high tenor of cross-site activity to continue in the new funding cycle.

Long-Term Core Data and Their Management

All of our findings depend on high-quality, comprehensive, long-term datasets on the physical, chemical, biological, and socioeconomic properties and processes of the LTER lakes and the surrounding landscapes (Kratz et al. 1986, Magnuson and Bowser 1990, Magnuson et al. 2006). All of these data are available electronically to LTER investigators and collaborators, and data are freely available to the public on the World Wide Web within two years (Table S2A, Supplementary Documentation). Documentation of use of on-line data is provided in Table S2B (Supplementary Documentation). Information management at our site is described in Section 4.

Development of Human Resources in Science and Engineering

Graduate education and graduate students have been direct and indirect beneficiaries of our LTER research. In a typical year we supported an average of six graduate students fully or in part from the NTL LTER grant. In addition, about 20 graduate students were affiliated with our LTER project each year and received training and education benefits even though they were not directly supported. 14 MS and 20 Ph.D. theses were based on LTER research between 2002-2007.

Undergraduate education and undergraduate students were also direct and indirect beneficiaries of the NTL LTER program. In an average year 23 undergraduate students worked directly for our NTL project. Principal investigators routinely use recent results from NTL in their courses. Approximately 1150 undergraduate students each year took classes taught by NTL PIs where NTL results were used to enrich the curriculum. In addition, NTL data available on the web were used by faculty at other institutions to enhance their classes.

Education and outreach activities included development, testing, and dissemination of educational materials and activities, as well as events for elementary, middle, and high school students and teachers, undergraduates, faculty, and staff, and community organizations. Eight hundred and forty elementary and middle school students participated in events held in the YLD and NHLD as part of Schoolyard LTER, College for Kids, Saturday Enrichment, and the Precollege Enrichment Opportunity Program for Learning Excellence (PEOPLE). Nine hundred and twenty four high school students participated in NTL-LTER events as part of a partnership with Middleton Cross Plains High School, PEOPLE, and the Summer Science Institute for Minority Students. Newly developed case-based activities using NTL and other LTER databases were tested and implemented with about 600 Introductory Biology students at UW-Madison.

During 2002-2007, more than 1300 K-12 teachers participated in activities that integrated NTL findings, led by NTL faculty, staff, and students. These included: single day workshops for elementary and middle school teachers in Vilas County, week-long summer institutes for elementary, middle-school and high-school teachers in Madison, WI and Los Angeles, CA, and 3-week summer graduate-credit-earning courses for middle and high school teachers. We advised 7 research experiences for teacher (RET) participants.

2. CONCEPTUAL FRAMEWORK

Freshwaters are foci of ecological and social processes on landscapes throughout the world. Lakes, such as those prominent throughout the Great Lakes region of North America, play critical roles in hydrological and biogeochemical cycles, ecological interactions, and human activities. Land use and cover change (deforestation, agriculture, urbanization), nutrient mobilization, species invasions, and direct human use of freshwater resources have transformed landscapes and lakes and fundamentally altered the interactions of freshwaters, landscapes, and people. For current and future generations, livelihoods and quality of life are inextricably linked to freshwater resources. The North Temperate Lakes Long-Term Ecological Research (NTL-LTER) program seeks to understand changes in freshwater ecosystems and their interactions with terrestrial, atmospheric, and human processes. Our overarching question is:

How do climate, social-ecological interactions, land use and cover, and ecological processes act in concert to shape the history, status, and future of lake districts?

Our conceptual framework considers freshwater ecosystems in a regional network of interacting aquatic, terrestrial, and social elements. We employ a nested set of spatial scales, from an individual lake and its watershed, to sets of neighboring lakes, entire lake districts, multiple lake districts within the Great Lakes region, lake districts of the northern hemisphere, and finally to comparative studies of lake districts with other kinds of ecoregions. Our core study areas are the Northern Highland and Yahara lake districts (NHL and YLD, respectively) in Wisconsin (Fig. 4). Our temporal perspective includes analyses of paleoecological data and recorded history, NTL data collected since 1981, a variety of shorter comparative and experimental studies, and forecasts of the next few decades of change. Over the past 150 years the tempo of change has increased in the NHL and YLD (Fig. 5). The mission of NTL is to understand the drivers, key interactions, consequences, and potential future directions of emerging regional changes. Within the context of our overarching question, we have organized our research for the next six years under four interrelated goals, each with a thematic question:

A. Perception of Long-Term Change: *How and why have the lake districts changed, and how will they change in the future?* Long-term observations and experiments are necessary to perceive and understand the causes and consequences of change. The NTL-LTER program is committed to collecting, maintaining, analyzing, and synthesizing a long-term, comprehensive set of physical, chemical, biological, and socioeconomic data.

B. Climatic Forcing of Change: *What are the major ecological and social responses of lake districts to climate change?* Climate change and climatic variability are important drivers of change in the Great Lakes Region of North America. We explore the consequences of climate-induced changes in regional hydrology, lake hydrodynamics, biogeochemistry, and biota for the socio-ecological systems in the NHL and YLD.

C. Interacting Drivers, Scales of Space and Time, and Regional Change: *How do multiple interacting drivers affect regional change in lake districts at multiple scales?* In addition to climate, human action is an important driver of change. Here we explore how interactions between climate and human activity affect ecological and social processes and their interactions

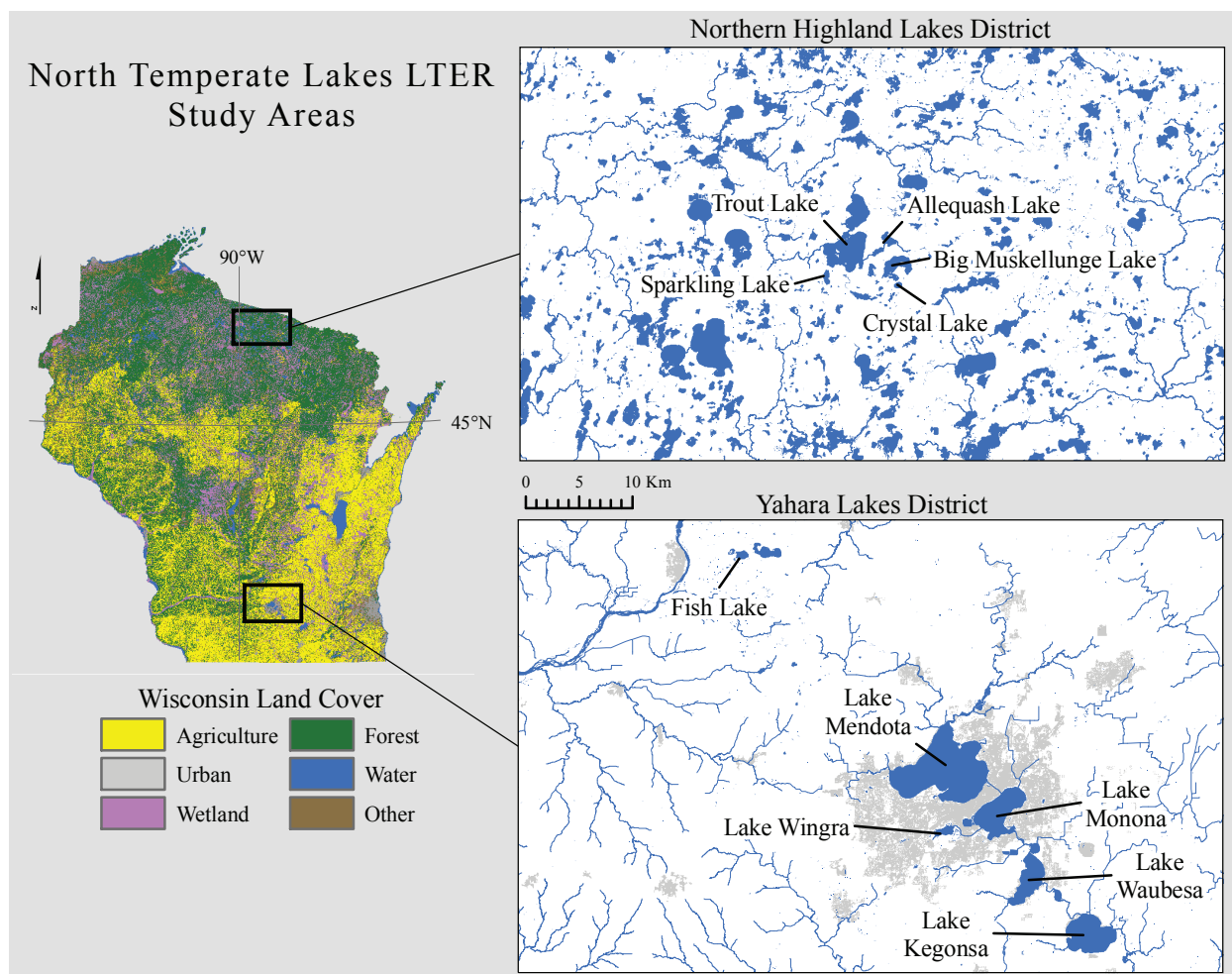


Figure 4. The Northern Highland Lake District and Yahara Lake District, primary study areas for NTL-LTER, represent regions with distinctly different land cover.

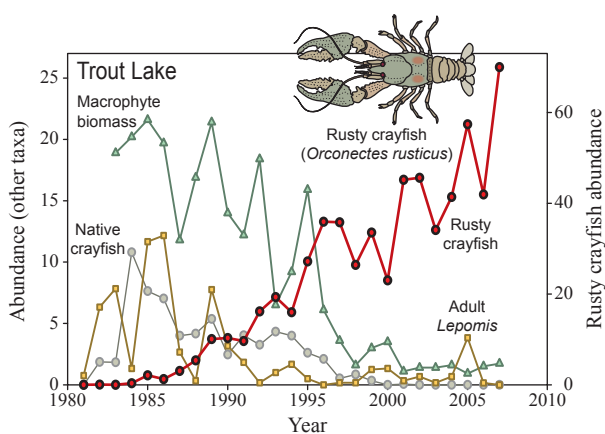


Figure 6. The invasion of Trout Lake by rusty crayfish was associated with declines of macrophyte biomass, sunfish (*Lepomis spp.*) and native crayfish.

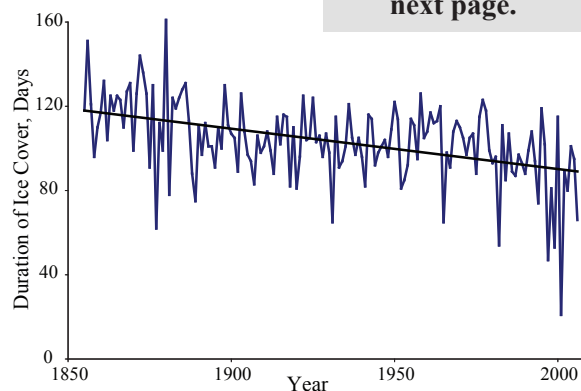
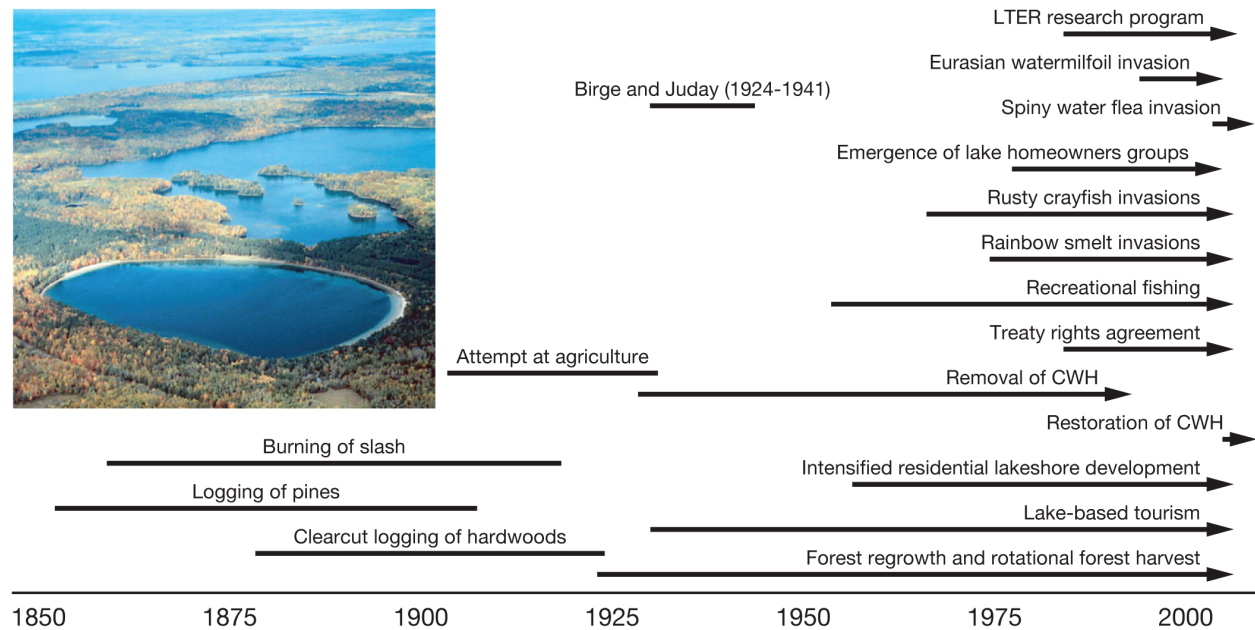


Figure 7. Duration of annual winter ice cover on Lake Mendota has trended downward for more than 150 years.

Note: Figure 5 is located on the next page.

A) Northern Highland Lake District



B) Yahara Lake District

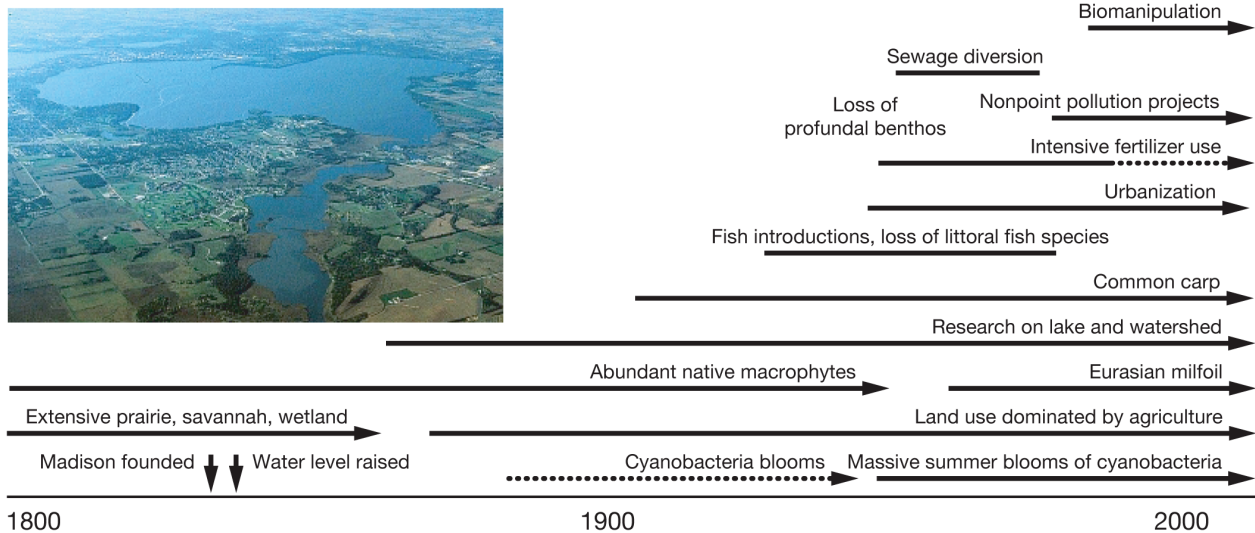


Figure 5. Since 1850, the NHL and YLD have been shaped by different trends and sequences of events. (A) Timeline of major changes in the NHL. (B) Timeline of major changes in the YLD. Source: Carpenter et al. 2007.

at several scales within each lake district. In particular, we focus on three interdisciplinary topics: regional carbon cycles, landscape ecology of invasive species, and self-organization of land owners.

D. Ecosystem Services: Past, Present and Future: *What are the magnitudes, interactions and potential future flows of ecosystem services in lake districts?* Understanding ecosystem services, the benefits that people receive from ecosystems, requires interdisciplinary analysis. We explore effects of climate, land-use change, and biofuel production on freshwater ecosystem services, interaction of lake ecosystem services with development patterns around lakes, and feedbacks among species invasions, lake ecosystem services, and human actions to manage invasions.

These four goals are connected by our common study regions, long-term perspective, multi-scale interdisciplinary approaches, and focus on lakes as receptors and integrators of regional change. In the following sections, we describe research priorities in each of the four focal areas, followed by a synthesis section that addresses the significance of the research.

A. Perception of Long Term Change

One of the foundations of the NTL LTER program is the ability to perceive and understand causes of long-term change in the coupled human and natural systems of the NHL and YLD. The collection and management of ecologically relevant data that allow investigators to observe and analyze long-term changes are crucial to understanding these regions (Carpenter et al. 2007, Liu et al. 2007). Natural phenomena, such as strong year-classes of long-lived predators or a series of drought years, can cause multi-year to decadal effects in lakes, often with substantial time lags between cause and effect (Magnuson 1990, Magnuson et al. 1990, Carpenter and Leavitt 1991, Webster et al. 2000, Kratz et al. 2003). In addition, many human-induced pressures influencing lakes, such as nutrient enrichment, climate change, or transport and establishment of exotic species operate over time scales of years to decades or longer (Fig. 6). The accumulation and interactions of the effects of these drivers can cause changes that are difficult to understand without a long-term context (Magnuson et al. 2006, Carpenter et al. 2007). To provide such a context for our research, we collect and maintain a series of core, associated, and reference datasets (see Supplementary Documents and Section 4. Information Management). These datasets provide the basis for addressing most of our research questions and constitute one of the most comprehensive and accessible long-term limnological databases in the world. Our thematic question is: ***How and why have the lake districts changed and how will they change in the future?***

Several major changes are likely in our lake districts in coming years. For example:

- New exotic species are likely to appear. Non-native fishes (ruffe, rudd, round goby, Asian carp, etc.), zooplankton (*Bythotrephes cederstroemi*, *Eurytemora affinis*, etc.), molluscs (zebra and quagga mussels, fingernail clams, and a variety of snails), a macrophyte (Eurasian watermilfoil), and a highly toxic cyanobacterium (*Cylindrospermopsis raciborskii*) are poised either to invade our primary study lakes or spread from one study lake to another. In 2007, we discovered the first known instance of spiny water flea (*Bythotrephes cederstroemi*) in a Wisconsin inland lake only 15km from our NHL primary study lakes. Zebra mussels now thrive in lakes 50 km from the YLD.

- It is probable that the first ice-free winter in history in the Yahara Lake District will occur within the next two decades (Fig. 7). An ice-free winter would fundamentally alter the physical mixing regime of lakes with important consequences for heat balance, nutrient cycling, carbon dynamics, and community composition of most taxonomic groups.
- Turbulence in the lending market, changing distributions of human age and wealth, and changes in demand for ecosystem services are likely to affect the housing market in our lake districts, with implications for socioeconomic patterns and feedbacks to ecosystems.

We maintain a measurement system of physical, chemical, biological, and socioeconomic data that will allow us to detect and understand the impacts of these and other, unanticipated, changes.

A.1. Background.

Since 1981 we have been conducting a balanced and integrated data collection program (e.g., Kratz et al. 1986, Magnuson and Bowser 1990, Magnuson et al. 2006; online data catalog at http://lterquery.limnology.wisc.edu/index_new.jsp?project_id=LTER1). We selected lakes and measurements to address important interdisciplinary questions regarding the ecology and management of lakes from a long-term perspective at individual lake, multiple lake, lake-district and regional scales.

Study regions. We focus our data collection on two sets of lakes and their surrounding landscapes (Table 1, Fig. 4). Both regions have a substantial history of ecological research dating back to the early 1900s (Frey 1963).

From 1981 onwards, we have focused on seven primary lakes and their surrounding terrestrial areas in the NHLD. These lakes are linked by a common groundwater and surface water flow system and share a common climatic, edaphic, and biogeographic regime (Fig. 4). The lake set includes oligotrophic, dystrophic, and mesotrophic lakes (Table 1) chosen to represent marked differences in size, morphometry, habitat diversity, thermal and chemical features, species richness and composition, and position in the groundwater flow system. In 1994, we expanded our regional and disciplinary scope by adding four primary study lakes in the YLD (Table 1, Fig. 4). These four eutrophic lakes were chosen in a 2x2 design of urban vs. agricultural setting and headwater vs. lower in the landscape. Substantial historical data are available on YLD lakes (Watson and Loucks 1979, Brock 1985, Kitchell 1992, Lathrop et al. 1992). In addition to the 11 primary lakes we also have a set of secondary lakes for which less-complete information is collected on an ad hoc basis to address specific research questions.

Core data collection. Our sampling program allows comparisons of parameters and processes among seasons, years, lakes, and lake districts. We sample most major physical, chemical and biological components (Table S2C) with sampling frequencies tuned to the dynamics of individual parameters. We sample most intensively at four key times of the year: spring overturn, maximum stratification in summer, fall overturn, and winter stratification. Complete cation-anion balances are determined at these times. Nutrients, pH, and inorganic and organic carbon are sampled every two or four weeks, depending on the lake and the nutrient. Temperature,

Table 1. Characteristics of the eleven primary LTER study lakes. For each region and land use type, the lakes are ordered by their landscape position in the hydrologic flow systems.

	NORTHERN HIGHLANDS LAKE DISTRICT							YAHARA LAKE DISTRICT			
	~~~~~ Forested ~~~~~							~~~ Agricultural ~~~ ~~~~~ Urban ~~~~~			
Characteristic	Crystal Bog (27-2)	Trout Bog (12-15)	Crystal Lake	Big Muskellunge Lake	Sparkling Lake	Allequash Lake	Trout Lake	Fish Lake	Lake Mendota	Lake Wingra	Lake Monona
Landscape position	high	high	high	intermediate	intermediate	low	low	high	low	high	low
Area (ha)	0.5	1.1	36.7	396.3	64.0	168.4	1607.9	87.4	3937.7	139.6	1324
Mean Depth (m)	1.7	5.6	10.4	7.5	10.9	2.9	14.6	6.6	12.8	2.7	8.2
Maximum Depth (m)	2.5	7.9	20.4	21.3	20.0	8.0	35.7	18.9	25.3	6.7	22.5
Duration of ice cover (days)	152	154	138	141	136	147	135		86	107	86
Water Temperature (°C)	19.9	17.9	21.0	21.2	21.1	21.6	20.1	23.9	22.4	23.9	23.3
Secchi Depth (m)	1.5	1.1	7.5	6.6	6.2	3.2	4.7	2.4	3.0	0.7	2.4
pH	5.2	4.8	6.1	7.3	7.4	7.6	7.6	8.1	8.4	8.5	8.5
ANC (µeq/L)	14	11	23	390	631	831	846	2921	3665	3745	3547
Conductivity (µS)	11	23	13	50	86	92	96	280	412	500	434
Total P (µg/l)	18.2	46.6	8.3	17.5	15.0	29.3	13.5	22.4	109.5	40.3	73.5
Total N (µg/l)	722	961	210	441	371	379	247	835	860	933	845
SiO ₂ (µg/l)	834	1927	48	309	7217	13853	9529	367	771	5551	454
Chlorophyll (µg/l)	9.9	16.2	1.8	3.1	2.2	7.8	3.1	5.1	4.8	10.5	8.1
Fish species (cumulative)	1	3	24	34	30	36	42	26	43	29	41
Development on shoreline	low	low	low (campground)	moderate	moderate	low	moderate	high	high	high	high

Water temperature (0-2m) and Secchi from June 1 - August 31; pH, ANC, and conductivity from the average of spring and fall mixis sampling; total P, total N, and SiO₂ from spring mixis; chlorophyll (surface) from open water season; Northern Highlands Lake District lakes averaged from 1982 – 2006, Yahara Lake District averaged from 1996 – 2006.

dissolved oxygen, chlorophyll a, light penetration, and zooplankton abundance are sampled every two weeks during the open-water season and every five weeks under ice cover. Primary production rates are measured every two weeks from selected lakes, and samples for phytoplankton community composition are collected six times throughout the year. Parameters that vary over longer time scales are measured annually in August. These include macrophyte distribution and abundance, fishes (abundance, lengths/weights, and community structure), and benthic invertebrate abundance. Groundwater levels in selected wells are measured monthly, and groundwater chemistry from a subset of these wells is measured annually. Statistical studies in 2007 evaluated the ability of our sampling program to detect differences between lakes and between years for a diverse set of physical, chemical and biotic variables. Our sample sizes are adequate and efficient; we are not over- or under-sampling.

Through our leadership in the Global Lake Ecological Observatory Network (GLEON) (<http://gleon.org>, Porter et al. 2005, Kratz et al. 2006, Tilak et al. in press, Williamson et al. in press), we operate instrumented buoys on selected primary lakes in the NHLD and YLD, and we help to develop, deploy, operate, and analyze data from instrumented buoys on lakes throughout the world. GLEON has members in the Americas, Asia, Oceania, the Middle East and Europe. One goal of GLEON is to make near real-time data from these sites available to the research community and the public. The buoys deployed in the NHLD and YLD measure water temperature profiles, surface dissolved oxygen, and relevant meteorological variables at 1-10 minute frequencies. Some of the buoys measure additional variables, including currents via acoustic Doppler and algal biomass via fluorescence. In addition, in the NHLD we maintain an automated land-based weather station at the Minocqua airport 10 km from Trout Lake. In the YLD we use National Weather Service data from the Dane County Regional Airport.

Our long-term measurements are complemented by whole-lake experiments. We are currently assessing ecological responses to an experimental removal of two invasive species, rusty crayfish and rainbow smelt, from Sparkling Lake. We manipulated woody habitat in two lakes to assess effects on fish growth and community structure (Sass et al. 2006). Interventions to restore lakes of the YLD comprise an ongoing program of management experiments for which NTL provides data, analysis and synthesis (Carpenter et al. 2006).

To provide basic information about the terrestrial landscapes surrounding our study lakes, we have developed a geographic information system (Table S2D) that includes data layers on land use/land cover, soils, topography, roads, and other landscape features. We have a particularly strong foundation of spatial data on land use and land cover, including a statewide pre-settlement vegetation database, detailed historical land-use/land-cover databases from the 1930s, 1960s, and 1990s for watersheds or riparian zones of selected study lakes, and the statewide WISCLAND land-cover database (Lillesand et al. 1998).

In addition to land use and land cover, we collect a series of socioeconomic datasets. We have developed a historical (1974-2006) GIS layer of parcel subdivisions for Vilas County in the NHLD. This layer was developed by using a 1996 GIS layer of parcel boundaries created by Vilas County as a foundation from which to backcast parcel subdivision to 1974, and to update parcel subdivision to 2006, using commercial plat maps. We maintain a dataset of market prices for shoreline parcels that is matched to the GIS layer of parcel boundaries. This dataset is

developed from market sales records provided each year by the Wisconsin Department of Revenue. We also maintain a long-term record of boat use in the YLD.

Finally, we manage an extensive archive of airborne and satellite imagery for both the northern and southern lake regions (Table S2D). The majority of this archive consists of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images from 1984 to the present as well as daily MODIS imagery from 2001 to the present. Other available image data sources include the EO-1/Advanced Land Imager and Hyperion imaging spectrometer, high resolution (1m to 4m) IKONOS images for the NHL and YLD, daytime and nighttime thermal images from ASTER, the NASA ATLAS airborne multispectral and thermal scanner, and the Shuttle Imaging Radar-C (SIR-C) system (Table S2D).

## **A.2. Proposed New Initiatives**

The core datasets listed in Table S2 provide the foundation for addressing most of the research questions presented in this proposal. We will continue to collect and maintain these datasets. New initiatives for our long-term datasets are described below.

Synthesis of Change. Over long periods of time, ecosystems exhibit many different dynamical patterns, for example, gradual change, regime shifts, multi-year oscillations, or pulse events (Fig. 8). The empirical characteristics of these patterns are fundamental for developing and testing theories of ecosystem stability and change, yet the prevalence of the various patterns has rarely been determined for multiple variables in multiple ecosystems over long periods of time (Ives and Carpenter 2007). We will evaluate temporal trends, variability, and correlations in the NTL time series to evaluate question such as: What are the patterns of change (e.g., stochastic stability, trends, oscillations, regime shifts, etc.)? How does variance in time change with the spatial scale of aggregation? What variates (abiotic, biotic, social) are most sensitive to change? What new, and potentially causal, linkages are suggested by temporal correlation? Past analyses have focused on parts of our long-term data to evaluate occurrence, causes, and consequences of change (Magnuson et al. 2006, Hanson et al. 2006, Carpenter et al. 2007). Here, we propose a more comprehensive assessment of change across the diverse variates of our core datasets. We will employ graphics, simple descriptive time series models, trend and changepoint analyses, multivariate autoregressions and other time-series methods, starting with a simple search for pattern and adding complexity to the analysis as appropriate (Fortin et al. 2005, Harvey 1991, Hilborn and Mangel 1997, Ives et al. 2003, Powell and Steele 1995, Seurant and Strutton 2004, Wei 1990). Where we find evidence of regime shifts, we will evaluate leading indicators such as changing variance, slower return time from perturbation, or reddened spectra (Carpenter et al. 2007, van Nes and Scheffer 2007).

Long-Term Surveys. Land use of NTL watersheds and shorelands is changing as road networks and building densities increase (Carpenter et al. 2007). In the NHL change is most conspicuous on lakeshores (Fig. 9). In the YLD, agricultural lands are converted to urban uses (Fig. 10) with effects on runoff and nutrients. Freshwater systems are increasingly important for flood regulation and cooling of power plants in the YLD. Use of lakes for recreation is increasing in both regions. As attractors of human activity and icons of quality of life, lakes are a magnet for

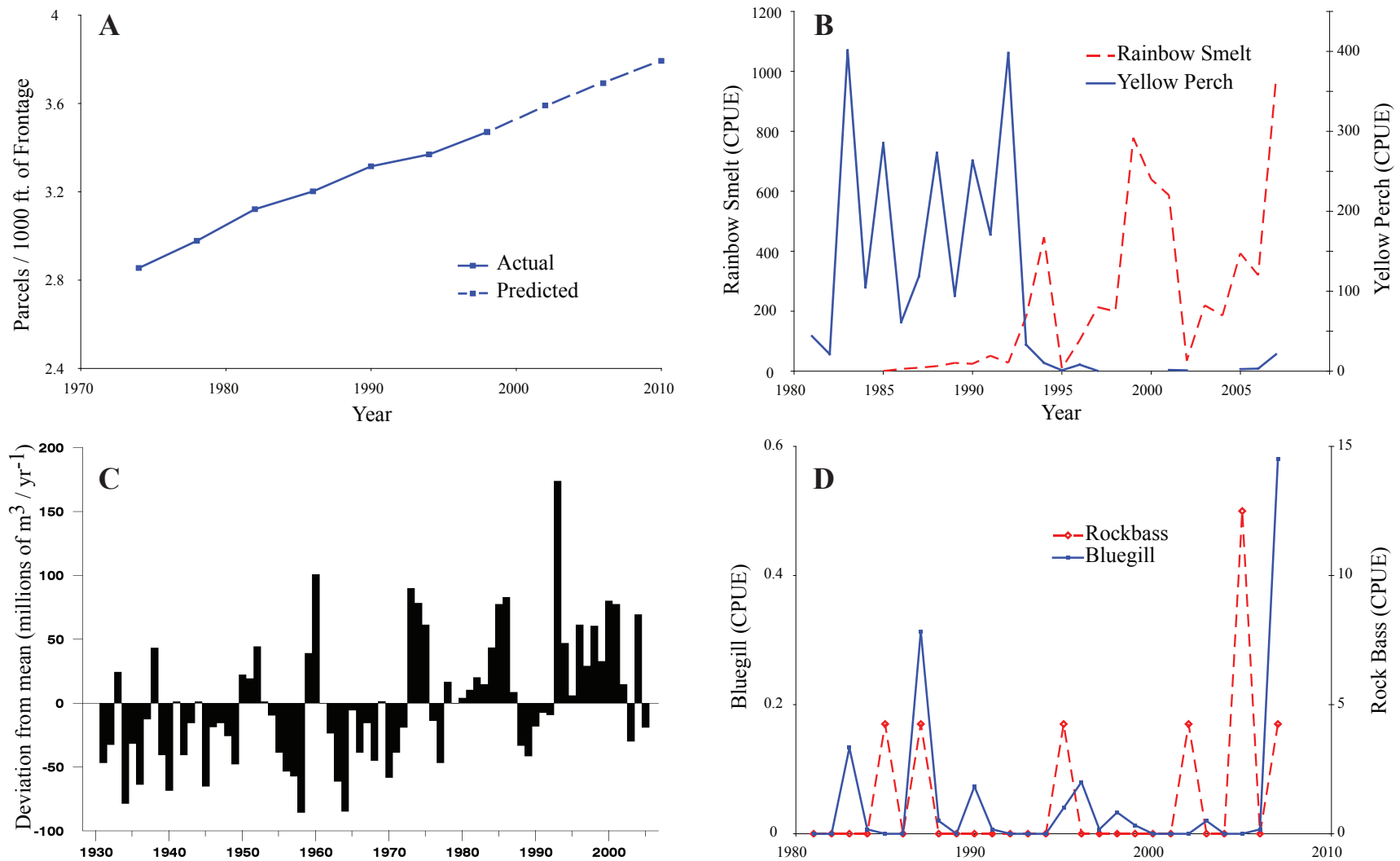
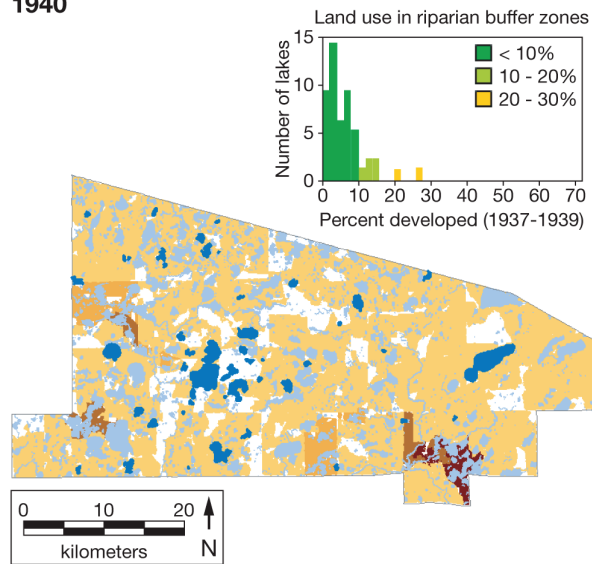


**Figure 8.** NTL datasets exhibit diverse kinds of change, illustrated here by four different examples. (A) Linear trend: residential development on lakeshores of the NHLD. (B) Abrupt change: abundance of yellow perch and rainbow smelt in Crystal Lake. Rainbow smelt invaded the lake in the late 1980s and caused the extirpation of yellow perch. (C) Multiyear oscillations: discharge of the Yahara River. Oscillations result from variations in precipitation passing through a series of lakes with different water residence times. (D) Pulse events: abundance of young-of-year (YOY) bluegill and rock bass in Allequash Lake is the result of sporadic recruitment events.

### Northern Highlands Lake District 1940



2000

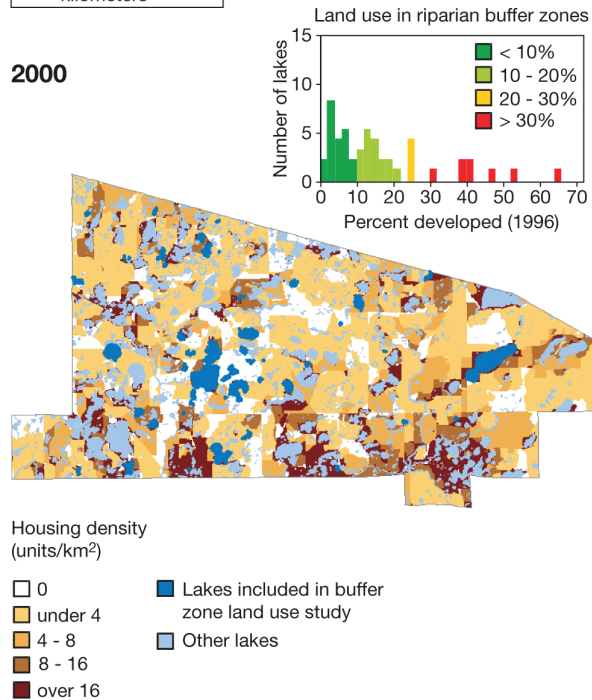
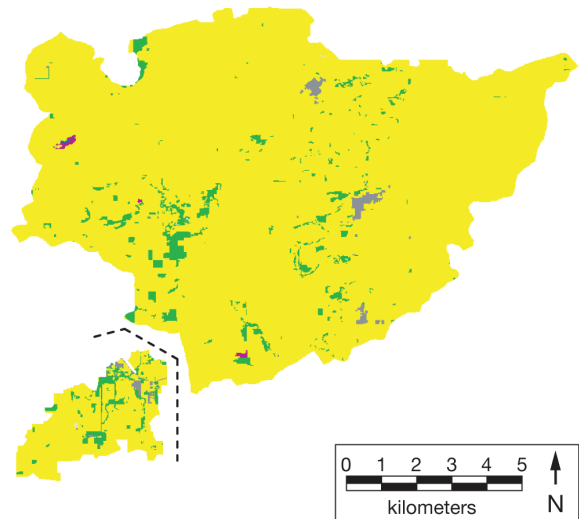


**Figure 9.** In the NHLD, housing density increased from 1940-2000 and the new development tended to occur on lake shores. Maps show Vilas County land use in 1940 and 2000. Inset histograms show increases in residential development within 100 m of lakeshore in 1937-1939 and in 1996.

### Yahara River Lake District: Upper Yahara and Spring Harbor subwatersheds 1937



1995

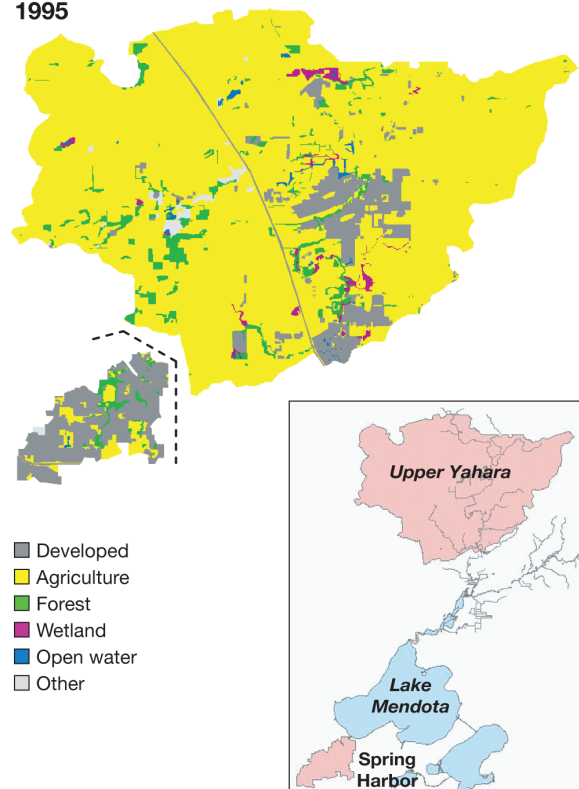


**Figure 10.** In the YLD, residential and urban development tended to replace farmland between 1937 and 1995. Maps show the Upper Yahara watershed (larger image) and Spring Harbor watershed (smaller image) in 1937 and in 1995. Inset shows the locations of these watersheds relative to the lakes.

social-ecological interactions at NTL and are therefore a natural focus of interdisciplinary research.

We propose to add two surveys of shoreline and near-shore property owners as new, long-term, social science core datasets. We plan to repeat these surveys in each subsequent 6-year funding cycle, thereby creating a long-term dataset of social-ecological interactions around lakes. In each funding cycle, one survey will focus on shoreland and upland property owners (Provencher and Schoen 2007), and the other will focus on lake users (i.e., boaters and anglers). Each survey will comprise a set of base questions to be repeated in each funding cycle, and a set of cycle-specific questions designed to inform research questions specific to the funding cycle. Some survey questions will be region-specific to reflect the different social and ecological characteristics of the NHL and YLD. Base questions are intended to elicit four types of data: (1) value that respondents place on such ecosystem services as lake water quality, lake biodiversity, fish production, prevention/control of aquatic invasive species, and shoreline open space; (2) respondent activities with implications for lake ecology (boating, fishing, modification of habitat, etc.); (3) role of social interactions in the willingness of respondents to participate in collective action to influence lake or watershed conditions; and (4) comparisons of household values and behaviors across the NHL and YLD regions. As opportunities emerge for collaborative social-ecological research across the LTER network, we expect to coordinate questions for the fourth type of data with other LTER sites.

As noted above, we will add questions to address research themes particular to current and funding cycles. This time, questions will be added to the surveys to address research goals about human perceptions of climate change (section B), household sorting (section C.3), development patterns around lakes (section D.3), and invasive species (section D.4).

To the extent possible, the survey of property owners will target the same set of parcels (not necessarily the same people) in each cycle which will allow us to develop a long-term dataset connecting social data to particular spatial locations. By understanding how the attitudes and behaviors of people occupying the same properties change over time we will be able to assess how changes in lake ecology co-evolve with changes in preferences and behaviors along a lakeshore. Answers to the survey questions will be used in social-ecological models. We will quantify the values that shoreland property owners place on lake characteristics such as water clarity and shoreland open space. We will derive economic values for these aspects of ecosystems using established economic methods, including hedonic valuation and contingent valuation (Haab et al. 2002, Champ et al. 2003). Recent studies stress heterogeneity in household preferences (Boxall et al. 2002, Provencher and Bishop 2004, Morey et al. 2006, Provencher and Moore 2006). Thus, our analysis will examine variability among property owners in the value they place on ecosystem goods and services by modifying the econometric models to allow for multiple “latent classes” of preferences over ecosystem goods and services. In addition, the survey of boaters and anglers will allow us to use travel cost methods to estimate value of ecosystem characteristics.

Spatial Analysis Tools. Because understanding spatial dynamics in a long-term context is fundamentally important at our site, we propose to develop new functionality that allows us to analyze and visualize long-term dynamics across space. We will develop tools that dynamically

segment, display, and export NTL-LTER datasets based on a user-provided spatial extent (e.g., a watershed, riparian buffer, or groundwater recharge zone). In addition, we will customize existing geoprocessing algorithms for use with these derived data. By creating the capacity for user-guided mapping and spatial analysis, we intend to catalyze new analyses of physical, chemical, biological, and social data based on spatial operators such as proximity and intersection.

## **B. Climatic Forcing of Change**

We are on the cusp of significant changes in temperature and precipitation at regional and global scales (IPCC 2008). Specific predictions vary, but it is expected that the Midwestern U.S. will experience warmer winters, longer droughts, and more intensive and protracted stormy periods (Magnuson et al. 1997, Kling et al. 2003). These climate changes may have substantial consequences for lakes as well as human uses of lake resources. The intent of work proposed in this section is not to predict specific future conditions driven by climate change, but rather to understand the range of possible changes that might occur in lake districts. To this end, we will use multiple approaches, including examination of climate-lake relationships from different historic datasets, modeling, and experiments, all of which are organized around the thematic question: ***What are the major social-ecological responses of lake districts to climate change?*** We address this question at multiple scales: across our two lake districts, within each lake district, and within individual lakes. We focus on three topics: hydrological networks, hydrodynamics, and biogeochemical and biotic change.

Social, biotic and abiotic processes: This section of the proposal emphasizes abiotic and biotic responses to climate change. Research on social-ecological interactions at NTL has emphasized aspects of land-use change and policy, shoreland issues, and invasive species and we build on that foundation in other sections of this proposal. To initiate studies of social-ecological aspects of climate change, we will add questions to our surveys (A.2, Long-Term Surveys) to address social perceptions and attitudes about climate change in the NHL and YLD. Analyses of these responses will provide a foundation for further social science research on climate change in future funding cycles.

### **B.1 What nodes of regional hydrologic flow networks are most sensitive to climate-driven changes?**

Causes and effects in complex systems such as lake districts are not necessarily close in space and time (Senge 2006). Because of the distribution of flowpaths and transit times from uplands to surface waters, we can expect that individual freshwater ecosystems differ in their sensitivity, resilience, and response time to climate change based on their location in the local to regional flow system. Similarly, chemical and biological attributes of lakes and lake districts should show a range of responses to direct and indirect effects of a changing climate. Are there particular lakes, streams or wetlands, or components of these ecosystems that are exceptionally sensitive indicators of change? What is the relative sensitivity of different ecosystems or different variables? The goal of this research is to examine the sensitivity of ecosystems and variables within flow networks of the NHL and YLD so that we can identify indicators and potential consequences of a changing climate.

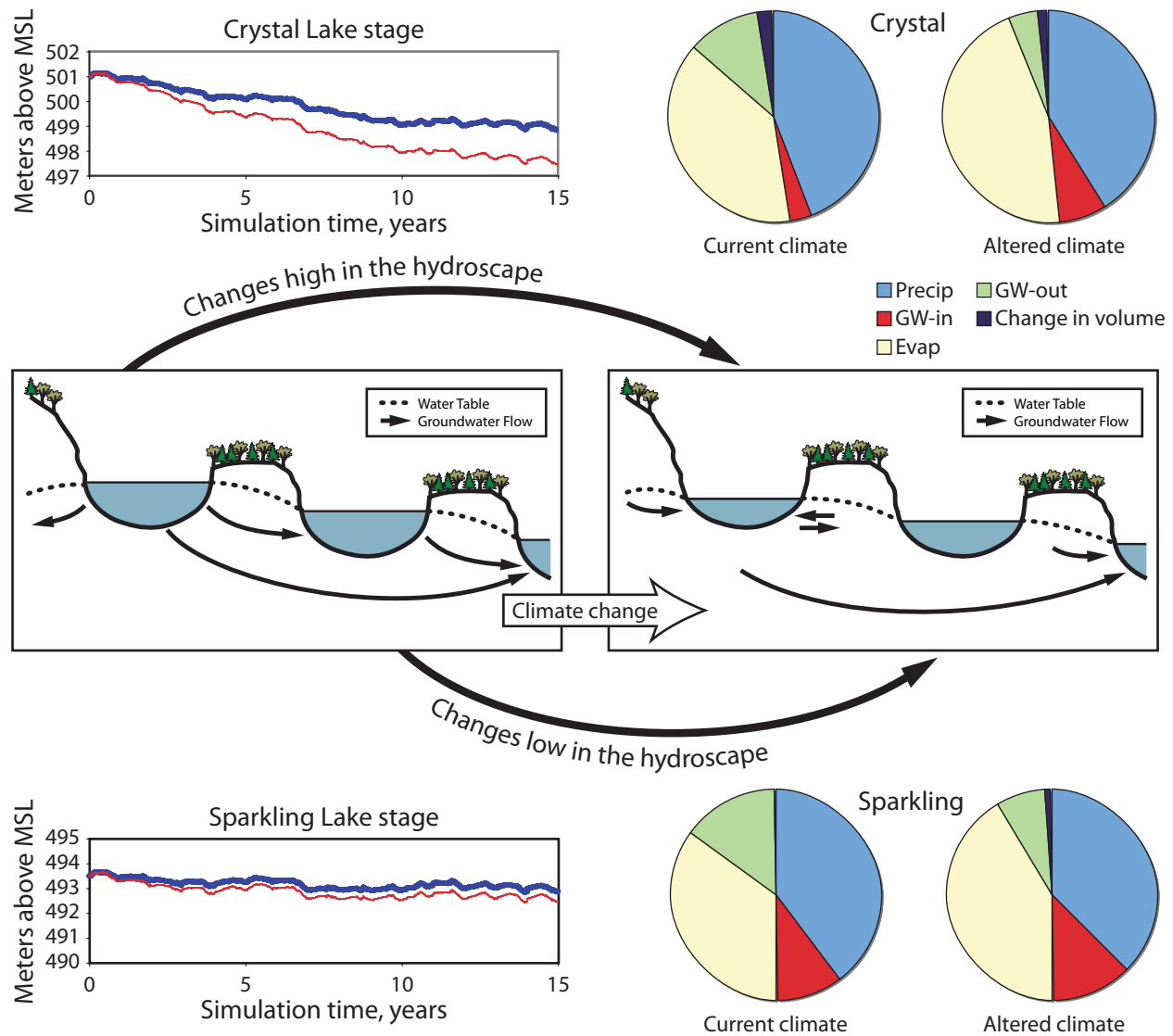


**Figure 11.** Climate change influences the hydrology of lakes, and the effect depends on landscape position. The two cross-sections showing lake-groundwater interactions under current climate conditions and a future warmer climate scenario illustrate our hypothesis of differential hydrologic response as a function of landscape position. We simulated lake level (line graphs on left), groundwater flow paths, and lake water budgets (pie charts on right) for a 15-year period under current and altered climate conditions in the NHLD using GSFLOW (see Section B.1). Crystal Lake, a lake high in the landscape, experiences a decline in lake stage (meters above mean sea level [MSL]) of nearly 6 times the annual lake stage variation (thin red line) in a warmed climate relative to current conditions (thick blue line), whereas stage shows little change among the two scenarios for Sparkling Lake lower in the landscape. Further, in a warmed climate, high landscape lakes such as Crystal Lake shift from their current status of groundwater sources (GW-out; pie charts) to sinks (GW-in), whereas groundwater fluxes and overall water budgets change little for Sparkling Lake lower in the landscape.

Past NTL research has emphasized effects of landscape position on lake attributes (including sensitivity to climate change; Webster et al. 1996, 2000) because different landscape positions are associated with relatively predictable and distinct suites of flowpaths (Kratz et al. 1997, Magnuson et al. 2006). Over the next six years, we will continue to investigate watershed and hydrologic influences on lakes to extend the Lake Landscape Position paradigm toward quantitative analysis of hydrologic and limnological consequences of changing regional drivers. To identify sensitive hydrologic indicators in such a quantitative framework, we will take advantage of the newly developed coupled Ground-Water/Surface-Water Flow model (GSFLOW, Markstrom et al. 2007), recently applied to the Trout Lake Watershed (Hunt et al. in prep., Walker et al. in prep.) and calibrated with parameter estimation software (PEST, Doherty 2006). PEST uniquely provides an advanced framework to assess model prediction uncertainty and the value of future data for reducing uncertainty (Doherty 2006). The latter capability allows comparison of the ability of different monitoring locations and data types to detect changes in a given variable. Thus we can use this modeling approach to assess when and how lakes with different landscape positions respond to altered climate and thereby evaluate their value as sentinels of change (Fig. 11).

## **B.2 What climate conditions change lake hydrodynamics?**

Climate change will directly affect the physics of lakes, for example by changing heat budgets, water volumes, and residence times. In temperate zones, seasonal weather patterns create thermal and hydrodynamic patterns of complete water column mixing in spring and fall separated by periods of thermal stratification in summer and winter (i.e., a dimictic mixing regime). In turn, these phases of stratification and mixing influence most ecological aspects of lakes (Wetzel 2001). Increases in air temperature across the Northern Hemisphere have shortened the duration of ice cover on lakes, with trends showing both later freeze and earlier thaw (Magnuson et al. 2000, Jensen et al. 2007, Sellinger et al. 2008). These changes in ice phenology are leading to earlier onset of thermal stratification, and deeper thermocline depths in late summer and fall in larger and deeper lakes (Robertson and Ragotzkie 1990, De Stasio et al. 1996, Magnuson et al. 2006). If lakes fail to freeze in winter, mixing should continue throughout the winter. That is, the absence of ice would shift lakes from dimictic (mixing in spring and fall) to monomictic (mixing continually from late fall until spring). Summer mixing regimes can also be affected by climate change, depending on lake size and depth (King et al. 1991, Austin and Colman 2007, George et al. 2007). For example, shallower lakes may mix multiple times during summer (polymixis) because the deep water is warmer and thereby weakens stratification. Even in Lake Mendota, a relatively deep lake, we have observed variability in the strength of stratification among summers, with significant effects on nutrient upwelling and primary producers (Lathrop et al. 1999). Given that a lake's thermal structure and mixing regime represent a fundamental physical template for the ecosystem, determining if and how this template changes is an essential first step for understanding the limnological consequences of climate change in lakes.

Because the features of each lake filter the way that climate signals are expressed in a lake's behavior (Magnuson et al. 2006), we are interested in the following questions: How do thermal/hydrodynamic conditions vary among lakes for a particular climate scenario? What climate conditions are needed to alter the mixing regimes of different lakes? We will examine

relationships between climate conditions and thermal regimes in lakes using both 1- and 3-dimensional hydrodynamic models. We will use a 1-D model that specifically includes an ice component (DYRESM; Hamilton et al. 2002) to examine hydrodynamics in different lakes and different climate scenarios to identify lakes that are susceptible to shifts in mixing pattern for a given climate future. These cases will then be examined in greater detail with a more complex 3-D model (3DNYHS) developed during the prior funding cycle (Yuan and Wu 2004a,b, Wu and Yuan 2006, Yuan 2007). 3DNYHS is capable of simulating 3D circulation patterns and spatio-temporal gradients in temperature (Fig. 12), and is calibrated and validated using NTL-LTER datasets. Sensitivity analysis will evaluate the effects of meteorological variables on model results. Using these models and climate change scenarios, we will predict the magnitude of warming that is likely to alter winter and summer mixing regimes of shallow (Allequash in the NHL, Wingra in the YLD) and deep (Sparkling in the NHL, Mendota in the YLD) lakes.

### **B.3. How do changes in lake thermal structure affect biogeochemistry and ecology?**

Longer ice-free periods, altered mixing, warmer summer water temperatures, and prolonged changes in water levels all have diverse chemical and biological impacts in lakes (Hill and Magnuson 1990, Brooks and Zastrow 2002, Petterson et al. 2003, Webster et al. 2006). For example, precipitation affects nutrient loads in the ice-free season (Fig. 13), suggesting that the relationship of annual load to precipitation may change if ice-free seasons become longer. Drought affects dissolved organic carbon concentrations in lakes (Fig. 14), a key factor in light attenuation and ecosystem metabolism (Hanson et al. 2003, Houser et al. 2003).

Present understanding of the sensitivity of different limnological parameters to climate change is based on a few case studies and extrapolations of a limited set of variables (e.g., Niemisto and Horpila 2007, Sharma et al. 2007). We propose to build on these sorts of analyses and expand their scope by integrating three complementary approaches to identify chemical and biological parameters that are particularly responsive to climate dynamics: a retrospective analysis of NTL data, paleolimnological studies, and experiments that manipulate water column mixing.

Retrospective analyses: What variables have been sensitive to changes in temperature and precipitation patterns during the decades of LTER research, and how have they changed? A full suite of physical, chemical, and biological parameters will be examined (see A.2, Synthesis of Change). Examples include physical measures such as lake temperatures and groundwater levels, dissolved CO₂ (Hanson et al. 2006), oxygen deficits (Stefan et al. 1995) and biota such as fishes (Willis and Magnuson 2006). The availability of P has a wide range of consequences for both of our lake districts (Beisner et al. 2003, Carpenter et al. 2007), and we have preliminary evidence that internal N and P loading (i.e., release of inorganic nutrients from anoxic lake sediments) is sensitive to changes in lake levels in wet and dry years (Stauffer and Lee 1973, Soranno et al. 1997). Therefore, we will pay particular attention to nutrients, including calculated rates of internal loading. We will address average trends as well as variances and autocorrelation coefficients that may indicate incipient thresholds (Carpenter and Brock 2006).

Paleolimnology: Studies of lake cores will be used to reconstruct components of lake hydrology, chemistry, and biology during periods with contrasting climate regimes across lakes with contrasting physical characteristics (large vs. small, shallow vs. deep). By coordinating the

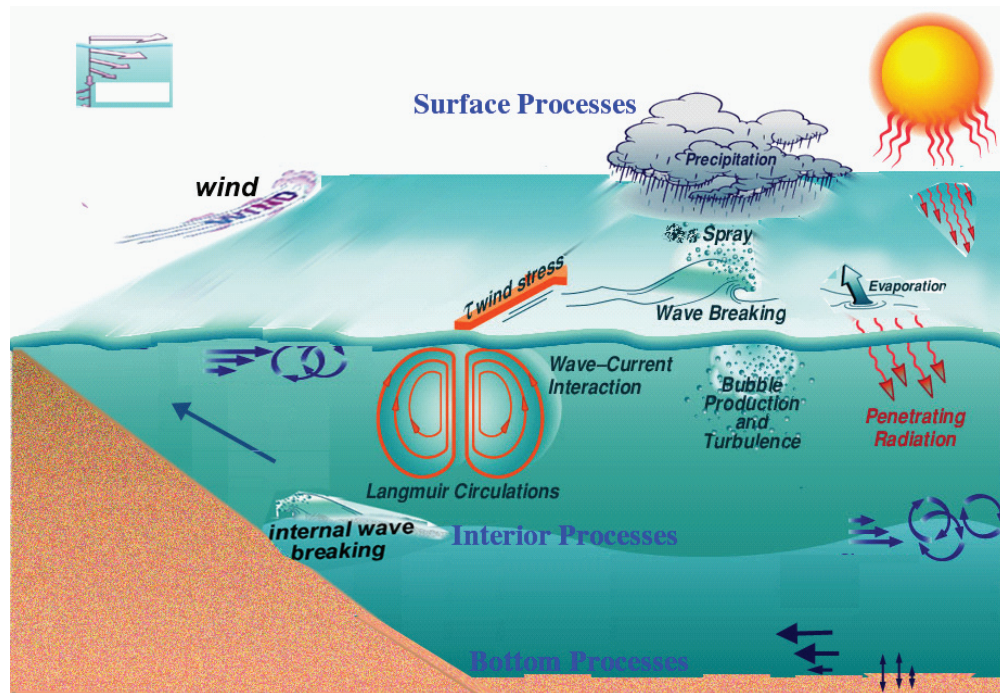


**Figure 12.** The 3-dimensional non-hydrostatic model of hydrodynamic flows integrates the flows of water and solutes depicted in this illustration. Inset at upper left shows Ekman transport.

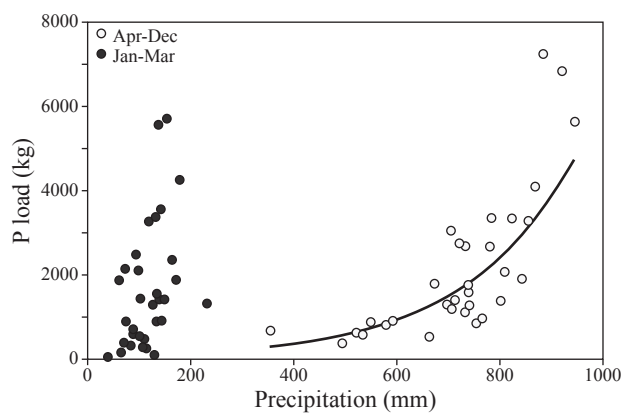


**Figure 13.** Phosphorus (P) input to lakes are variable and sometimes high during January to March (black dots) due to manure runoff caused by snowmelt or light rain when the ground is frozen or water-saturated. Much of this P is dissolved. During the remainder of the year, P input increases exponentially with precipitation (open circles), indicating the importance of large storms transporting huge loads of sediment-bound P. If climate change increases the frequency or intensity of large storms during the spring and summer months, P inputs to lakes would increase.

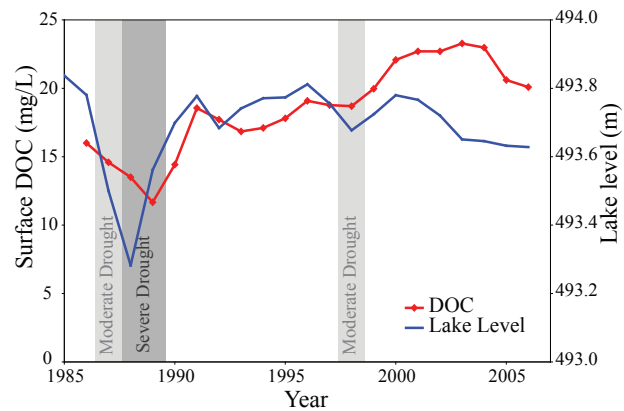


**Figure 14.** Dissolved organic carbon (DOC) concentrations in Trout Bog decreased during a severe drought (more than 3 months with Palmer Drought Severity [PDS] index below -4) due to decreased inputs (reflected in lowered lake levels) and increased photodegradation. Moderate drought (PDS index between -3 and -4) had lesser effect.

retrospective and paleo analyses, we will compare detailed histories of specific variables during particular climatic periods in several lakes with a degree of replication and calibration usually unavailable in paleolimnological studies. Well-calibrated paleolimnological techniques will give us access to observations over a much broader range of climatic conditions than has been observed during recent decades. This broader range will give us greater statistical power to identify those variables that have been responsive to past climate change extremes.

Mixing Experiments: We will conduct enclosure experiments manipulating both the frequency and intensity of mixing events, while measuring both proximate limnological drivers (O₂ and nutrients) that are altered by mixing, as well as the responses of microbial and plankton communities. These short-term mixing events should have the strongest impact on microbes and phytoplankton due to their short generation times and sensitivity to environmental conditions (e.g., Yannarell et al. 2003, Kent et al. 2004, Reynolds 1997). We expect that mixing will (1) increase rates of ecosystem primary production and respiration, (2) increase rates of community turnover in microbes and phytoplankton, and (3) shift dominance of the phytoplankton to larger-celled or colonial species.

We have started to investigate the possibility of a whole-lake mixing experiment to simulate the consequences of an ice-free winter, which may occur naturally for some of the YLD lakes in the foreseeable future. Using the 3DNYHS model (Section B.2) we will evaluate the feasibility of breaking down the stratification of a lake by aeration (Ashley 1985). We have begun discussions with government authorities to explore the policy framework for such a whole-lake mixing experiment. If modeling and the discussions indicate that the project is feasible, we expect to initiate the experiment late in this grant cycle or in the next one. This whole-lake experiment would allow us to evaluate the integrated responses of biogeochemistry, microbes, and phytoplankton with longer-lived zooplankton and fishes relative to a nearby undisturbed reference lake (Carpenter 1998). We expect that mixing will increase rates of nutrient recycling, primary production and total ecosystem respiration, decrease the rate of carbon storage in sediment, extirpate fishes that require a cold-water refuge in summer such as the invasive rainbow smelt, shift zooplankton communities toward species with shorter generation times, shift phytoplankton toward larger-celled or colonial species, and increase the rate of species turnover in microbial communities.

### **C. Interacting Drivers, Scales of Space and Time, and Regional Change**

Ecological research has substantially enhanced the understanding of ecosystem response to individual disturbances or driving variables. However, ecological systems face an array of drivers and disturbances that may occur simultaneously or sequentially. Consequently, understanding and predicting ecological responses to ensembles of drivers is a key research frontier (Folt et al. 1999, Frost et al. 1999, Christensen et al. 2006). The challenge of multiple causation is increasingly important as the combined effects of climate change, land-use change, altered disturbance regimes, nutrient mobilization, and invasive species are considered in the NTL lake districts (Carpenter et al. 2007). Interactions among drivers are unlikely to be additive, and ecosystems may show increased vulnerability to particular combinations or sequences, leading to changes that are difficult to anticipate (Peters et al. 2004, Groffman et al. 2006). Interactions among drivers may either amplify or dampen a particular response, depending on

whether positive or negative feedback is elicited (Peters et al. 2004). These considerations prompt our thematic question: ***How do multiple interacting drivers affect regional change in lake districts at multiple scales?***

While this broad question captures the scope of our ambitions, a complete analysis of all drivers, interactions and scales is not practical within a single grant cycle. With this in mind, we have selected three interdisciplinary topics which address important changes in our lake districts, require the long-term perspective of LTER, and are logical extensions of our past work: regional carbon cycles, landscape ecology of invasive species, and self-organization of landholders in lake districts. These topics embrace a wide range of disciplinary perspectives, and each illuminates a distinct aspect of the thematic question.

### **C.1. How do interactions of climate and land use change influence carbon dynamics of lake districts?**

We are in an era of significant global changes in climate and land use (M.A. 2005). Prolonged droughts and storm intensification, along with ongoing trends of shortened winter ice duration (Section B) are projected to occur in landscapes that are simultaneously undergoing shifts in land use and cover. Both the NHL and YLD are experiencing population increases that expand shoreland development in the NHL and urban extent in the YLD. Farm practices are also changing in the YLD, with a trend toward fewer, larger farms with more intensive practices (e.g., expanded corn acreage or animal density). Lake carbon cycles (Fig. 15) are affected by climate and land use change through a number of avenues. For example, progressive P enrichment associated with human land use in the basin can push lakes across a threshold in which eutrophication is stabilized by P recycling (Carpenter 2003, Lathrop 2007), primary production is high, and CO₂ is undersaturated, so the lake becomes a sink for atmospheric carbon that is fixed by primary production and stored in sediments (Hanson et al. 2003, 2004). With respect to climate change, comparison of the 5 driest and wettest years between 1951-2000 revealed that increasingly wet conditions tended to shift lakes from storing organic carbon (OC) in sediments to exporting CO₂ to the atmosphere or downstream (Fig. 16). Considered alone, each driver has substantial consequences for the fate of carbon in lakes; considered together, the interaction between land use and climate change is not obvious and is the focus of this research element.

Lakes are hotspots of OC processing on landscapes (Cole et al. 2007). These ecosystems process terrestrial OC at high rates and most unenriched lakes are net sources of CO₂ to the atmosphere (Cole et al. 2000, 2006). Yet lakes also store organic carbon at rates per unit area that generally exceed those of forest soils (Cole et al. 2007). Moreover, lake sediment OC has a longer residence time (tens of thousands of years) than terrestrial soil OC (decades to centuries). Globally, freshwater lakes and rivers cover somewhat more than 3% of earth's continents (Downing et al. 2006) although this figure is higher in lake districts (e.g., 13% for NHL and 8% for YLD). Because of high areal rates of carbon processing, lakes could be a significant component of regional carbon budgets even though their area is small.

We will build on recent NTL developments in carbon cycle modeling that exploit diverse datasets available for the two study regions (Table 2) and compare fates of carbon for scenarios that consider changes in one driver alone and both drivers together. Core data from the NTL-

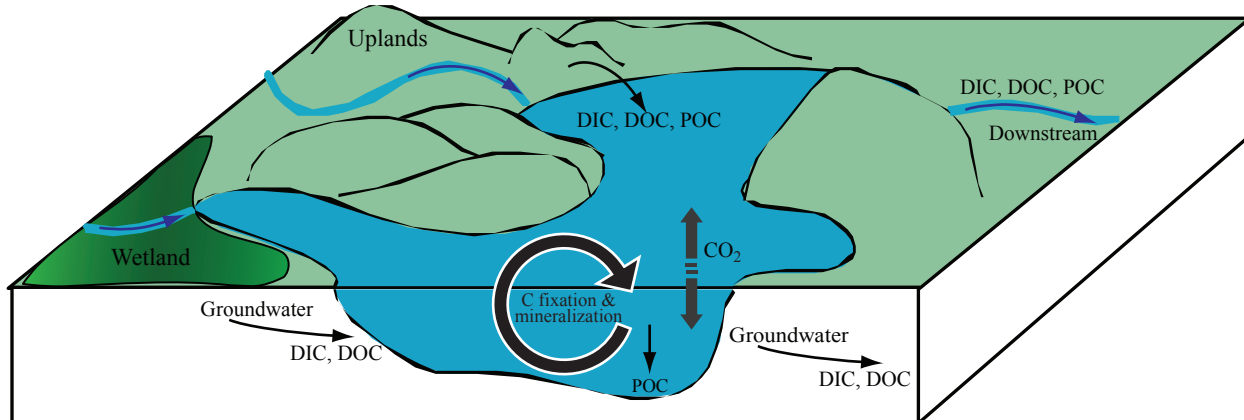


**Figure 15.** The major flows of a lake carbon cycle include water-borne inputs and outputs, airborne deposition, metabolism (primary production and respiration), photodegradation, sedimentation, and exchange of  $\text{CO}_2$  with the atmosphere. We focus on differentiating three important alternate fates for lake organic carbon: loss to the atmosphere as  $\text{CO}_2$ , storage in sediments, and export to downstream ecosystems.

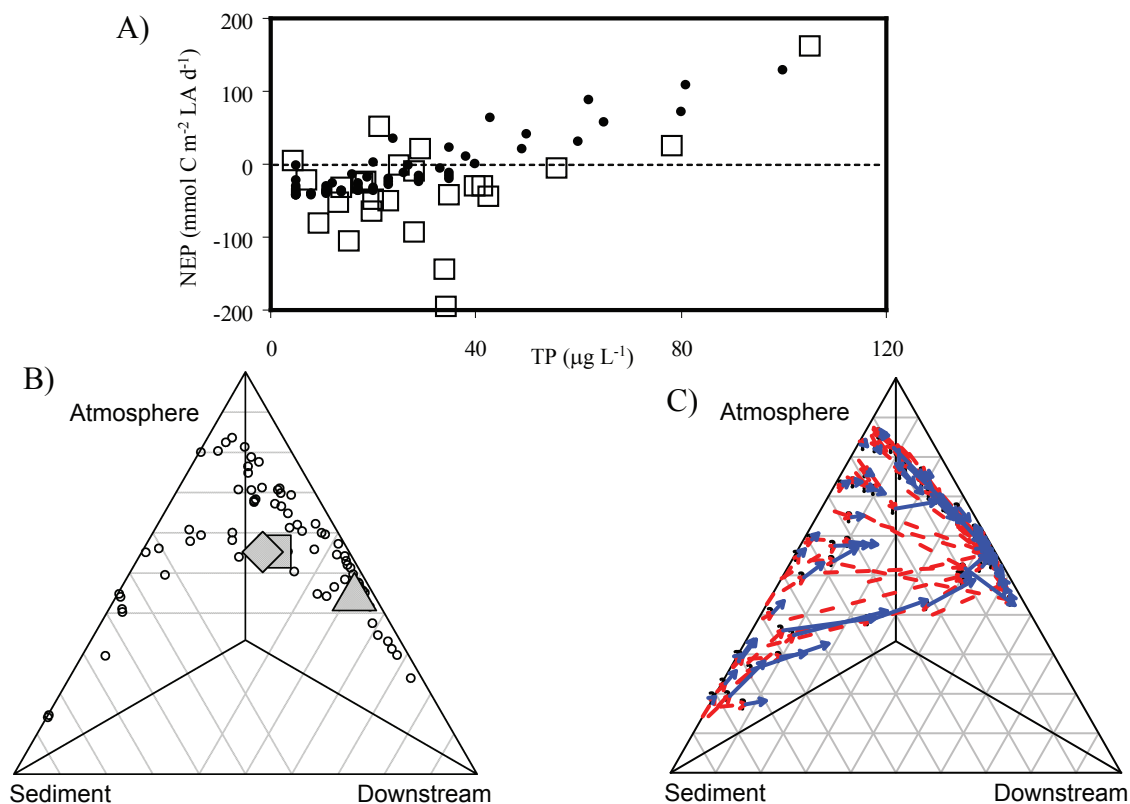


**Figure 16.** Fates of organic carbon in lakes shift from sedimentation toward outflow or flux of  $\text{CO}_2$  to the atmosphere as climate becomes wetter. (A) Net ecosystem production versus total P modeled across a gradient of landscape position (solid dots, Hanson et al. 2004) and measured in a random set of lakes (open squares, Hanson et al. 2003). (B) Fates of organic carbon for lakes in the Allequash Lake drainage, modeled under average climate conditions for 1951-2000 (Cardille et al. 2007). (C) Predicted changes in fates of organic carbon as climate becomes wetter, based on simulation of climate scenarios (Cardille et al. in review). Red arrows are from a dry scenario (driest 5 years of 1951-2000) to mean conditions (mean of 1951-2000). Blue arrows are from mean conditions to a wet scenario (wettest 5 years of 1951-2000).

LTER include decades of carbon variables measured monthly, and these are supplemented with (1) lake sediment data that provide a historical perspective on climate patterns dating back centuries and (2) new datasets from instrumented buoys that provide detailed physical and chemical dynamics in lakes spanning scales of minutes to months. We have already combined a simulation model with some of these data to evaluate effects of nutrient and DOC concentrations on gross primary production, total respiration and net ecosystem production (Fig. 16A). This lake ecosystem model has been integrated with a landscape model of water and OC flow to compare the fates of organic carbon (stored in sediment, oxidized to CO₂ and evaded to the atmosphere, or exported downstream) in lake districts (Fig. 16B,C). In future research we will validate and improve these models using new data, and expand our analyses to a wider set of scenarios for contrasting combinations of climate and land use change.

These modeling efforts will improve our understanding of how changes in climate and land use alter the fates of organic carbon, especially the role of lakes as sources of CO₂ to the atmosphere versus long-term sinks of organic carbon. It is not known how land use and climate change act together. Do warmer conditions and more erosion cause lakes to fix more atmospheric carbon and store more terrestrially-derived carbon in sediments? Or do warmer conditions and more erosion increase respiration of terrestrially-derived carbon in lakes, increasing CO₂ flux from lakes to the atmosphere? Such questions will be answered by our data and modeling analyses of joint changes in climate and land use.

## **C.2 How do lake characteristics and climate interact to determine the vulnerability of lakes to invasive species?**

With the increasing number and distribution of aquatic invasive species, there is a need for forecasting invasive species spread. One useful conceptual framework for forecasting species invasions considers the invasion process as a series of sequential steps involving the risk of propagule introduction, site suitability to the invader, and potential for adverse impact (Fig. 17, Vander Zanden 2004). Efforts to forecast species invasions on landscapes also need to account for environmental change. For example, changing climate and eutrophication could alter lake suitability for invaders, while changing economic and social conditions can affect how lakes are developed and how boaters move on landscapes, which would alter invasive species propagule pressure. Our objective is to develop spatially-explicit forecasts of invasive species spread for the NHLD and YLD that take into account changing climate as well as other regional ecological and socio-economic changes. Spiny water flea will be used as a model invader for this purpose because it is easily spread by boaters and can affect fish populations, with implications for human use of lakes (Yan and Pawson 1997, Yan et al. 2002). LTER researchers discovered the spiny water flea in two northern Wisconsin lakes in 2006-2007, one within 15 km of our NHLD study lakes, and we anticipate that this species will spread in the NHLD in the coming decades. We will develop forecasts of their spread and be in the position to test these forecasts with future observations.

Because boaters spread spiny water flea, models of boater movements will be used to characterize spatial patterns of potential propagule pressure. We will develop a random utility travel cost model of boater movements among lakes (Ben-Akiva and Lerman 1985, Provencher and Bishop 2004). Estimation of the random utility model of lake choice by boaters will require

**Table 2.** Datasets available for calibration and validation of landscape and freshwater carbon cycle models.

Project	Years	n Sites	DIC	DOC
Survey of Random Lakes (Hanson et al. 2007)	2004	168	Y	Y
Survey of Random Streams (Lottig & Stanley, <i>in prep</i> )	2006	52	Y	Y
Biocomplexity Project	2001-2004	62	Y	Y
Landscape Position Project	1998-1999	50	Y (& TIC)	Y (& TOC)
Metabolism in the NHLD	2001	25	Y	Y
NTL-LTER	1981-2007	7	Y	Y
EPA – Eastern Lake Survey	1984	64	Y	Y
Lake pCO ₂ survey (Hope et al. 1994)	1994	27	Y (pCO ₂ )	Y

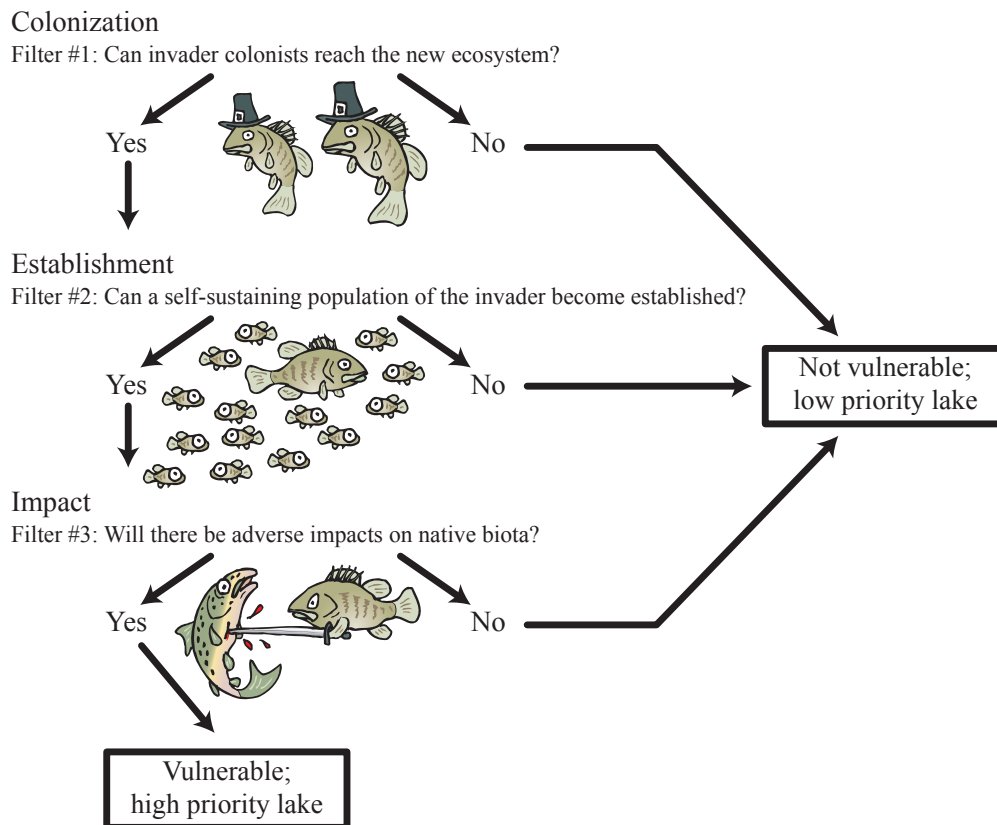


**Figure 17.** Invading species must pass through three landscape filters to become established and cause significant change in a lake. Risk of introduction considers the extent to which propagules of an invader are introduced into an uninvaded lake. Likelihood of establishment tends to increase with propagule pressure (Kolar 2001). For invaders spread by recreational boaters, propagule pressure can be estimated using gravity models (Leung 2004, Leung 2006) or a random utility model (Ben-Akiva and Lerman 1985, Provencher and Bishop 2004). Suitability considers whether the invader can survive and establish a population in the new ecosystem. Propagules may reach a new ecosystem, but the biotic or abiotic conditions may be inappropriate for establishment. Species presence/absence is often predictable from environmental variables, and these relationships can be formalized using statistical models (Olden 2002). Impact is whether an established invader has an adverse impact on the native ecosystem or biota. Impact has been estimated from food web structure, level of human disturbance, and other environmental variables (Ricciardi 2003).

a survey of boaters that elicits their boating activity on the lake system (the number and location of trips made). The well-documented patterns of spiny water flea spread observed in Ontario (MacIsaac et al. 2004, Muirhead and MacIsaac 2005) will be used to translate the boater movement model into spiny water flea propagule pressure. In order for an invader to establish a population, environmental conditions must be suitable. Ecological niche models will be developed based on current spiny water flea distributions in Ontario and Eurasia; previous work suggests that spiny water flea invades large and clear lakes (Grigorovich et al. 1998, MacIsaac et al. 2000). Impoundments are also more invulnerable compared to natural lakes (Johnson et al. in press). Thus, these variables (and possibly others) will be used to identify lakes that are suitable for spiny water flea. Impact is a poorly understood aspect of spiny water flea invasions. We will assess ecological impacts of spiny water flea using our long-term datasets along with analysis of literature data, food web models, and ongoing comparisons of NTL lakes with lakes of Dorset Research Centre, Ontario. Dorset lakes were invaded by spiny water flea more than a decade ago (Yan et al. 1992) with large effects on zooplankton communities (Yan and Pawson 1997, Yan et al. 2002).

We will develop spatially-explicit simulations of invasive species spread on landscapes. Forecasts of the species distribution in the NHLD will be generated under current conditions, and under several scenarios of climate change and residential development (Section C.1). Several future scenarios of boater movement patterns will also be examined. This conceptual approach is applicable to a suite of potential invaders in both the NHLD and the YLD. Thus, we will use this framework in conjunction with existing invasive species distribution data to forecast invasions for potentially high-impact invaders such as zebra mussel, Asian carp, rainbow smelt, and rusty crayfish. Our approach significantly improves upon models that assume static environmental conditions. Moreover, the effects of climate change alone on invaders may differ from those of climate combined with land-use change. For example, warming plus eutrophication may increase potential for invaders such as Asian carp because temperature and habitat become more suitable, while diminishing potential for others such as rainbow smelt because the metalimnion becomes anoxic. We expect therefore that interactions of climate and land-use change have species-specific implications for different potential invaders.

### **C.3. How do human perceptions and behavior interact with ecological conditions and landscape context to affect household sorting on lakes?**

Heterogeneity in development across lakes, and in household preferences for the ecosystem goods and services provided by lakes, leads naturally to questions of how this heterogeneity reflects human perceptions and behavior. How do households with different preferences for the ecosystem goods provided by lakes sort themselves across lakes providing different levels of these goods? What are the ecological implications of this sorting process? Figure 18 illustrates residential sorting of households for a simple case where the landscape involves two lakes and two alternative locations.

Especially intriguing is the possibility that the sorting process may generate significant secondary effects on local ecosystems. Human interactions with lakes are most intensive in shorelands and nearshore (littoral) zones of lakes. Shoreline residential development impacts the littoral zone through loss of physical structure from macrophytes and woody habitat (Radomski

## Local Population of Households

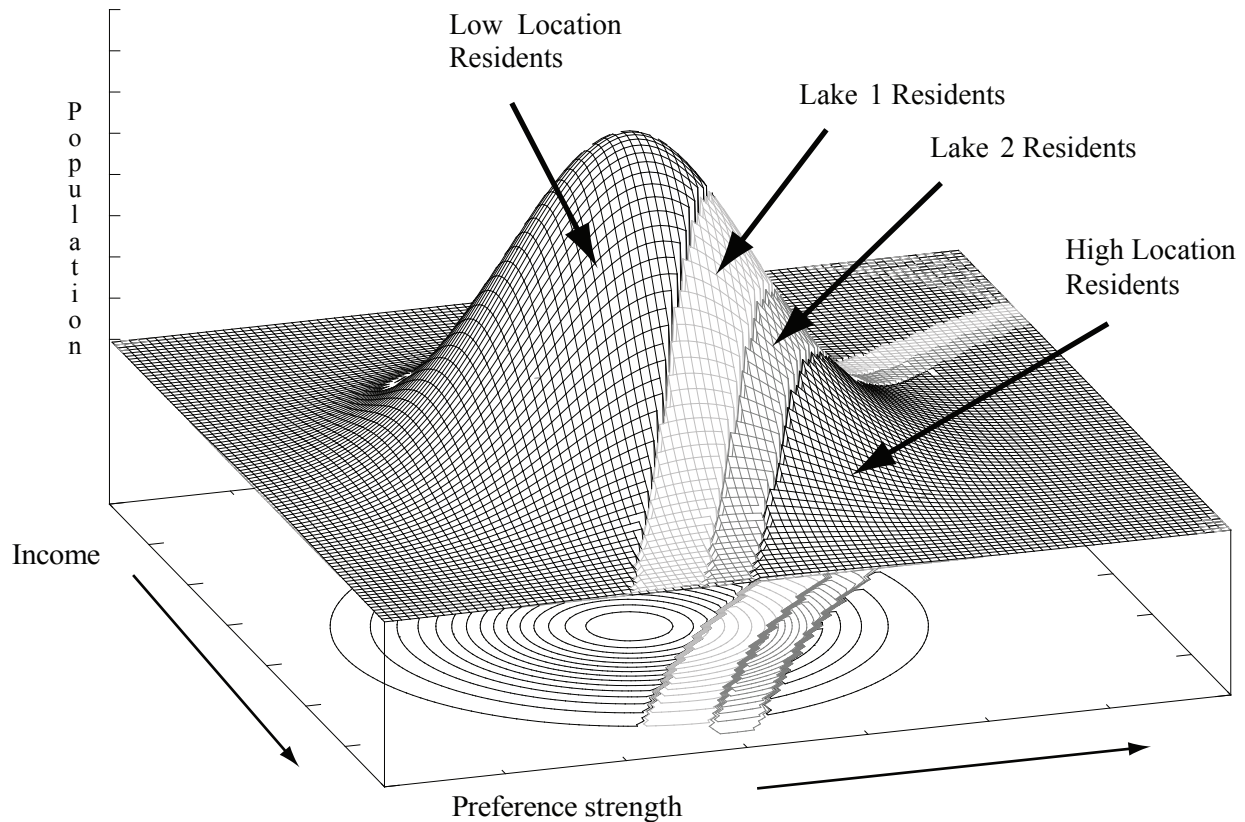


**Figure 18.** Residential sorting across a landscape by people with heterogeneous characteristics. The surface describes the distribution of the local human population with regard to two characteristics: income and the strength of preference for an ecosystem good provided by lakes. The landscape is comprised of four locations: two lakes, an unspecified “low” location, and an unspecified “high” location. The quantity of the lake ecosystem good is negatively impacted by residential density. Lake 1 has more people on it compared to Lake 2, and so it has less of the ecosystem good. The sorting process is facilitated by residential price premiums for preferred locations. Relatively few people are located on the lakes because of the relatively high price of lake residency. Similarly, Lake 2 has fewer people, and consequently more of the ecosystem good, than Lake 1 because of the relatively high price of residency on Lake 2. The sorting process generates an equilibrium in which lake residents are those with a relatively high income and a high preference for the ecosystem good, with Lake 2 residents having generally higher values for both income and ecosystem preference. The boundaries on the population surface identify those individuals who, given equilibrium prices for residential locations, are just indifferent between two locations. (From Lewis and Provencher 2007)

and Goeman 2001, Marburg et al. 2006) and can also increase the probability of introductions of exotic species. Lakes lower in the landscape tend to be more developed, have more boat landings, and be more exposed to inputs of invasive species from boaters and anglers than lakes higher in the landscape. These secondary effects of sorting come in two general forms: private and collective. Private effects arise if the value that households place on ecosystem goods and services are correlated with their individual behaviors affecting these services. The argument for collective effects is rooted in the literature on the management of common property. The National Research Council (2002), Baland and Platteau (1998), Ostrom et al. (1994), Ostrom (1990), Ostrom and Narendra (2006), and many others have shown theoretically and empirically that collective action to manage a commons, such as a lake, is more likely if individuals are fairly homogenous in their attitudes and use of the resource. So, for instance, a lake association formed to protect a valuable fishery is more likely to be active and effective if the lake is dominated by households that place a high value on the fishery.

We focus on three specific research questions. (1) Do different types of individuals sort themselves across lakes according to their preferences for lake characteristics? (2) Is this sorting affected by land and shoreline conservation policies? and (3) What are the implications of the sorting process for land-use policies and ecosystem change? These questions will be addressed using data gathered in the survey proposed in Section A.2, Long-Term Surveys. A latent class econometric model will serve as the basis for examining household sorting across a lake system. The latent class model identifies household “types” by their demands for various lakeshore parcel characteristics, including lake-specific ecosystem goods and services (water clarity, fishing quality, etc.). This model can be embedded in an equilibrium model of sorting where, given the supply of lakeshore properties providing various levels of the environmental goods, an equilibrium price for the goods emerges and households sort themselves over a lake system according to their demand for environmental goods and the prices of these goods (Ioannides and Zabel In Press). Underlying the econometric model is a dynamic model of ecological change driven in part by human feedbacks; lakes in the system change over time in part due to the private and collective activities of households, with such activities differing across household types. As the lake environment changes, the equilibrium price of these environmental goods changes, and households re-sort on the lake system (Fig. 18).

We hypothesize that results will show that people sort among lakes according to their preferences (question 1), that lakeshore zoning intensifies sorting (question 2), and that sorting feeds back to determine land-use policies that affect particular lakes and ecosystem characteristics (question 3). Formation of a lake association is a primary mechanism for people concerned about changes in a lake. While lake associations can have a diversity of goals, most of them are focused on improving water quality, fishing, or other ecological amenities of lakes.

#### **D. Ecosystem Services: Past, Present and Future**

Ecosystem services are the benefits that people receive from ecosystems (Ehrlich and Mooney 1983, Odum 1989, DeGroot 1992, Daily 1997). Ideas about ecosystem services have motivated studies and scientists throughout the history of ecology; indeed much ecological science can be integrated using a framework of ecosystem services (Odum 1989, M.A. 2005). Moreover, ecosystem services are central for frameworks of interdisciplinary regional research on social-

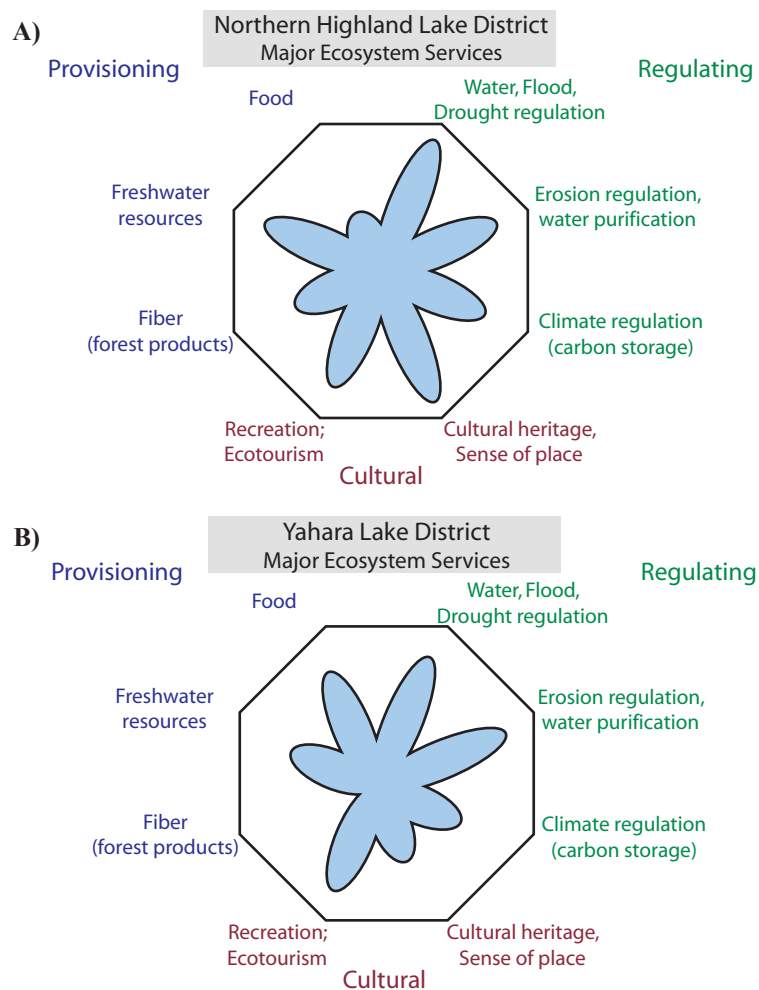


**Figure 19.** The NHLD and YLD have different combinations of ecosystem services. (A) Petal diagram for ecosystem services of the NHLD. (B) Petal diagram for ecosystem services of the YLD. Length of the petal depicts the relative importance of the ecosystem services. Classification of ecosystem services follows the MA (2005a,b).

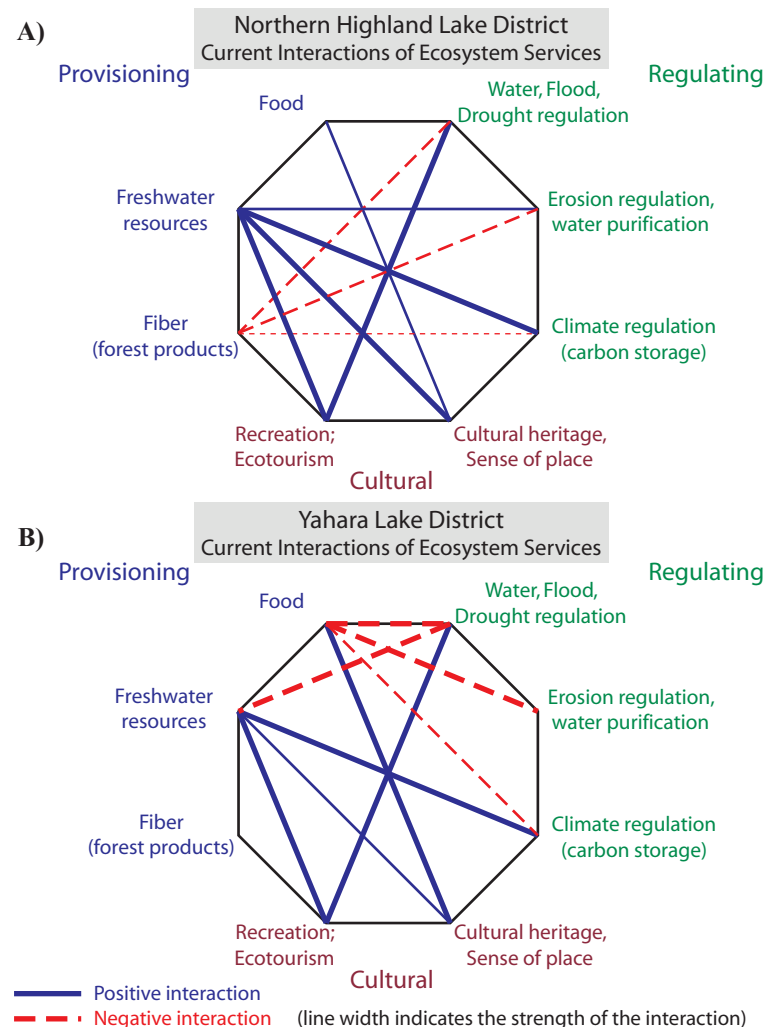


**Figure 20.** The most important interactions among ecosystem services differ between the NHLD and the YLD. (A) In the NHLD, many interactions are positive and the few negative interactions are not strong ones. (B) In the YLD, there is a mix of positive and negative interactions, many of them related to the inverse relationship of agricultural production to freshwater quality and quantity.

ecological systems (Carpenter and Folke 2006, Liu et al. 2007). Recognizing the implicit role of ecosystem services in much of our past research, NTL now uses ecosystem services as an explicit component of our approach (Carpenter et al. 2007).

Ecological forecasting has been a component of NTL research since our 2002 proposal. Here, we extend these initiatives, guided by the objective of forecasting some of the ecosystem services of the NHL and YLD. The process of forecasting evokes interdisciplinary synthesis, and the forecasts themselves serve as hypotheses for future interdisciplinary research. Yet there are many gaps in forecasting ecosystem services (Carpenter et al. 2006). For example, few studies evaluate the roles of landscape configuration, structural complexity of landscapes, and feedbacks between process and pattern that affect ecosystem services (Tscharntke et al. 2005, Cumming 2007), although there are important exceptions (Chan et al. 2006). These issues will be addressed by the research that we propose.

Our primary study regions, the NHL and YLD, show notable contrasts in ecosystem services even though freshwater resources are important in both regions (Carpenter et al. 2007). In the NHL, outdoor recreation and forest products are major elements of the economy and are connected directly to ecosystem conditions (Fig. 19A). In the YLD, food production and recreation are important activities with direct connections to ecosystems (Fig. 19B), but many economic activities (such as government, biotech, high-tech and service industries) are connected to ecosystems only indirectly. Interactions of ecosystem services differ between the regions (Fig. 20). In the NHL, many positive (synergistic) interactions are connected to freshwater resources or to recreation, and many negative (tradeoff) interactions involve forest products. In the YLD, there are positive interactions between recreation and regulation of erosion, water quality and water flows, and many negative interactions involve food production. Our goals for understanding ecosystem services are reflected in the thematic question: ***What are the magnitudes, interactions and potential future flows of ecosystem services in lake districts?***

This broad question motivates many more specific questions. What are the ecosystem services of a region? What are the magnitudes of ecosystem service flows relative to ecosystem fluxes and human needs? What are the values of ecosystem services? And how will human behavior and ecosystem dynamics affect ecosystem services in the future? Comprehensive answers to such questions would be an enormous task. For this grant cycle, we selected four specific topics that are natural extensions of current research, address emerging questions in the basic science of ecosystem services, and are likely to open up promising future research paths.

#### **D.1. How will projected changes in climate and land use affect ecosystem services?**

Freshwaters are the nexus of several ecosystem services – provision of freshwaters and important biota that depend on freshwater; regulation of water supply, floods and droughts; regulation of climate through carbon sequestration; regulation of water quality; and many cultural ecosystem services (M.A. 2005, Brauman et al. 2007). These ecosystem services are expected to change as climate, land use and cover, and other factors change. Annual patterns of precipitation and temperature are important drivers of the hydrologic cycle. Land use and cover influence the apportionment of water among evapotranspiration, runoff or infiltration, thereby influencing water levels in groundwater, wetlands, streams, and lakes and regulation of water supply,

drought, and flood effects. Land use and cover also affect flows of nutrients and organic carbon that in turn dictate water quality, CO₂ exchange, and organic carbon storage by freshwater ecosystems (Carpenter et al. 1998, Cardille et al. 2007, Cole et al. 2007). Basic understanding of these ecosystem services has been identified as an important scientific frontier (Carpenter et al. 2006). NTL is poised to address this need.

We will develop scenarios for land-use and climate change in the NHL and YLD for 2050 (Fig. 21). Drivers will be obtained from the global scenarios of the Millennium Ecosystem Assessment (M.A. 2005) as well as published reports and scenarios specific to our regions (Magnuson et al. 1997, Kling et al. 2003, Peterson et al. 2003, Biggs et al. 2007). Region-specific scenarios will be designed to investigate contrasts in temperature, precipitation, seasonality and variability of precipitation, and contrasting patterns of land use and cover. Scenarios will be analyzed using models that we have developed, or are developing, for the NHL and YLD. These include models for water balance and hydrology (Kucharik et al. 2000, Cardille et al. 2004, Markstrom et al. 2007), lake organic carbon dynamics (Cardille et al. 2007, Cole et al. 2006), nutrient inputs to lakes (Soranno et al. 1996, Kirsch et al. 2002, Gassman et al. 2007), and lake water quality (Lathrop et al. 1999, Stow et al. 1997). Modeled output will be used to compare ecosystem services across scenarios and between our study regions. Freshwater supply will be indicated by recharge of soil- and groundwater and surface outflows. Regulation of drought or flood will be indicated by extreme water levels in lakes and water quality by nutrient inputs and algal biomass in lakes. Contributions to climate regulation will be indicated by carbon sequestration in wetland peat and lake sediments. Products of this research will include the suite of contrasting scenarios for regional climate and land-use/cover change, improvements in the models and linkages among them, and comparison of freshwater ecosystem services among scenarios and between the NHL and YLD regions.

## **D.2 How will biofuel-driven changes in land use and cover alter flows of water, carbon and nutrients to freshwaters, and what are the consequences for freshwater ecosystem services?**

Farm crops are increasingly being planted to take advantage of growing interest in biofuels; in the U.S. this has centered predominantly on corn-based ethanol (Naylor et al. 2007). In 2007, the USDA reported total corn-planted acreage topped 90 million acres across the U.S. – a 16% increase over the previous 3-year average (USDA 2007). Although grain is the major feedstock for ethanol production at present, advances within the next decade in cellulose-feedstock technology will likely make it cost-effective to produce ethanol from switchgrass, native prairie vegetation (Tilman et al. 2006), or fast-growing trees such as hybrid poplar (Naylor et al. 2007). The rapidity of this development has limited the opportunity to consider many of the environmental ramifications of this change, including effects on aquatic ecosystems (NRC 2007). Such radical shifts in agricultural land management could create large changes in water, C, N, and P cycling through terrestrial and aquatic ecosystems (Hill et al. 2006). This trend motivates two specific research questions: (1) How may the changing distribution of croplands affect nutrient flux to freshwaters, and carbon cycling in the terrestrial-aquatic system? (2) How might alternative biofuel feedstocks other than corn grain impact water quality?

Our approach across the NTL-LTER couples terrestrial and aquatic systems. We will rely on both process-based modeling and development of new datasets of land management and land

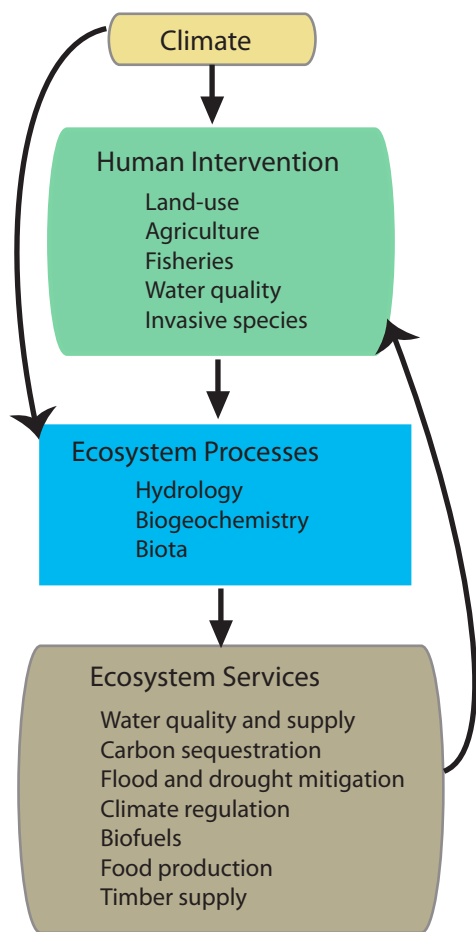


**Figure 21.** The proposed models will connect climate, land-use change, ecosystem processes, and major ecosystem services of NTL-LTER.

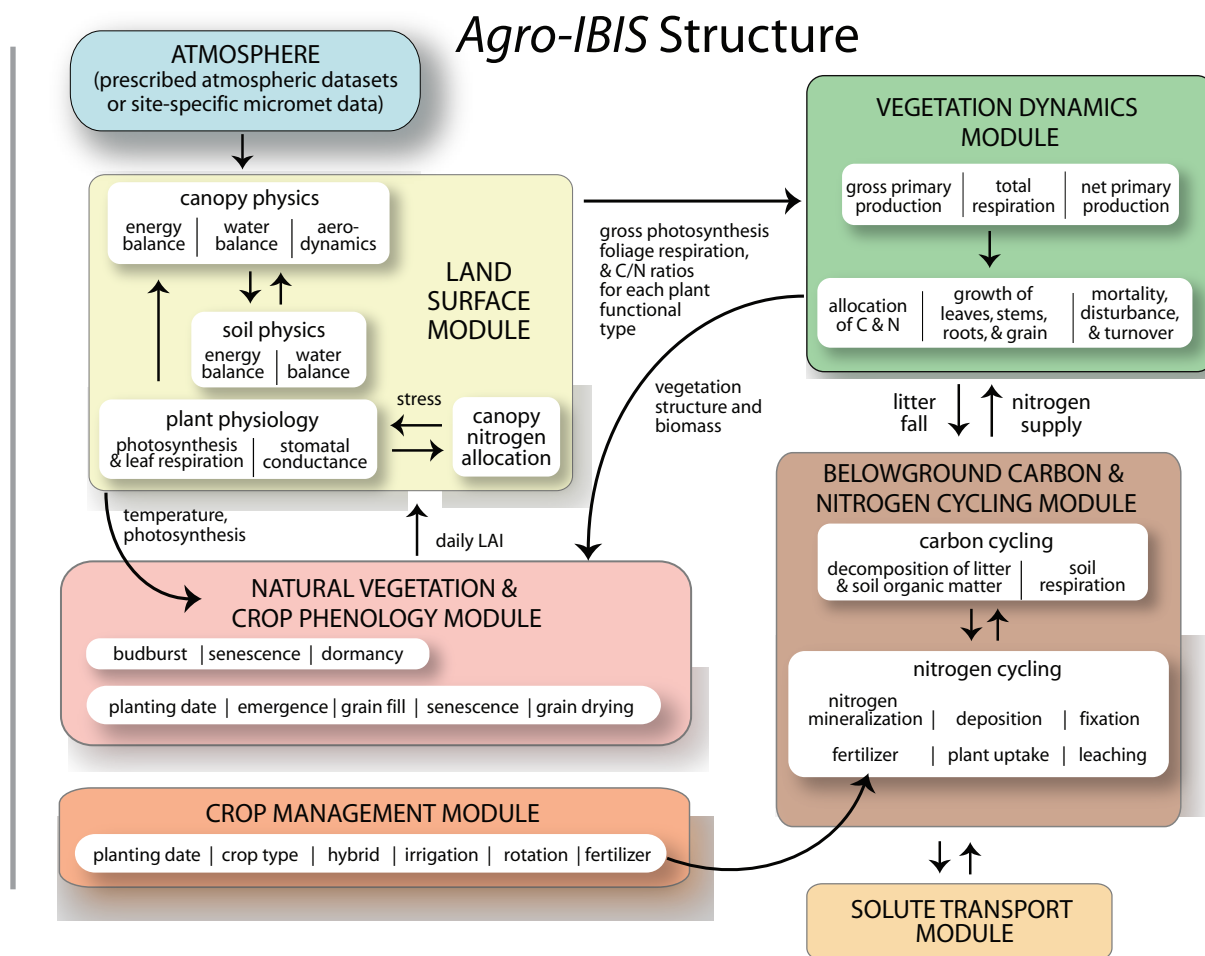


**Figure 22.** The IBIS ecosystem model will be used to study how changes in plant physiology, ecology, and biogeochemistry - affected by drivers of change such as climate, atmospheric chemistry, and land use - will be used to simulate provisioning of ecosystem goods and services such as carbon sequestration, water quality, and ethanol production in the NTL-LTER. Because IBIS can be coupled with an aquatic model that accounts for hydrological routing and lake biogeochemistry (Cardille et al. 2007), we can better understand the net response of the key ecosystems while perturbing the drivers of change one-by-one, or simultaneously.

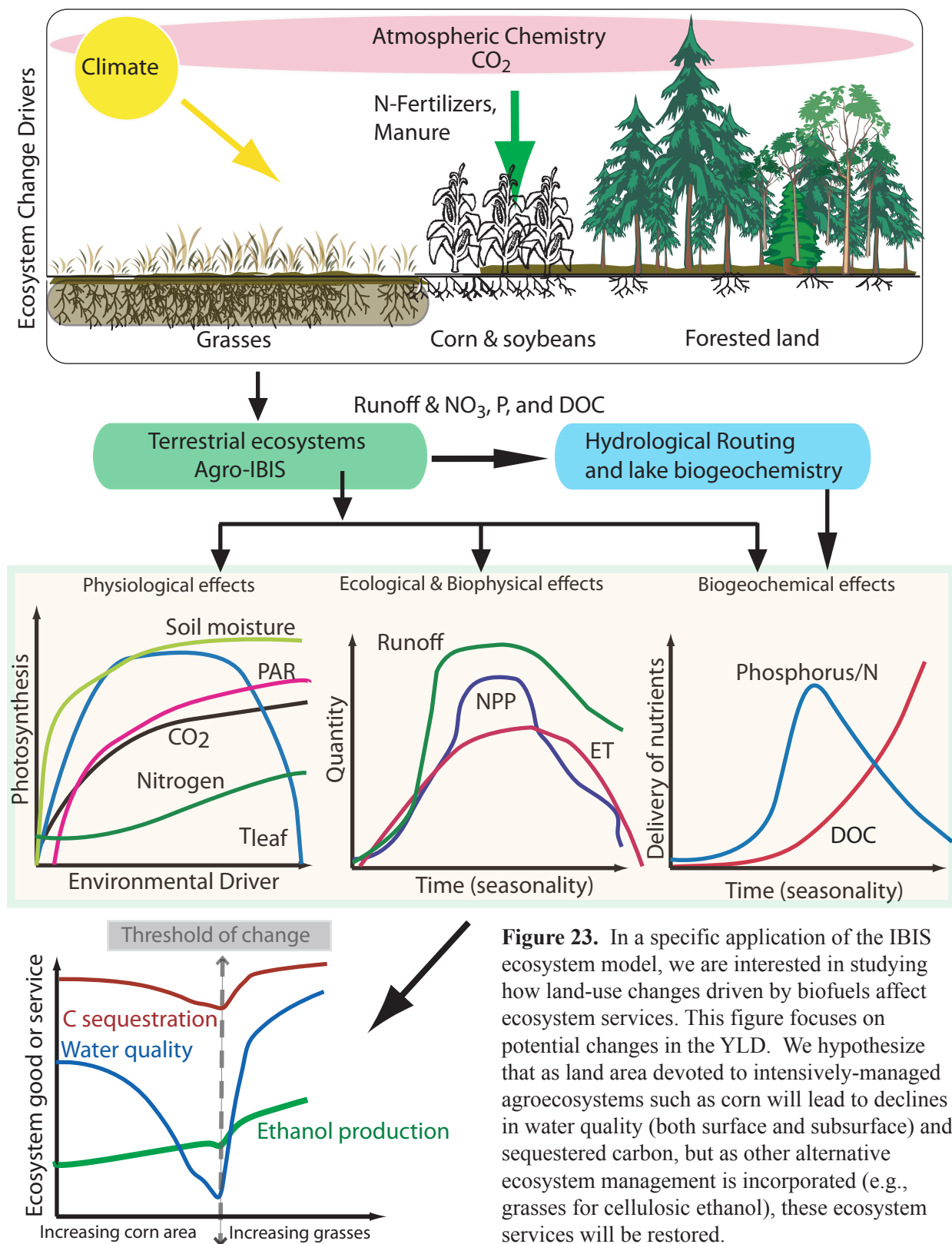


**Figure 23.** In a specific application of the IBIS ecosystem model, we are interested in studying how land-use changes driven by biofuels affect ecosystem services. This figure focuses on potential changes in the YLD. We hypothesize that as land area devoted to intensively-managed agroecosystems such as corn will lead to declines in water quality (both surface and subsurface) and sequestered carbon, but as other alternative ecosystem management is incorporated (e.g., grasses for cellulosic ethanol), these ecosystem services will be restored.

cover across each region. We will use a process-based biosphere model (IBIS, Fig. 22; Kucharik and Brye 2003, Donner and Kucharik 2003, Vano et al. 2006) of C, water, and nitrogen (N) balance and the vegetation structure of crops, forests, and grasslands to investigate how varied land management and climate impact biogeochemical cycling in the NHLD and YLD (Fig. 23). We will also rely on our models of carbon dynamics already developed for NTL lakes (Hanson et al. 2004, Cardille et al. 2007), and measurements of terrestrial carbon balance from eddy covariance towers (Vano 2005). To drive the model and analyze the tradeoffs of current and future land management scenarios, we will create high-resolution (500 m – 1km) datasets of crop and forest cover, forest management, crop rotations, fertilizer use, and daily climate, thereby incorporating a socioeconomic perspective into our ecological and biological modeling approach. The modeling system will be enhanced to link terrestrial and aquatic C, N, and P cycles, and model output will be validated with available measurements in each study region (Fig. 23).

The significance of this research will be an improved understanding of how increased production of biofuels may impact water quality in the region. These new analyses of environmental tradeoffs could help inform future policy making and lead to a heightened awareness of the impacts large landscape management changes have to the biological systems and hydrologic functioning across the NTL regions.

### **D.3. How do freshwater ecosystem services and the policies intended to protect them affect development patterns around lakes?**

Although heavy development of Wisconsin lakes is well documented, and such development has clear implications for lake ecology, the economics of development and the role of public policy in affecting the spatial dynamics of development are not well understood. This observation evokes several questions about factors that explain shoreline and near-shore development. Do changes in ecosystem services, such as water clarity, fish habitat, or presence of harmful invasive species affect shoreland development? How do land use policies intended to protect lake ecosystem services (such as zoning or conservation easements) affect the rate and spatial pattern of shoreland development? Do these policies have unintended effects, such as short-term stimulation of development (by making the lake more attractive) or long-term stimulation of upland development (via a substitution effect as lakeshores become fully developed)? Recent econometric studies of open space conservation policies have found that such policies may have the unexpected effect of stimulating local development (Irwin and Bockstael 2004, Walsh 2007).

We will address these questions using unique parcel-level historical GIS data constructed from rectified county plat maps available commercially in four-year intervals. These data will be used in an econometric analysis that jointly estimates both the probability that a parcel is subdivided, and the number of new parcels created upon subdivision, as functions of various explanatory variables, including lake characteristics such as water quality and the amount of public shoreline. Simulations will be used to forecast the rate and spatial pattern of development in a portion of the Northern Highland Lake District. By combining the econometric model of the dynamics of land development with models of the effect of development on ecological characteristics (such as sport fish) we will generate quantitative forecasts of ecological responses to land use policies.

#### **D.4 How do invasive species affect ecosystem services and human responses? And how do management responses affect persistence or spread of invasive species?**

Invasive species have well-documented ecological impacts on lake ecosystems (Wilson et al. 2004, McCarthy et al 2006,). Understanding how these translate to changes in ecological services provided by lakes requires an economic approach to the study of invasions (Naylor 2000, Leung et al. 2002). Here, we will develop economic-ecological models of invasions for several species with different ecological and economic repercussions. Successful public policy with respect to aquatic invasive species must account for the costs of invasions to residents and boaters, as well as the role of residents and lake visitors in the spread of the invader (Fig. 24).

Strategies for managing invasive species can be broadly classified as either prevention or control (Naylor 2000). The goal of prevention is to stop the spread of invasive species to avoid unwanted outcomes, while the goal of control is to minimize the consequences of unwanted events that have already occurred. Few studies have compared the cost-effectiveness of different combination of control and prevention strategies. What mix of control and prevention strategies generate the greatest social gain and/or minimize impacts on ecosystem services? How do local (individual lake) and regional (management agency) responses to species invasions compare in terms of minimizing invasive species impacts on a landscape?

To address these questions, we will build upon existing invasive species distribution data and we will conduct additional field surveys to estimate the geographic distribution of three problematic invasive species in the NHL: Eurasian watermilfoil, rusty crayfish, and rainbow smelt. Characterization of ecological impacts will be derived from our long-term studies of invasive species impacts in NHL lakes, recognizing that impacts are heterogeneous among lakes (Hrabik et al.1998, Wilson et al. 2004, McCarthy et al. 2006).

Based on the assessment of the impacts of invasive species on ecosystem services, we will compare different prevention and control management scenarios. The comparison will be made in the context of a spatial-dynamic model that accounts for how boaters respond to management strategies (MacPherson et al 2006), and will incorporate the random utility model of boater behavior based on surveys (Section A.2, Long-Term Surveys). Simulations of different management strategies (prevention vs. control) using the model will generate benefit-cost comparisons across management strategies at the landscape level. The ecological-economic models of the spread of invasive species developed in this research can be tested against the observed spatial-dynamics of an invasion as it unfolds over time. Perhaps more importantly, by developing such models across a range of species it becomes possible to develop forecasts of the spatial-dynamics of new invasions – with estimates of the economic costs – based on previously estimated ecological-economic models.

This approach also compares the effectiveness of local and regional management of species invasion. The spatial-dynamic model will be used to examine the effect of management activities by individual lake associations and regional authorities on spread and impact of invasive species. Our hypothesis is that effective management of species invasions requires action at both lake and regional scales, and that in the absence of coordinated management across scales, lake-level actions may contravene effective management at a regional scale.

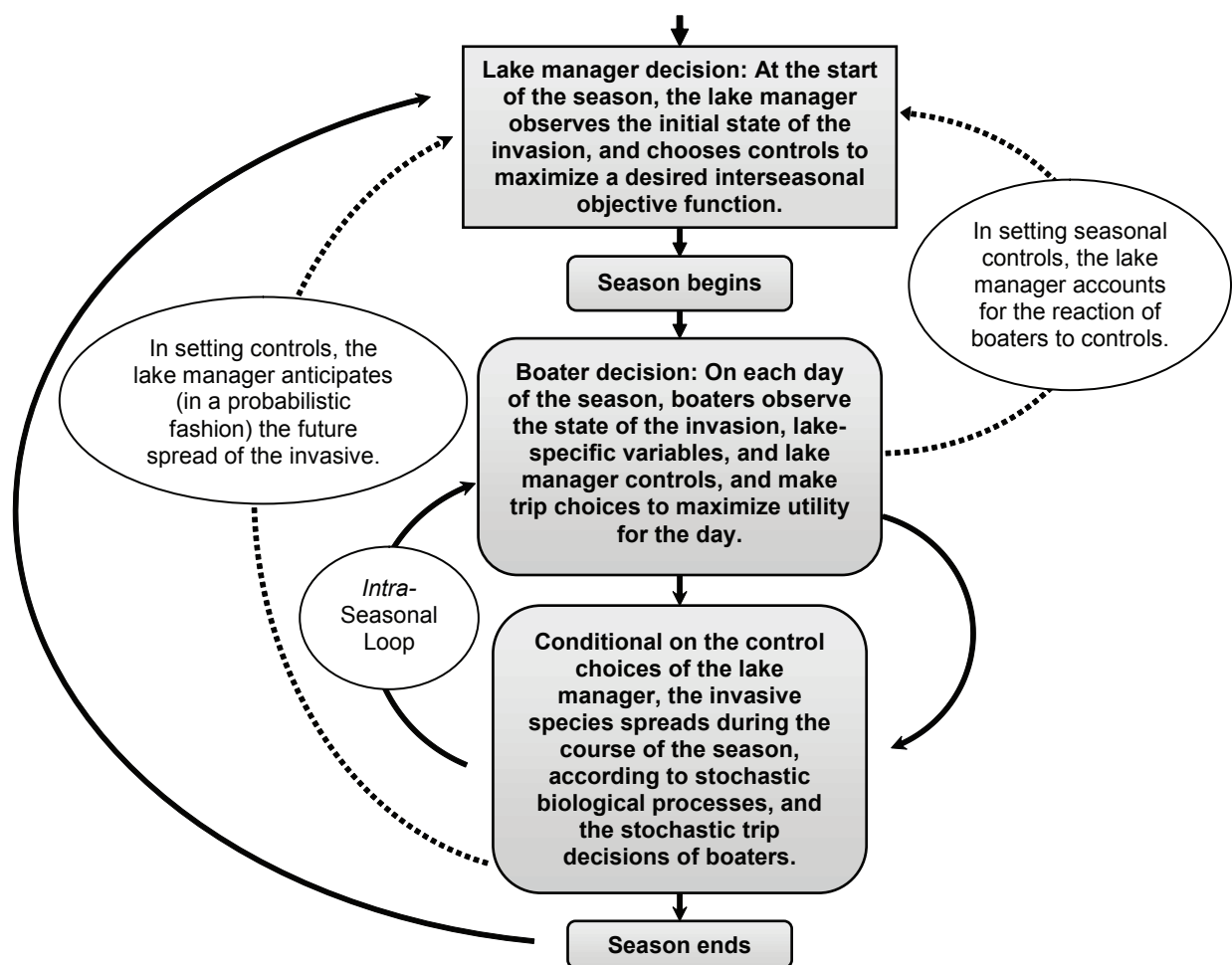


**Figure 24.** Dynamic model of invasive species management. The model has two levels of decisions at different time scales. At the start of each season the lake system manager chooses a set of controls that act upon boaters (such as lake closures or restrictions on boat movement between lakes) and the invader itself (such as eradication on some lakes). The objective of the manager is part of a political process that is exogenous to the model. Possibilities include the maximization of boater welfare, the minimization of the rate of spread of the invasive species, the maximization of the welfare of shoreline property owners on certain lakes, and many others. Regardless of the objective function, in setting the controls the forward-looking manager anticipates the reaction of boaters to the set of controls. For their part, boaters make decisions about what lakes to visit on a daily basis to maximize seasonal utility from recreation. Trip decisions account for the lake controls set by the manager, and the state of the invasion. Throughout the season the state of the invasion updates stochastically as governed by the ecology of the invader, and in response to boater activity and manager controls. (Adapted from MacPherson et al. 2006).

## **E. Synthesis and Significance**

The proposed research addresses key challenges in ecology that are of global importance. We address four of the most important drivers of ecosystem change (M.A. 2005) – climate, land use and cover, nutrient mobilization, and species invasion – and their effects on lake districts and freshwater ecosystem services (Fig. 25). We study these drivers and their effects in a rural, forested lake district and in an agricultural, urbanizing lake district at multiple scales of space and time. By studying the feedbacks between ecosystem services and human perceptions, behavior and institutions, we address an emerging frontier of sustainability science (M.A. 2005, Clark 2007, Liu et al. 2007). Our interdisciplinary research embraces the physical, biological and socio-economic sciences, and touches on the humanities through outreach and education activities that employ art and stories.

Our proposal builds on 27 years of data collected by NTL-LTER. At the end of the proposed grant cycle we will have collected a 33-year, detail-rich dataset using standard and well-validated methods while integrating new automated sensor technologies. We will also expand data collections (e.g., long-term data on human perceptions) and analyses (e.g., detecting patterns of change across multiple variables) to pursue new and pressing environmental questions as our collective research interests continue to grow and broaden. Because these data include variables with a wide range of characteristic tempos, we anticipate new insights related to how fast and slow variables (Bender et al. 1984, Carpenter and Turner 2000, Ives et al. 2003) interact to produce unexpected outcomes.

We will conduct new empirical analyses of ecological change, employing synthetic approaches to build understanding (Pickett et al. 2007). Our long-term record provides essential context for detecting and interpreting changes of all sorts, including major changes – such as the occurrence of ice-free winters – that we anticipate in the future. Place-based studies that combine field data and models are needed to advance understanding of factors that affect stability and transformation of ecosystems (Ives and Carpenter 2007). To interpret data, we will use well-grounded simulation models to conduct new analyses of the roles of climate and land-use change in ecosystem processes. Linkage of landscape heterogeneity with ecosystem processes has advanced more slowly than other aspects of landscape ecology, yet it is crucially important for understanding regional dynamics (Turner 2005, Lovett et al. 2005). We will analyze the dynamics of ecosystem services in temporally varying and spatially heterogeneous environments (e.g., Metzger et al. 2006, Potschin and Haines-Young 2006, Termorshuizen et al. 2007).

Long-term research provides opportunities for studying natural experiments by analyzing regional variability, historic data, and both episodic and chronic events (Magnuson et al. 2006). We will also examine management experiments, such as the ongoing restoration of lakes in the YLD, and continue deliberate whole-ecosystem experiments such as the invasive species control in Sparkling Lake and the habitat manipulations of Little Rock and Camp lakes.

Interdisciplinary studies are strongly developed at our site (Carpenter et al. 2007). We have a well-integrated approach that considers biophysical setting, climate, social-ecological feedbacks, land-cover change, hydrology, biogeochemistry and biotic change. The faculty, staff and students directly involved with the NTL-LTER represent 14 departments and 5 colleges at the

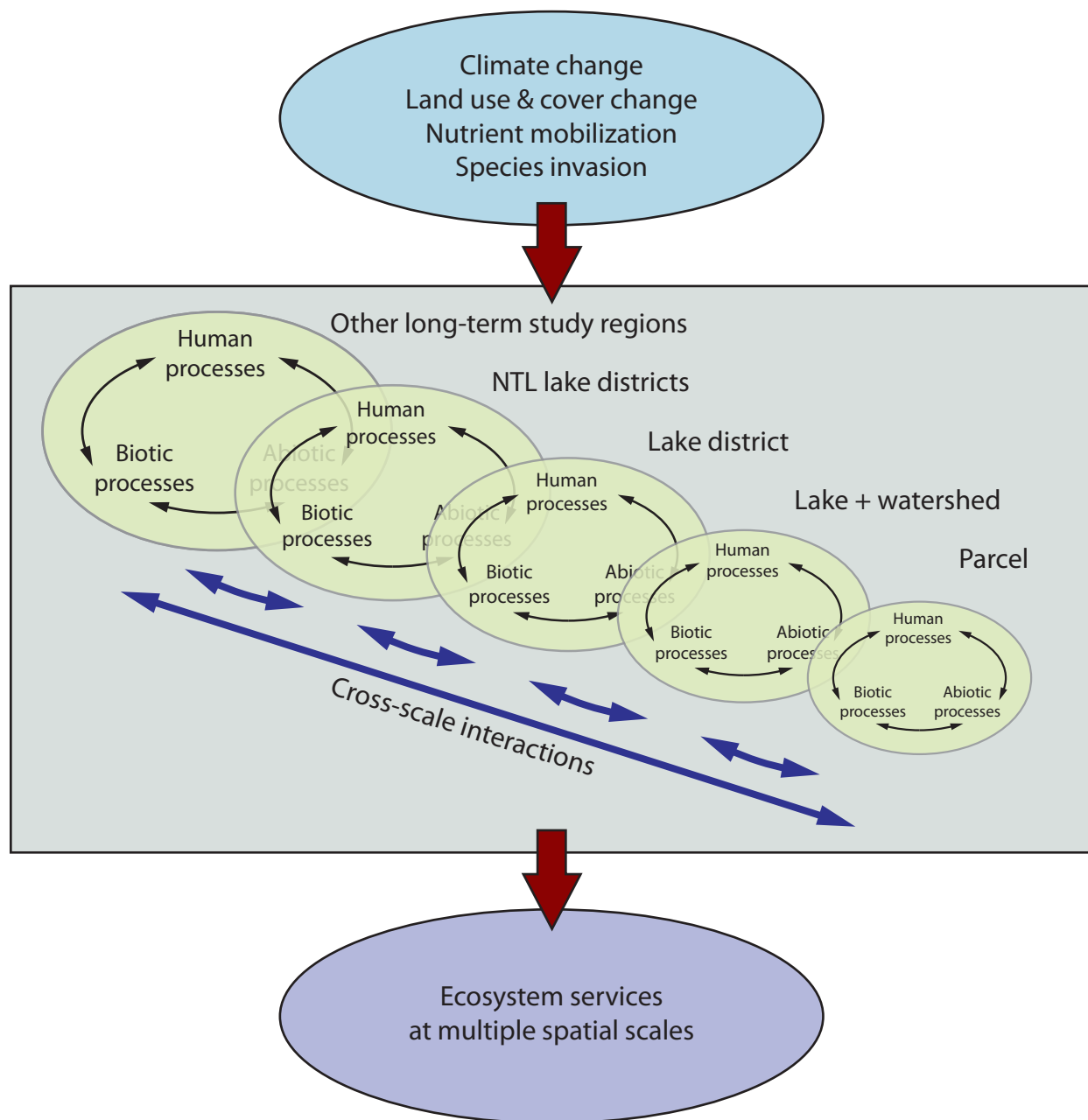


**Figure 25.** Interactions of abiotic, biotic and human processes at multiple scales are the centerpiece of our proposal. We consider interactions across scales from individual land parcels, to lakes and watersheds, to the lake district as an integrated whole, between the two NTL lake districts, and among multiple long-term research sites. We address the effects of drivers such as climate change, land-use change, nutrient mobilization and species interactions, and the consequences for ecosystem services.

UW-Madison, and these core participants are involved in collaborations that pull in an even greater range of expertise. We recognize the unique contributions of different approaches from different disciplines and we will continue our interdisciplinary tradition. .

Education – K-12, undergraduate, graduate and continuing – has been a mainstay of NTL and will continue to be so in the future. We contribute to K-12 education through Schoolyard LTER, curriculum development and teacher training. Hundreds of undergraduates are connected to NTL through activities ranging from lectures to research training. Graduate and postdoctoral education are central to our program and graduate students and postdocs will contribute to most of the research presented in this proposal. NTL public outreach activities include many people interested in freshwater resources and integrate with our contributions to public policy.

NTL-LTER research has been and will continue to be directly relevant to management and policy at global, national, state and regional scales. Scenario approaches used in the Millennium Ecosystem Assessment were piloted at NTL-LTER (Walker and Salt 2006, Carpenter 2008). Results from NTL-LTER research have informed decisions that affect water quality made by the Wisconsin Department of Natural Resources (DNR) and the Dane County Lakes and Watersheds Commission (Lathrop 2007, Magnuson 2007, Stedman et al. 2007). NTL-LTER will continue to contribute information to important policy processes. For example, our studies of how climate, land use and land cover, and human activities affect the vulnerability of lakes to invasion by non-native species will be of wide interest (National Invasive Species Council, 2001).

NTL LTER research has produced new insights and has consistently contributed to fundamental knowledge of the long-term ecology of lakes and their interactions with important landscape, atmospheric and human processes. As we begin a new chapter of LTER research, we will continue in the tradition of addressing fundamental scientific questions that demand a solid foundation of long-term, sustained interdisciplinary research.

### Section 3. Project Management

**Project Governance:** Direction of NTL-LTER is provided by the Lead PI (Carpenter) with the participation of the Principal Investigators, research staff, and students. PIs meet monthly for an hour to address program, personnel, and budget issues; minutes are taken. The entire group of researchers meets monthly for 2 hours to discuss scientific results, concepts, and plans. In addition, subgroups of researchers meet frequently to work on collaborative projects as needed, both on the Madison campus and at Trout Lake Station. The technical staff of the project meets at least twice a year for 2-4 hours to discuss project operations and protocols. Minutes are taken. We have no formal executive committee; instead the Lead PI consults regularly with the individual PIs most closely involved with issues as they arise. We normally operate by consensus with the lead PI acting on hard choices.

NTL has a history of smooth leadership transitions. Prior to the mid-term site review of 2011, Emily Stanley will succeed Carpenter as Lead PI. Carpenter will continue as a co-PI to help coordinate NTL's participation in new regional social-ecological science which may develop through ISSE or other initiatives.

Our PIs are involved in many LTER Network activities: Benson (PI on LTER Network Planning Grant, PI on ISSE writing team, Core Team member for CI supplement to LTER Network Planning Grant, Chair of Information Managers Committee 2003-2006, member of the LTER Information Management Executive Committee 2001-2006, member of the LTER Network Information System Advisory Committee 2002-2006, member of the hiring team for a technical outreach staff person at the LTER Network Office); Bohanan (Chair of the Network Education Committee 2003-2005, co-Chair 2006); Carpenter (Advisory Committee for ISSE, co-organizer of Network collaboration on ecosystem services); Hanson (Organizer of Cross-Site Workshops on Sensor Technology); Kratz (Member of LTER Network Information System Advisory Committee 2003-2006, Member of the Trends Editorial Committee); Magnuson (Interim Chair of Network Executive and Science Council). Benson and Carpenter have served on site visit teams.

NTL PIs have attended network meetings on various specialized topics. We participated in LTER All-Scientist Meetings, sending 13 researchers to Seattle in 2003 and 16 researchers to Estes Park in 2006. Eight NTL PIs participated in one or more meetings for development of the ISSE.

**Project Administration:** The project is administered through the Center for Limnology (CFL, College of Letters and Sciences, University of Wisconsin-Madison). The Center has field stations at both primary sites (Trout Lake Station in the NHL, and the Hasler Laboratory of Limnology in the YLD). Both sites have a LTER site manager (Rusak in the NHL, Lathrop in the YLD) and LTER field technicians. Rusak will be leaving NTL for another position and we will be seeking a replacement. Information Management (led by Benson) is concentrated at the Hasler Laboratory. Spatial analyses and modeling make use of facilities at the Hasler Laboratory, the Landscape Ecology Laboratory of Monica Turner, and the Center for Sustainability and the Global Environment (directed by Foley). Chemical analyses supervised by Stanley are conducted in the Hasler Laboratory and adjacent Water Science and Engineering

Laboratory. PIs (Table 3) are based at Trout Lake Station or around the Madison campus in 5 colleges and 14 departments. Three PIs are agency personnel based in Madison.

Project operations come from the lead PI, Marilyn Larsen (fiscal officer), Denise Karns (project officer) and administrative staff in Madison and at Trout Lake.

The College of Letters and Science provides substantial direct costs annually for CFL management, operations, capital equipment and general building services which directly benefit LTER. When direct costs paid by the college and endowments are accounted for, the actual overhead rate on the LTER grant was 15.3% in 2006-2007. This rate was calculated as  $100 * (\text{NSF indirect cost} - \text{total UW contribution}) / \text{NSF direct cost}$ .

**PI Additions:** Since our 2002 proposal we have added PIs to accommodate the expanding intellectual agenda of NTL and replace expertise lost to retirements or departures from UW.-Madison (Table 5). Brock and Ives bolster our strength in theory. Hunt and Loheide contribute expertise in hydrology. Hotchkiss adds to our long-term view of ecosystem development. Kucharik supplements our skills in regional data analysis and modeling of water and biogeochemical flows. Lewis and Brock broaden our expertise in environmental economics. McMahon has assumed leadership of the Microbial Observatory and the microbial component of NTL. Five of 24 PIs are women and one is an ethnic minority.

**Coordination with other Projects:** NTL-LTER is the organizing force for a portfolio of grants with interlocking groups of PIs. A few examples are the Global Lake Ecological Observatory Network (GLEON; <http://gleon.org>; multiple grants to Kratz, Hanson), a NSF Microbial Observatory (McMahon), a Mellon Foundation project on the role of lakes in regional carbon cycles (Carpenter, Foley, Turner), multiple EPA STAR grants linking hydrology, biogeochemistry and water quality (Armstrong, Carpenter, Foley, Lathrop, Turner), USDA projects on shorelands, housing markets and land-use change (Provencher and Lewis), and a USGS Water, Energy, and Biogeochemical Budgets program based at Trout Lake (Walker, Hunt).

We collaborate regularly with staff from the state management agency (Wisconsin Department of Natural Resources), with other LTER sites (e.g., the Trends and Ecosystem Service projects), and internationally. At present we have active research collaborations in 28 nations on 4 continents plus Oceania.

We encourage others who wish to use our LTER site via posters and talks at national and international meetings, workshops (e.g., GLEON meetings), a comprehensive site web page (<http://lter.limnology.wisc.edu>), an open policy of sharing data in collaborative research, and by helping to develop joint projects with other scientists. We often facilitate participation of outside scientists at the Hasler Laboratory or at Trout Lake Station to encourage startup of pilot projects. We regularly write letters in support of researchers at other universities who wish to use our sites.

**Table 3. PIs involved in NTL-LTER.**

<b>PI</b>	<b>Department</b>	<b>Specialty Area</b>
Barbara Benson	Limnology	Ecoinformatics
William Brock	Economics	Economics and environment
Robert Bohanan	Center for Biology Education	Science education, aquatic & urban ecology
Steve Carpenter	Zoology	Ecosystem studies, social-ecological modeling
Stanley Dodson	Zoology	Community ecology, toxicology
Jonathan Foley	Atmospheric & Ocean Sciences	Regional hydrologic and biogeochemical models
Paul Hanson	Limnology	Computing systems, wireless data acquisition
Sara Hotchkiss	Botany	Ecosystem history and development, disturbance
Randy Hunt	US Geological Survey	Hydrogeological modeling
Anthony Ives	Zoology	Community ecology and population biology
Tim Kratz	Limnology	Lake landscape ecology
Chris Kucharik	Center for Sustainability and the Global Environment	Regional analysis of natural and managed ecosystems
Dick Lathrop	Wisconsin Department of Natural Resources	Lake and watershed management
David Lewis	Agricultural and Applied Economics	Effects of policies on landscapes and ecosystem services
Steve Loheide	Civil and Environmental Engineering	Hydrogeology, hydroecology, remote sensing
John Magnuson	Zoology	Fish ecology, limnology
Katherine McMahon	Civil and Environmental Engineering	Microbial ecology, environmental biotechnology
Pete Nowak	Nelson Institute	Social-agricultural systems, rural sociology
Robert (Bill) W. Provencher	Agricultural & Applied Economics	Economics, econometrics
Emily Stanley	Zoology	Biogeochemistry, river and wetland ecology
Monica Turner	Zoology	Landscape ecology
Jake Vander Zanden	Zoology	Aquatic food web, invasive species, & fish ecology
John Walker	US Geological Survey	Hydrology, modeling and isotope geochemistry
Chin Wu	Civil & Environmental Engineering	Physical limnology

## Section 4. Information Management

**Philosophy and Goals.** Information management is an integral part of the research process at our site. The NTL information management system is designed to facilitate interdisciplinary research. From the design of data collection, to incorporation in the centralized database, to analyses, we focus on linkages among the components of the ecological and social systems we study. Our primary goals for information management are to (1) maintain database integrity, (2) create a powerful and accessible environment for the retrieval of information, (3) facilitate linkages among diverse data sets, and (4) provide adequate metadata for data interpretation and analysis.

**Information Management System (IMS) Scope.** Most of the core data collected by NTL (Table S2C) reside in the North Temperate Lakes LTER Database implemented in Oracle. Core spatial imagery, i.e., MODIS, is stored on network hard drives at the Center for Limnology and is accessible to NTL researchers. Non-core data of general interest such as regional limnological surveys are also maintained in Oracle as are data from associated projects (e.g., the NTL Microbial Observatory). Other data such as student research data of less broad application are archived in text format. Under our current operating procedure, all LTER graduate students meet with the information management staff to be advised on data management and to assure that their data and metadata are archived. In the past, LTER graduate student data were archived as resources permitted according to priorities set by the PIs. Core data are available to all NTL researchers as soon as the data are entered and quality screened.

NTL zooplankton samples, phytoplankton slides, fish scales, and benthic invertebrate samples are stored at the University of Wisconsin-Madison Zoology Museum. Periodic maintenance is performed to prevent drying out of wet samples. An electronic catalog provides information on this collection.

**Data Release, Access, and Use Policies.** Our longstanding policy is that all core data sets are available as soon as possible to all project PIs and staff. Core data sets are collected and managed centrally as opposed to being collected and managed by individual PIs. Typically, physical limnology data are available within a month, fish data within two months, and other data, including chemical limnology and other biological data, within a year but often much sooner. Data from instrumented buoys are uploaded to the database and published on the website in near real-time (approximately hourly).

We encourage collaborative explorations of our data (Table S2B). Our policy is to provide all core data prior to the most recent two years online on the website, and, in actual practice, much of the data are available publicly on the NTL website considerably sooner. Non-core data that are not restricted for access are also made available publicly. Very few data sets have restricted access, and the reasons for these access restrictions are almost always either proprietary (e.g., data sets produced by another source) or human subject confidentiality issues. Our data access/data use policy is available at [http://lter.limnology.wisc.edu/data_policy.html](http://lter.limnology.wisc.edu/data_policy.html).

**IMS Design.** Core data are entered, updated, and maintained in the Oracle database using scripts and applications on a Sun workstation as well as through use of an application installed on

networked Windows workstations. Most physical and chemical limnology data are entered through a web application developed locally to manage samples and data from the core data sampling. Data from the Oracle database (Table S2A) are made available by several methods (Table 4) for viewing and/or downloading over a network connection. The Oracle database has broad functionality to maintain database integrity (e.g., passwords for access, privileges and roles to control read/write, recovery from system crashes, backup utilities). Files archived as text may also be downloaded through the online data catalog.

A major area of recent innovation has been the development of IM tools for handling sensor data streams. These data bring new challenges of near-real time processing and increased data volumes. We are collaborating with computer scientists (the San Diego Supercomputer Center, Indiana University, and SUNY-Binghamton) on automated processing of sensor network data. At NTL we are exploring an alternative data model more suited to automated reconfiguration necessitated by changes in sensor deployment as well as developing tools to query, edit, display, and download sensor data (<http://www.gleonrcn.org/index.php?pr=Vega>).

NTL LTER has computer facilities at the Hasler Laboratory and Trout Lake Station. Specific details on networking, the web and database servers, backup protocols, and other components of the infrastructure are presented in Table 4 and the Facilities section of this proposal.

**IMS Staffing.** Barbara Benson has been our information manager since 1983, providing stability and continuity to information management and its linkage to our science. With a Ph.D in ecology, she is directly engaged in design of research and frequently serves as lead or co-author of ecological papers in addition to papers on information management. She consults with students and other researchers on research data management. Our remote sensing/GIS specialist, Jeff Maxted, received an M.S. in environmental monitoring and has been working with spatial data at the Center for Limnology since 2003. The laboratory manager, Paul Hanson, maintains the local area network and computers at the Center for Limnology with the help of student hourly staff. With a Ph.D. in Limnology, he is a frequent contributor to NTL publications. Two persons with backgrounds in computer science assist the information manager: Dave Balsiger who serves as system and database administrator for NTL and an advanced undergraduate computer science student who serves as a project programmer.

**IMS Support for Science.** The client/server environment provides researchers with the powerful search and linkage capabilities of a relational database together with end-user query tools for simple, direct access. Currently, most NTL researchers and the public access data and metadata through the dynamic query application available on the NTL web site ([lter.limnology.wisc.edu](http://lter.limnology.wisc.edu)) within the online data catalog. For more sophisticated queries, some NTL researchers use a commercial end-user query tool with a point-and-click interface. With this tool, a researcher may retrieve information from the database to answer questions such as "What was the average epilimnetic chlorophyll concentration in Trout Lake during the ice-free season for each year since 1982?" The relational database supports the linking of the chlorophyll concentration table with the ice duration table, and the subsetting and aggregation that this request entails.

Information management staff provides support to project scientists and staff by developing data acquisition tools for technicians and assisting data analysis by researchers. To speed data

acquisition and reduce data entry errors, custom software has been written for recording fish field data and counting and measuring zooplankton. Numerous programs have been written to manipulate raw data into forms requested by researchers (e.g., hypsometric averages of depth profile data, estimation of mixed layer depth, histograms of fish lengths). We have developed tools for querying sensor data to facilitate the use of these data in modeling, including nowcasting. Three internet map servers, available on the NTL website, allow researchers to explore spatial data dynamically via the web for the NHLD, YLD, and the State of Wisconsin.

**Metadata.** Metadata are a crucial part of our information system. Ecological Metadata Language (EML), a metadata standard based on the XML Schema specification, is the standard adopted by the LTER Network. Each NTL online data set has associated metadata online in text file and EML formats. Metadata for spatial data include copyrights, map scale, coordinate accuracy, and data lineage information and are available as text or EML. Field and lab methods are documented for each core data set and available online for most data sets.

The metadata for the non-spatial data are stored in the Oracle database and drive the dynamic database application in the data catalog, allowing forms for querying to be generated dynamically for each data set that is maintained in the Oracle database and provided in the catalog. We have harvested the EML documents for the NTL core data sets into the central metadata catalog, Metacat, for the LTER Network. These harvested EML documents are valid EML and contain EML describing identification, discovery, evaluation, access, and integration information.

**Data Quality Assurance / Quality Control.** A number of quality-control mechanisms have been established. For example, the sampling and analysis protocol for physical and chemical parameters includes random blind samples and replicate analyses at the ratio of approximately 1:10 (replicate:sample). Quality of the chemical results is verified by comparison with previous years' data and parameter consistency checks. Water chemistry analytical performance is also evaluated every six months via analysis of blind samples provided through the USGS laboratory accreditation process. Error checking occurs in some data entry software and through proofreading. Data sets have a system of flags to indicate quality conditions such as non-standard routine or equipment used. Database triggers perform range checks on data captured in the database in near-real time from instrumented lake buoys. For other data sets, information management staff and technicians follow data-specific protocols for visual and computer-aided screening of data.

**Future Directions and Challenges.** The universal access of the web makes our web site the main entry point for external data distribution. We plan future enhancements to the data catalog for searching and browsing that will allow searches based on study site, thematic area, and selected metadata fields. To enhance the dissemination of our spatial data, we will be extending our current web-mapping applications. New tools will allow for searching, segmenting, and downloading spatial data sets based on a user-specified spatial extent (e.g., a watershed, riparian buffer, or groundwater recharge zone). In addition, we plan to offer tools that enable users to integrate spatial and tabular data using geoprocessing algorithms that can be served over the web. We will continue our leadership role in IMS design and tools for sensor network data both within LTER and GLEON.

Table 4. North Temperate Lakes LTER Information Management infrastructure

Local Area Networks (LAN)	Windows 2000 domain supporting Macintosh, Solaris, Linux and Windows-based computers at the Hasler Laboratory and Trout Lake Station, laser and color printers, document scanners
Connection to Wide Area Networks (WAN)	Hasler Laboratory LAN linked by a 100baseT connection to the campus-wide WAN; Trout Lake Station connected via a T1 land line
Web Server	Apache web server running on Dell Poweredge server (Linux operating system)
Databases	Oracle 10g and MySQL 5 RDBMS's installed on Sunblade 2000 workstation (Solaris operating system); Oracle 10g and ESRI Spatial Data Engine installed on Dell PowerEdge SC440 (Red Hat Enterprise Linux 4 operating system)
Data Retrieval	Oracle Browser application installed on networked Windows workstations; ODBC connections on networked workstations with installed Oracle Clients; dynamic query of the database through the NTL website
System Backup	Daily backups of server workstations to DAT tape; daily Oracle database exports; regular backups to tape of data on CFL file servers; regular backup of spatial data to CD-ROM and disk storage
Wireless Communication	Full wireless cloud within both Hasler Laboratory and Trout Lake Station; 900MHz Freewave radios serving instrumented autosampling field equipment / sensors
Video Conferencing Equipment	Video cameras and software, Microsoft NetMeeting software, computer projector
Remote Sensing	Space Science and Engineering Center (SSEC) X-band satellite receiving antenna and ingest capability

## **Section 5. Outreach and Education**

NTL-LTER personnel participate in educational activities at all levels (K-12, university, continuing education), public outreach, and communication of scientific findings to decision makers, media, and the public (Fig. 26). NTL contributes scientific information to policy discussions at local, state, national, and international levels.

The main focus of our educational program is and will continue to be training of graduate students. Their work figures prominently in this proposal and many of their published accomplishments are described in Section 1, Results of Prior Support. NTL students are productive researchers who have been highly successful in obtaining post-graduate positions in academia, agencies, and the private sector.

We provide undergraduate students with rewarding first-hand research experiences. At least 2 NSF-REU students and an additional 2 to 5 undergraduates supported on endowed funds or other grants conduct individual LTER-related research projects each summer. These projects often open doors to future careers. We employ additional undergraduates as research assistants in the field and laboratory. Many of our undergraduate students continue on to graduate work in the sciences. After more than 25 years of NTL research, a large number of professionals trace their roots to early experiences with our LTER program. In addition to undergraduates involved directly with research, an additional ca. 1150 undergraduates each year take classes taught by NTL-LTER principal investigators and featuring NTL-LTER data. NTL-LTER data published on the web are used by faculty at many universities in support of their teaching.

NTL's participation in the Schoolyard LTER program, which brings the excitement of the research and discovery process to K-12 teachers and students, continues to grow. Education activities and materials development for K-12 students, for middle and high school science teachers, and for undergraduates build upon existing infrastructure through a partnership of NTL- LTER and the Center for Biology Education (CBE) at UW-Madison. Dr. Robert Bohanan, an ecologist and science educator with CBE has collaborated with NTL scientists and students to create and test education materials and to provide education activities. Education materials using NTL-LTER research and methods have been developed and tested for K-12 students, middle and high school science teachers, and for undergraduate introductory biology and ecology courses (Bohanan et al. 2005a,b; Lucas et al. 2005).

We are especially excited to further develop and continue our work with middle and high school science teachers and students from underrepresented communities in the Milwaukee area and in tribal communities. We plan to expand the current professional development course for teachers on inquiry-based teaching and learning using the Lake Wingra watershed as a context to include a web-based wiki to support a year-round professional development sequence for course participants and for our growing cadre of Research Experiences for Teachers participants. During 2002-2007, 1764 students and 1367 teachers participated in our K-12 programs. We anticipate similar numbers of participants through this proposal period.

We propose to foster development of new materials and activities by conducting an annual workshop for faculty, staff, and students on integrating LTER research, data, and methods in

educational materials. The workshop will have two aspects. The first is to describe the repository of existing materials to NTL-LTER scientists and students and to University of Wisconsin science, technology, and engineering faculty and science educators. The second aspect of the workshop will be to begin the development of new educational materials and activities. Dr. Bohanan will lead the development of the workshop, will recruit participants, and will provide on-going support for the development of new materials and activities. Dr. Bohanan will collaborate with other outreach and education leaders in the LTER network to develop a companion workshop at the Ecological Society of America, American Society of Limnology and Oceanography, and the LTER All Scientists meetings.

We will continue to revise and adapt existing materials and activities throughout Wisconsin, and especially in the NHL and YLD, focal regions for NTL. We will develop new web-based interfaces providing increased interactivity for selected educational resources (e.g., trophic cascades lake model, invasive species predictions). We will develop a new partnership with the BioQuest Consortium at Beloit College to deploy existing and new NTL-related materials for undergraduate education in their Investigative Case Based Learning repository.

Beyond our formal educational activities, NTL scientists make many presentations to the general public. NTL scientists routinely meet with town, county and state officials to provide information about water resources. We provide public access to real-time data collected by our suite of instrumented buoys during the ice-free season (approximately late April – November). These data are used by anglers, boaters, and others interested in lake conditions. We have been among the leaders of local and regional citizen science projects such as Lake Futures (<http://lakefutures.wisc.edu>), Climate Change and the Northwoods (<http://www.wisc.edu/cbe/K12/paradiselost.html>), Scenarios for the Lake Winnebago Basin (<http://limnology.wisc.edu/courses/zoo955/spring2007/index.html>), and Waters of Wisconsin (WASAL 2003). Vander Zanden and Maxted received a 'Wisconsin Idea' Endowment award to collaborate with resource managers to apply the findings of ongoing LTER research forecasting aquatic invasive species spread in the NHL. Nationally, NTL scientists have participated in science policy forums through the NAS and NRC. Internationally, NTL scientists have contributed to the Intergovernmental Panel on Climate Change and the Millennium Ecosystem Assessment, as well as committees and working groups of international bodies such as the International Council of Science.

Our unique perspective of long-term regional change centered on freshwater resources provides valuable information to individuals of all ages, private organizations, public agencies, and elected leadership. We provide this information freely to all. In addition, we synthesize the information into forms that are useful for students of all ages through our educational activities and development of educational materials. We also synthesize our findings in ways that are useful to private and public decision makers in a range of situations. No synthesis can fit all needs, but we have consistently worked to meet the needs of local, regional, national, and international users for information. We expect to continue and expand this effort over the next 6 years.



**Figure 26.** Clockwise, from upper left: A film crew for the Big Ten Network records Limnology students aboard the Limnos. Limnology students, led by Dr. Emily Stanley, explore Fallison Bog. Participants in Winter Limnology examine an icy Lake Mendota. Dr. Jake Vander Zanden gives a public lecture to a full house at Lakeland Union High School. NTL-LTER Lead PI Steve Carpenter facilitates a collaborative meeting with the Friends of Lake Wingra. REU Jeff Watters measures discharge in the NHLD.

## Section 6. Literature Cited

- Adler, P.B., E.P. White, W.K. Lauenroth, D.M. Kaufman, A. Rassweiler, J.A. Rusak. 2005. Evidence for a general species-time-area relationship. *Ecology* 86: 2032-2039.
- Ashley, K.I. 1985. Hypolimnetic aeration: practical design and application. *Water Research* 19: 735-740.
- Austin, J.A., and S.M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback, *Geophysical Research Letters*, 34 (6): Art. No. L06604.
- Baland, J.M. and J.P. Platteau. 1998. Division of the Commons: A Partial Assessment of the New Institutional Economics of Land Rights. *American Journal of Agricultural Economics*, 80(3): 644-650.
- Beisner, B.E., C.L. Dent and S.R. Carpenter. 2003. Variability of lakes on the landscape: roles of phosphorus, food webs and dissolved organic carbon. *Ecology* 84: 1563-1575.
- Ben-Akiva, M., S.R. Lerman. 1985. *Discrete Choice Analysis: Theory and Application to Travel Demand*, MIT, Cambridge, MA.
- Bender, E.A., T.J. Case and M.E. Gilpin. 1984. Perturbation experiments in community ecology – theory and practice. *Ecology* 65: 1-13.
- Biggs, R., M. Diebel, J. Fox, D. Gilroy, A. Kamarainen, M. Kornis, N. Preston, J. Schmitz, C. Uejio, M. Van de Bogert, B. Weidel, P. West, D. Zaks and S.R. Carpenter. 2007. Scenarios for the Future of Lake Wingra. Available on the internet: <http://limnology.wisc.edu/courses/zoo955/spring2007/index.html>
- Bohanan, R., M. Krasny, and A. Wellman. 2005. Changes in lake ice: Ecosystem response to global change. *Teaching Issues and Experiments in Ecology* 3:12.
- Bohanan, R.E., K.J. Niemi, and L.A. Wachtel. 2005. Motivating students to ask scientifically production questions. *Bulletin of the Ecological Society of America* 86:103-108.
- Boxall, P.C. and W.L. Adamowicz. 2002. Understanding heterogeneous preferences in random utility models: a latent class approach. *Environmental Resource Economics*. 23: 421–446.
- Brauman, K.A., G.C. Daily, T.K. Duarte and H.A. Mooney. 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. *Ann. Rev. Environ. Resour.* 32: 6.1-6.32
- Brock, T.D. 1985. *A eutrophic lake: Lake Mendota, Wisconsin*. New York, Springer- Verlag.
- Brock, W.A. and S.R. Carpenter. 2006. Variance as a leading indicator of regime shift in ecosystem services. *Ecology and Society* 11 (2): 9. [online] URL: <http://www.ecologyandsociety.org/vol11/iss2/art9/>
- Brooks, A.S., and J.C. Zastrow. 2002. The potential influence of climate change on offshore primary production in Lake Michigan. *J. Gt. Lakes Res.* 28: 597–607.
- Cardille, J.A., M.T. Coe, and J.A. Vano. 2004. Impacts of climate variation and catchment area on water balance and lake hydrologic type in groundwater-dominated systems: a generic lake model. *Earth Interactions* 8:1-24.
- Cardille, J.A., S.R. Carpenter, M.T. Coe, J.A. Foley, P.C., Hanson, M.G. Turner, and J.A. Vano. 2007. Carbon and water cycling in lake-rich landscapes: Landscape connections, lake hydrology, and biogeochemistry. *J. Geophys. Res.*, 112, G02031, doi:10.1029/2006JG000200.

- Carpenter, S.R. 1998. The need for large-scale experiments to assess and predict the response of ecosystems to perturbation. pp. 287-312 in M.L. Pace and P.M. Groffman (eds.), *Successes, Limitations and Frontiers in Ecosystem Science*. Springer-Verlag, N.Y.
- Carpenter, S.R. 2003. Regime Shifts in Lake Ecosystems: Pattern and Variation. Volume 15 in the *Excellence in Ecology Series*, Ecology Institute, Oldendorf/Luhe, Germany.
- Carpenter, S.R. 2005. Eutrophication of aquatic ecosystems: Bistability and soil phosphorus. *Proceedings of the National Academy of Sciences* 102: 10002-10005.
- Carpenter, S.R. 2008. Seeking adaptive change in Wisconsin's ecosystems. In Waller, D.M. and T.P. Rooney (eds.), *The Vanishing Present: Wisconsin's Changing Lands, Waters and Wildlife*. University of Chicago Press, Chicago, Illinois USA.
- Carpenter, S.R. and C. Folke. 2006. Ecology for transformation. *Trends in Ecology and Evolution* 21: 309-315.
- Carpenter, S.R. and M.G. Turner. 2000. Hares and tortoises: Interactions of fast and slow variables in ecosystems. *Ecosystems* 3: 495-497.
- Carpenter, S.R. and P.R. Leavitt. 1991. Temporal variation in a paleolimnological record arising from a trophic cascade. *Ecology* 72:277-285.
- Carpenter, S.R. and W.A. Brock. 2006. Rising variance: A leading indicator of ecological transition. *Ecology Letters* 9: 311-318.
- Carpenter, S.R., B.J. Benson, R. Biggs, J.W. Chipman, J.A. Foley, S.A. Golding, R.B. Hammer, P.C. Hanson, P.T.J. Johnson, A.M. Kamarainen, T.K. Kratz, R.C. Lathrop, K.D. McMahon, B. Provencher, J.A. Rusak, C.T. Solomon, E.H. Stanley, M.G. Turner, M.J. Vander Zanden, C.-H. Wu and H. Yuan. 2007. Understanding regional change: Comparison of two lake districts. *BioScience* 57:323-335.
- Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8:559-568.
- Carpenter, S.R., R. DeFries, H.A. Mooney, S. Polasky, W. Reid and R. Scholes. 2006. Millennium Ecosystem Assessment: Research Needs. *Science* 313: 257-258.
- Champ, P.A., K.J. Boyle, and T.C. Brown. 2003. *A Primer on Nonmarket Valuation*. Springer, 588 pgs.
- Chan, K.M.A, M.R. Shaw, D.R. Cameron, E.C. Underwood,, G.C. Daily. 2006. Conservation planning for ecosystem services. *PLoS Biology* Vol. 4, No. 11, e379  
doi:10.1371/journal.pbio.0040379
- Christensen, M.R., M.D. Graham, R.D. Vinebrooke, D.L. Findlay, M.J. Paterson, and M.A. Turner. 2006. Multiple anthropogenic stressors cause ecological surprises in boreal lakes. *Global Change Biology* 12:2316-2322.
- Clark, W.C. 2007. Sustainability science -- a room of its own. *Proceedings of the National Academy of Sciences* 104: 1737-1738.
- Cole, J.J., M.L. Pace, S.R. Carpenter, and J.F. Kitchell. 2000. Persistence of net heterotrophy in lakes during nutrient addition and food web manipulation. *Limnol. Oceanogr.* 45: 1718-1730.
- Cole, J.J., S.R. Carpenter, M. L. Pace, M. C. Van De Bogert, J. L. Kitchell, and J. R. Hodgson. 2006. Differential support of lake food webs by three types of terrestrial organic carbon. *Ecology Letters* 9: 558-568.

- Cole, J.J., S.R. Carpenter, M.L. Pace, M.C. Van de Bogert, J.F. Kitchell, and J.R. Hodgson. 2006. Differential support of lake food webs by three types of terrestrial organic carbon. *Ecology Letters* 9:558-568.
- Cole, J.J., Y.T. Prairie, N.F. Caraco, W.H. McDowell, L.J. Tranvik, R.G. Striegl, C.M. Duarte, P. Kortelainen, J.A. Downing, J. Middleburg and J. Melack. 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* 10: 171-184.
- Collins D.B.G., S.R. Carpenter and J.A. Foley. In Preparation. Projections of phosphorus loading to Lake Mendota under climate change.
- Cumming, G.S. 2007. Global biodiversity scenarios and landscape ecology. *Landscape Ecology* 22:671-685.
- Daily, G. (ed.). 1997. *Nature's Services*. Island Press, Washington, D.C.
- De Groot, R.S. 1992. *Functions of Nature*. Wolters-Nordhauf, the Netherlands.
- De Stasio Jr, B.T., D.K. Hill, J.M. Kleinhans, N.P. Nibbleink and J.J. Magnuson. 1996. Potential effects of global climate change on small north-temperate lakes: Physics, fish, and plankton, *Limnology and Oceanography*, 41: 1136-1149.
- Doherty, J. 2006. Manual for version 11 of PEST. Watermark Numerical Computing, Brisbane, Australia.
- Donner, S.D. and C.J. Kucharik. 2003. Evaluating the impacts of land management and climate variability on crop production and nitrate export across the Upper Mississippi Basin. *Global Biogeochemical Cycles* 17(3) 1085, doi:10.1029/2001GB001808.
- Downing, J.A., Y.T. Prairie, J.J. Cole, C.M. Duarte, L.J. Tranvik, R.G. Striegl, W.H. McDowell, P. Kortelainen, N.F. Caraco, J.M. Melack and J.J. Middleburg. 2006. The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography*, 51, 2388-2397.
- Dripps, W.R., R.J. Hunt, and M.P. Anderson. 2006. Estimating recharge rates with analytic element models and parameter estimation. *Ground Water* 44: 47-55.
- Ehrlich, P.R. and H.A. Mooney. 1983. Extinction, substitutions and ecosystem services. *BioScience* 33: 248-254.
- Finnoff, D., J.F. Shogren, B. Leung, and D. Lodge. 2007. Take a risk: Preferring prevention over control of biological invaders. *Ecological Economics* 62:216-222.
- Folt, C.L., C.Y. Chen, M.V. Moore, and J. Burnaford. 1999. Synergism and antagonism among multiple stressors. *Limnology and Oceanography* 44:864-877.
- Fortin, M.J. and M.R.T. Dale. 2005. *Spatial Analysis: A Guide for Ecologists*. Cambridge University Press, Cambridge, U.K.
- Fraterrigo, J.M., J.A. Rusak, and M.G. Turner. In Review Disturbance-driven changes in the variability of ecological patterns and processes. *Ecology Letters*.
- Frey, D.G. 1963. *Limnology in North America*. Madison, University of Wisconsin Press.
- Frost, T.M., P.K. Montz, T.K. Kratz, T. Badillo, P.L. Brezonik, M.J. Gonzalez, R.G. Rada, C.J. Watras, K.E. Webster, J.G. Wiener, C.E. Williamson, and D.P. Morris. 1999. Multiple stresses from a single agent: diverse responses to the experimental acidification of Little Rock Lake, Wisconsin. *Limnology and Oceanography* 44:784-794.
- Gassman P.W., M.R. Reyes., C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Trans. ASABE*, 50(4):1211-1250.

- George, G., M. Hurley, and D. Hewitt. 2007. The impact of climate change on the physical characteristics of the larger lakes in the English Lake District. *Freshwater Biology* 52:1647-1666.
- Gergel, S.H., M.G. Turner, and T.K. Kratz. 1999. Dissolved organic carbon as an indicator of the scale of watershed influence on lakes and rivers. *Ecological Applications* 9: 1377-1390.
- Graham, J.M., A.D. Kent, G.H. Lauster, L.E. Graham, T.K. Kratz, and E.W. Triplett. 2004. Seasonal dynamics of phytoplankton and planktonic protozoan communities in a northern temperate humic lake: diversity in a dinoflagellate dominated system. *Microbial Ecology* 48:528-540.
- Grigorovich, I.A., O.V. Pashkova, Y.F. Gromova, and C.D.A. van Overdijk. 1998. *Bythotrephes longimanus* in the Commonwealth of Independent States: variability, distribution and ecology. *Hydrobiologia* 379:183-198.
- Groffman, P.M., J.S. Baron, T. Blett, A.J. Gold, I. Goodman, L.H. Gunderson, B.M. Levinson, M.A. Palmer, H.W. Paerl, G.D. Peterson, N.L. Poff, D.W. Rejeski, J.F. Reynolds, M.G. Turner, K.C. Weathers, and J.A. Wiens. 2006. Ecological thresholds: The key to successful environmental management or an important concept with no practical application? *Ecosystems* 9:1-13.
- Haab, T.C. and K.E. McConnell. 2002. *Valuing Environmental and Natural Resources: The Econometrics of Non-market Valuation*. Edward Elgar Publishing, 256 pgs.
- Hamilton, D.P., C.M. Spillman, K.L. Prescott, T.K. Kratz and J.J. Magnuson. 2002. Effects of atmospheric nutrient inputs and climate change on the trophic status of Crystal Lake, Wisconsin. *Verh. Internat. Verein. Limnol.* 28:467-470.
- Hammer, R.B., S.I. Stewart, R.L. Winkler, V.C. Radeloff, and P.R. Voss. 2004. Characterizing dynamic spatial and temporal residential density patterns from 1940-1990 across the North Central United States. *Landscape and Urban Planning* 69:183-199.
- Hanson, P.C., A. Pollard, D.L. Bade, K. Predick, S.R. Carpenter, and J. Foley. 2004. A model of carbon evasion and sedimentation in temperate lakes. *Global Change Biology* 10: 1285-1298.
- Hanson, P.C., D.L. Bade, S.R. Carpenter, and T.K. Kratz. 2003. Lake metabolism: Relationships with dissolved organic carbon and phosphorus. *Limnol. Oceanogr.* 48: 1112-1119.
- Hanson, P.C., S.R. Carpenter, D. Armstrong, E.H. Stanley, and T.K. Kratz. 2006. Lake dissolved inorganic carbon and dissolved oxygen: changing drivers from days to decades. *Ecological Monographs* 76: 343-363.
- Harvey, A.C. 1991. *Forecasting, structural time series models and the Kalman filter*. Cambridge University Press, Cambridge, U.K.
- Hein, C.L., B.M. Roth, A.R. Ives, and M.J. Vander Zanden. 2006. Fish predation and trapping for rusty crayfish (*Orconectes rusticus*) control: a whole-lake experiment. *Canadian Journal of Fisheries and Aquatic Sciences* 63:383-393.
- Hein, C.L., M.J. Vander Zanden, and J.J. Magnuson. 2007. Intensive trapping and increased fish predation cause massive population crash of an invasive crayfish. *Freshwater Biology* 52:1134-1146.
- Hilborn, R. and M. Mangel. 1997. *The Ecological Detective*. Princeton University Press, Princeton, N.J.
- Hill, D.K. and J.J. Magnuson. 1990. Potential effects of global climate warming on the growth and prey consumption of Great Lakes fish. *Trans. Am. Fish. Soc.* 119: 265-275.

- Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci.* 103, 11206-11210.
- Hoffman, A.R., D.E. Armstrong, R.C. Lathrop, and M.R. Penn. In Review. Factors controlling the amounts and distribution of bioavailable phosphorus in stream sediments in an agricultural watershed. *Biogeochemistry*.
- Houser, J.N., D.L. Bade, J.J. Cole, and M.L. Pace. 2003. The dual influences of dissolved organic carbon on hypolimnetic metabolism: organic substrate and photosynthetic reduction. *Biogeochemistry* 64:247-269.
- Hrabik, T.R., J.J. Magnuson, and A.S. McLain. 1998. Predicting the effects of rainbow smelt on native fishes in small lakes: Evidence from long-term research on two lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 55:1364-1371.
- Hunt, R.J. and J. Doherty. In Preparation. Using advanced tools to calibrate and estimate prediction uncertainty using a steady-state ground-water flow model of the Trout Lake Watershed, Wisconsin, U.S. Geological Survey Scientific Investigations Report.
- Hunt, R.J., D.T. Feinstein, C.D. Pint, and M.P. Anderson. 2006. The importance of diverse data types to calibrate a watershed model of the Trout Lake Basin, Northern Wisconsin, USA. *Journal of Hydrology* 321: 286-296.
- Ioannides Y. and J. Zabel. In Press. Interactions, neighborhood selection, and housing demand. *Journal Of Urban Economics*.
- IPCC (Inter-Governmental Panel on Climate Change). 2008. *Climate Change 2007 – Impacts, Adaptation and Vulnerability*. Cambridge University Press. Cambridge, England.
- Irwin, E.G., and N.E. Bockstael. 2004. Land Use Externalities, Open Space Preservation, and Urban Sprawl. *Regional Science and Urban Economics* 34: 705-725.
- Ives, A.R. and S.R. Carpenter. 2007. Stability and diversity of ecosystems. *Science* 317: 58-62.
- Ives, A.R., B. Dennis, K.L. Cottingham and S.R. Carpenter. 2003. Estimating community stability and ecological interactions from time-series data. *Ecological Monographs* 73: 301-330.
- Jensen, O.P., B.J. Benson, J.J. Magnuson, V.M. Card, M.N. Futter, P.A. Soranno, and K.M. Stewart. 2007. Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period. *Limnol. Oceanogr.* 52(5): 2013–2026.
- Johnson, P.T., J.D. Olden, M.J. Vander Zanden. In press. Dam invaders: impoundments facilitate biological invasions in freshwaters. *Frontiers in Ecology and the Environment*.
- Johnson, P.T.J., D.E. Stanton, E.R. Preu, K.J. Forshay, and S.R. Carpenter. 2006b. Dining on disease: How interactions between infection and environment affect predation risk. *Ecology* 87:1973-1980.
- Johnson, P.T.J., J.E. Longcore, D.E. Stanton, R.B. Carnegie, J.D. Shields, and E.R. Preu. 2006a. Chytrid infections of *Daphnia pulex*: development, ecology, pathology and phylogeny of *Polycaryum laeve*. *Freshwater Biology* 51:634-648.
- Kent, A.D., A.C. Yannarell, J.A. Rusak, E.W. Triplett, and McMahon, K.D. 2007. Synchrony in aquatic microbial community dynamics. *The ISME Journal* 1: 38-47.
- Kent, A.D., Jones, S.E., Yannarell, A.C., Graham, J.M., Lauster, G.H., Kratz, T.K., and Triplett, E.W. 2004. Annual patterns in bacterioplankton community variability in a humic lake. *Microb. Ecol.* 48: 550.
- Kirsch K., A. Kirsch, and J.G. Arnold. 2002. Predicting sediment and phosphorus loads in the Rock River basin using SWAT. *Trans. ASAE*, 45(6):1757-1769.

- Kitchell, J.F. 1992. Food web management: a case study of Lake Mendota. New York, Springer-Verlag.
- Kling, G.K., K. Hayhoe, L.B. Johnson, J.J. Magnuson, S. Polasky, S.K. Robinson, B.J. Shuter, M.M. Wander, D.J. Wuebbles, D.R. Zak, S.C. Lindroth, S.C. Moser, M.L. Wilson. 2003. Confronting climate in the Great Lakes Region: Impacts on our communities and ecosystems. Union of Concerned Scientists, Cambridge Massachusetts and the Ecological Society of America, Washington, D.C.
- Kratz, T.K., J.J. Magnuson, C.J. Bowser, and T.M. Frost. 1986. Rationale for data collection and interpretation in the Northern Lakes Long-Term Ecological Program. Pages 22-33 in Isom, B. G., eds. Rationale for Sampling and Interpretation of Ecological Data in the Assessment of Freshwater Ecosystems: A Symposium sponsored by ASTM Committee D-19 on Water, Philadelphia, PA, 31 Oct.-1 Nov. 1983. American Society for Testing and Materials, Philadelphia.
- Kratz, T.K., K.E. Webster, C.J. Bowser, J.J. Magnuson, and B.J. Benson. 1997. The influence of landscape position on lakes in northern Wisconsin. *Freshwater Biology* 37:209-217.
- Kratz, T.K., L.A. Deegan, M.E. Harmon, and W.K. Lauenroth. 2003. Ecological variability in space and time: insights gained from the US LTER program. *Bioscience* 53:57-67.
- Kratz, T.K., P. Arzberger, B.J. Benson, C-Y. Chiu, K. Chiu, L. Ding, T. Fountain, D. Hamilton, P.C. Hanson, Y.H. Hu, F-P. Lin, D.F. McMullen, S. Tilak, C. Wu. 2006. Towards a Global Lake Ecological Observatory Network. *Publications of the Karelian Institute* 145:51-63.
- Kucharik, C.J. and K.R. Brye. 2003. Integrated Biosphere Simulator (IBIS) yield and nitrate loss predictions for Wisconsin maize receiving varied amounts of Nitrogen fertilizer. *Journal of Environmental Quality* 32, 247-268.
- Kucharik, C.J., J.A. Foley, C. Delire, V.A. Fisher, M.T. Coe, J. Lenters, C. Young-Molling, N. Ramankutty, J.M. Norman, and S.T. Gower. 2000. Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance and vegetation structure. *Global Biogeochemical Cycles* 14: 795-825.
- Lathrop, R.C. 2007. Perspectives on the eutrophication of the Yahara lakes. *Lake and Reserv. Manage.* 23: 345-365.
- Lathrop, R.C. 2007. Perspectives on the eutrophication of the Yahara lakes. *Lake and Reserv. Manage.* 23:345-365.
- Lathrop, R.C., S B. Nehls, C.L. Brynildson , and K.R. Plass. 1992. The Fishery of the Yahara Lakes. Technical Bulletin No. 181, Department of Natural Resources. Madison, Wisconsin.
- Lathrop, R.C., S.R. Carpenter, and D.M. Robertson. 1999. Summer water clarity responses to phosphorus, *Daphnia* grazing, and internal mixing in Lake Mendota. *Limnology and Oceanography* 44: 137-146.
- Leung, B., D.M. Lodge, D. Finnoff, J.F. Shogren, M.A. Lewis, and G. Lamberti. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society of London Series B* 269:2407-2413.
- Lewis, D.J. and B.Provencher The implications of heterogeneous preferences for environmental zoning. In Preparation.
- Lillesand, T., J. Chipman, D. Nagel, H. Reese, M. Bobo and R. Goldmann. 1998. Upper Midwest Gap Analysis Program Image Processing Protocol. EMTC Report 98- G001 prepared for the US Geological Survey, Environmental Management Technical Center, Onalaska, WI.

- Liu, J., T. Dietz, S.R. Carpenter, C. Folke, M. Alberti, C.L. Redman, S. H. Schneider, E. Ostrom, A.N. Pell, J. Lubchenco, W.W. Taylor, Z. Ouyang, P. Deadman, T. Kratz, W. Provencher. 2007. Complexity of coupled human and natural systems. *Science* 317:1513-1516.
- Lovett, G.M., C.G. Jones, M.G. Turner and K.C. Weathers. (eds.) 2005. *Ecosystem Function in Heterogeneous Landscapes*. Springer, NY.
- Lowry, C.S., J.F. Walker, R.J. Hunt, and M.P. Anderson. 2007. Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor *Water Resources Research* 43: W10408.
- Lucas, D., N. Broderick, R. Lehrer, and R. Bohanan. 2005. Making the Grounds of Scientific Inquiry Visible in the Classroom. *Science Scope*, November-05 Issue.
- Ludwig, D., S.R. Carpenter and W.A. Brock. 2003. Optimal phosphorus loading for a potentially eutrophic lake. *Ecological Applications* 13: 1135-1152.
- M.A. (Millennium Ecosystem Assessment). 2005. *Ecosystems and Human Well Being: General Synthesis*. Island Press, Washington D.C.
- MacIsaac, H.J., H.A.M. Ketelaars, I.A. Grigorovich, C.W. Ramcharan, and N.D. Yan. 2000. Modeling *Bythotrephes longimanus* invasion in the Great Lakes basin based on its European distribution. *Archiv Fur Hydrobiologie* 149:1-21.
- MacIsaac, H.J., J.V.M. Borbely, J.R. Muirhead, and P.A. Graniero. 2004. Backcasting and forecasting biological invasions of inland lakes. *Ecological Applications* 14:773-783.
- MacPherson, A., R. Moore, B. Provencher. 2006. A Dynamic Principal-Agent Model of Human-Mediated Aquatic Species Invasions. *Agricultural and Resource Economics Review*, 35(1):144-154.
- Magnuson, J.J. 1990. Long-term ecological research and the invisible present. *Bioscience* 40:495-501.
- Magnuson, J.J. 2007. Perspectives on the long-term dynamics of lakes on the landscape. *Lake and Reserve. Manage.* 23: 452-456.
- Magnuson, J.J. and C. J. Bowser. 1990. A network for long-term ecological research in the United States. *Freshwater Biology* 23:137-43.
- Magnuson, J.J., B.J. Benson and T.K. Kratz. 1990. Temporal coherence in the limnology of a suite of lakes in Wisconsin, U.S.A. *Freshwater Biology* 23:145-159.
- Magnuson, J.J., B.J. Benson, and T.K. Kratz. 2004. Patterns of coherent dynamics within and between lake districts at local to intercontinental scales. *Boreal Environment Research* 9:359-369.
- Magnuson, J.J., B.J. Benson, O.P. Jensen, T.B. Clark, V.Card, M.N. Futter, P.A. Soranno, and K.M. Stewart. 2005. Persistence of coherence of ice-off dates for inland lakes across the Laurentian Great Lakes region. *International Association of Theoretical and Applied Limnology* 29:521-527.
- Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart, and V.S. Vuglinski. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. *Science* 289: 1743-1746.
- Magnuson, J.J., K.E. Webster, R.A. Assel, C.J. Bowser, P.J. Dillon, J.G. Eaton, H.E. Evans, E.J. Fee, R.I. Hall, L.R. Mortsch, D.W. Schindler, F.H. Quinn. 1997. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian shield region. *Hydrol. Processes* 11: 825-871.

- Magnuson, J.J., T.K. Kratz, and B.J. Benson. 2006. Long-Term Dynamics of Lakes in the Landscape: Long-Term Ecological Research on North Temperate Lakes. Oxford University Press, New York, 400pp.
- Marburg, A., M.G. Turner, and T.K. Kratz. 2006. Natural and anthropogenic variation in coarse wood among and within lakes. *Journal of Ecology* 94:558-568.
- Markstrom, S.L., R.G. Niswonger, R.S. Regan, D.E. Prudic and P.M. Barlow. 2007. GSFLOW Coupled Ground-water and surface water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow model (MODFLOW-2005). U.S. Geological Survey Techniques and Methods 6-D1.
- Masbruch, M.D. 2005. Delineation of source areas and characterization of chemical variability using isotopes and major ion chemistry, Allequash Basin, Wisconsin. Masters thesis. University of Wisconsin.
- McCarthy, J.M., C.L. Hein, J.D. Olden, and M.J. Vander Zanden. 2006. Coupling long-term studies with meta-analysis to investigate impacts of invasive crayfish on zoobenthic communities. *Freshwater Biology* 51:224-235.
- Mercado-Silva, N., J.D. Olden, J.T. Maxted, T.R. Hrabik, and M.J. Vander Zanden. 2006. Forecasting the spread of invasive rainbow smelt in the Laurentian Great Lakes region of North America. *Conservation Biology* 20:1740-1749.
- Mercado-Silva, N., S. Gilbert, G.G. Sass, B.M. Roth, and M.J. Vander Zanden. 2007. Impact of rainbow smelt (*Osmerus mordax*) invasion on walleye (*Sander vitreus*) recruitment in Wisconsin lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 64:1543-1550.
- Metzger, M.J., M. D.A. Rounsevell, L. Acosta-Michlik, R. Leemans, and D. Schröter. 2006. The vulnerability of ecosystem services to land use change. *Agriculture Ecosystems and Environment* 114:69-85.
- Morey, E., J. Thacher and W. Breffle. 2006. Using Angler Characteristic and Attitudinal Data to Identify Environmental Preference Classes: A Latent-Class Model. *Environmental Resource Economics* 34:91-115.
- Muirhead, J.R., and H.J. MacIsaac. 2005. Development of inland lakes as hubs in an invasion network. *Journal of Applied Ecology* 42:80-90.
- National Invasive Species Council. 2001. Meeting the invasive species challenge: National invasive species management plan. USA Federal Government, Washington, DC.
- Naylor, R.L. 2000. The economics of alien species invasions. Pages 241-259 in H. Mooney and R. Hobbs, editors. *Invasive species in a changing world*. Island Press, Washington, D.C.
- Naylor, R.L., A.J. Liska, M.B. Burke, W.P. Falcon, J.C. Gaskell, S.D. Rozelle and K.G. Cassman. 2007. The ripple effect: Biofuels, food security and the environment. *Environment* 49(9): 30-43.
- Niemisto, J.P. and J. Horppila. 2007. The contribution of ice cover to sediment resuspension in a shallow temperate lake: possible effects of climate change on internal nutrient loading. *Journal of Environmental Quality* 36:1318-1323.
- NRC (National Research Council). 2002. *The Drama of the Commons*. National Academy Press, Washington DC.
- Baland, J.M. and J.P. Platteau. 1998. Division of the Commons: A Partial Assessment of the New Institutional Economics of Land Rights. *American Journal of Agricultural Economics* 80(3): 644-650.
- NRC (National Research Council). 2007. *Water Implications of Biofuels Production in the United States*. National Academy Press, Washington, D.C.
- Odum, E.P. 1989. *Ecology and Our Endangered Life-Support Systems*. Sinauer Associates.

- Ostrom E. and H. Narendra. 2006. Insights on linking forests, trees, and people from the air, on the ground, and from the laboratory. *Proceedings Of The National Academy Of Sciences, USA*, 103(51): 19224-19231.
- Ostrom E., R. Gardner, J. Walker. 1994. *Rules, Games And Common-Pool Resources*, University of Michigan Press
- Ostrom, E. 1990. *Governing the Commons*. Cambridge University Press.
- Papenfus, M., and B. Provencher. A hedonic analysis of environmental zoning. In Preparation.
- Peters, D.P.C., R.A. Pielke Sr., B.T. Bestelmeyer, C.D. Allen, S. Munson-McGee and K.M. Havstad. 2004. Cross-scale interactions, nonlinearities, and forecasting catastrophic events. *Proceedings of the National Academies of Science* 101: 15130-15135.
- Peterson, G.D., T.D. Beard Jr., B.E. Beisner, E.M. Bennett, S.R. Carpenter, G.S. Cumming, C.L. Dent, and T.D. Havlicek. 2003. Assessing future ecosystem services: a case study of the Northern Highlands Lake District, Wisconsin. *Conservation Ecology* 7(3): 1. [online] URL: <http://www.consecol.org/vol7/iss3/art1>
- Petterson, K., K. Grust, G. Weyhenmeyer, T. Blenckner. 2003. Seasonality of chlorophyll and nutrients in Lake Erken —effects of weather conditions. *Hydrobiologia* 506: 75–81.
- Pickett, S.T.A., J. Kolasa, and C.G. Jones. 2007. *Ecological understanding: the nature of theory and the theory of nature*. Second Edition. Academic Press, Inc., San Diego, California. 133 pp.
- Pint, C.D., R.J. Hunt, and M.P. Anderson. 2003, Flowpath delineation and ground water age, Allequash Basin, Wisconsin. *Ground Water* 41:895-902.
- Porter, J., P. Arzberger, H. Braun, P. Bryant, S. Gage, T. Hansen, P. Hanson, F. Lin, C. Lin, T. K. Kratz, W. Michener, S. Shapiro, and T. Williams. 2005. Wireless sensor networks for ecology. *Bioscience* 55:561-572.
- Potschin, M. and R. Haines-Young. 2006. "Rio+10", sustainability science and landscape ecology. *Landscape and Urban Planning* 75:162-174.
- Powell, T.M. and J.H. Steele. 1995. *Ecological Time Series*. Springer, N.Y.
- Seurant, L. and P.G.C. Strutton. 2004. *Scaling Methods in Aquatic Ecology*. CRC Press, London.
- Provencher, B. and J. Schoen. 2007. Results of the 2005-2006 Survey of Vilas County Shoreline Property Owners. [http://lter.limnology.wisc.edu/lakeresident_survey_summary.pdf](http://lter.limnology.wisc.edu/lakeresident_survey_summary.pdf)
- Provencher, B. and R.C. Bishop. 2004. Does accounting for preference heterogeneity improve the forecasting of a random utility model? A case study. *Journal of Environmental Economics and Management* 48(1):793-810.
- Provencher, B., and R. Moore. 2006. A discussion of using angler characteristics and attitudinal data to identify environmental preference classes: A latent-class model. *Environmental and Resource Economics* 34:117-124.
- Radomski, P. & T.J. Goeman. 2001. Consequences of human lakeshore development on emergent and floating-leaf vegetation abundance. *North American Journal of Fisheries Management* 21:46-61
- Reynolds, C.S. 1997. *Vegetation Processes in the Pelagic: A Model for Ecosystem Theory*. Excellence in Ecology Series Vol. 9, Ecology Institute, Oldendorf/Luhe, Germany.
- Robertson, D.M. and R.A. Ragotzkie. 1990. Thermal structure of a multibasin lake: Influence of morphometry, interbasin exchange, and groundwater. *Canadian Journal of Fisheries and Aquatic Sciences*, 47: 1206-1212.

- Sass, G.G., J.F. Kitchell, S.R. Carpenter, T.R. Hrabik, A.E. Marburg, and M.G. Turner. 2006. Fish community and food web responses to a whole-lake removal of coarse woody habitat. *Fisheries* 31:321-330.
- Sellinger, C.E., C.A. Stow, E.C. Lamon, and S.S. Qian. 2008. Recent water level declines in the Lake Michigan-Huron System. *Environmental Science and Technology* 42:367-373.
- Senge, P.M. 2006. *The Fifth Discipline, the Art & Practice of the Learning Organization*. Second Edition. New York: Doubleday/Currency.
- Seurant, L. and P.G.C. Strutton. 2004. *Scaling Methods in Aquatic Ecology*. CRC Press, London.
- Shade, A.L., A.D. Kent, S.E. Jones, R.J. Newton, E.W. Triplett, K.D. McMahon. 2007. Inter-annual dynamics and phenology of bacterial communities in a eutrophic lake. *Limnol and Oceanogr* 52(2): 487-494.
- Sharma, S., D.A. Jackson, C.K. Minns, and B.J. Shuter. 2007. Will northern fish populations be in hot water because of climate change? *Global Change Biology* 13: 2052-2064.
- Soranno, P.A., S.L. Hubler, S.R. Carpenter and R.C. Lathrop. 1996. Phosphorus loads to surface waters: A simple model to account for spatial patterns of land use. *Ecological Applications* 6: 865-878.
- Soranno, P.A., S.R. Carpenter and R.C. Lathrop. 1997. Internal phosphorus loading in Lake Mendota: Response to external loads and weather. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 1883-1893.
- Stauffer, R.E. and G.F. Lee. 1973. The role of thermocline migration in regulating algal blooms. Pages 73-81 in E.J. Middlebrooks, ed. *Modeling the Eutrophication Process*. Ann Arbor Science, Ann Arbor, Michigan USA.
- Stedman, R.C., R.C. Lathrop, B. Clark, J. Ejsmont-Karabin, P. Kasprzak, K. Nielsen, D. Osgood, M. Powell, A-M. Ventela, K.E. Webster, A. Zhukova. 2007. Perceived environmental quality and place attachment in North American and European temperate lake districts. *Lake and Reservoir Management* 23(4): 330-344.
- Stefan, H.G., M. Hondzo, J.G. Eaton, and J.H. McCormick. 1995. Predicted effects of global climate on fishes in Minnesota lakes. Pp. 1124-1135 in R.J. Beamish (ed.), *Climate change and northern fish populations*. Canadian Special Publication in Fisheries and Aquatic Sciences 121. National Research Council of Canada, Ottawa.
- Stow, C.A., S.R. Carpenter and R.C. Lathrop. 1997. A Bayesian observation error model to predict cyanobacterial biovolume from spring total phosphorus in Lake Mendota, Wisconsin. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 464-473.
- Termorshuizen, J.W., P. Opdam, and A. van den Brink. 2007. Incorporating ecological sustainability into landscape planning. *Landscape and Urban Planning* 79:374-384.
- Tilak, S., P. Arzberger, D. Balsiger, B.J. Benson, R. Bhalerao, K. Chiu, T. Fountain, D. Hamilton, P. Hanson, T. Kratz, F.P. Lin, T. Meinke, and L. Winslow. In Press. Conceptual Challenges and Practical Issues in Building The Global Lake Ecological Observatory Network. *Proceedings of the third International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP) 2007*, Melbourne, Australia.
- Tilman, D., J. Hill, and C. Lehman. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, 314, 1598-1600.

- Tscharntke, T., A.M. Klein, A. Kruess, I. Steffan-Dewenter and C. Thies. 2005. Landscape perspectives on agricultural intensification and biodiversity — ecosystem service management. *Ecology Letters* 8:857-874.
- Turner, M.G. 2005. Landscape ecology in North America: Past, present and future. *Ecology* 86: 1967-1974.
- USDA (U.S. Department of Agriculture). 2007. Prospecting Plantings. National Agricultural Statistics Service, Washington DC.
- van Nes, E. and M. Scheffer. 2007. Slow recovery from perturbations as a generic indicator of a nearby catastrophic shift. *Am. Nat.* 169: 738-747.
- Vander Zanden, M.J., J.D. Olden, J.H. Thorne, and N.E. Mandrak. 2004. Predicting occurrences and impacts of bass introductions in north temperate lakes. *Ecological Applications* 14:132-148.
- Vano, J.A. 2005. Land surface hydrology in northern Wisconsin, USA.: Influences of climate variability and land cover. M.S. thesis. University of Wisconsin-Madison, Wisconsin.
- Vano, J.A., J.A. Foley, C.J. Kucharik, and M.T. Coe. 2006. Evaluating the seasonal and interannual variations in water balance in northern Wisconsin using a land surface model, *Journal of Geophysical Research* 111, G02025, doi:10.1029/2005JG000112.
- Walker, B. and D. Salt. 2006. *Resilience Thinking*. Island Press, Washington DC.
- Walker, J.F., R.J. Hunt, and S.J. Westenbroek. In Preparation. A linked ground-water surface-water model of the Trout Lake basin, Wisconsin, U.S. Geological Survey Scientific Investigations Report.
- Walker, J.F., R.J. Hunt, T.D. Bullen, D.P. Krabbenhoft, and C. Kendall. 2003. Variability of Isotope and Major Ion Chemistry in the Allequash Basin, Wisconsin. *Ground Water* 41:883-902.
- Walsh, R. 2007. Endogenous Open Space Amenities in a Locational Equilibrium. *Journal of Urban Economics*, 61: 319-344.
- WASAL (Wisconsin Academy of Sciences, Arts and Letters). 2003. *Waters of Wisconsin: The Future of Our Aquatic Ecosystems and Resources*. Wisconsin Academy of Sciences, Arts and Letters, Madison, Wisconsin.
- Watson, V.J. and O.L. Loucks. 1979. An Analysis of Turnover Times in a Lake Ecosystem and Some Implications for System Properties. Pp. 355-383 in *Theoretical Systems Ecology: Advances and Case Studies*. E. Halfon (ed). New York, Academic Press.
- Webster, K.E., C.J. Bowser, M.P. Anderson, and J.D. Lenters. 2006. Understanding the Lake-Groundwater System: Just Follow the Water. In Magnuson, J.J., T.K. Kratz, and B.J. Benson. *Long-Term Dynamics of Lakes in the Landscape: Long-Term Ecological Research on North Temperate Lakes*. Oxford University Press, New York, 400pp.
- Webster, K.E., P.A. Soranno, S.B. Baines, T.K. Kratz, C.J. Bowser, P.J. Dillon, P. Campbell, E.J. Fee and R.E. Hecky. 2000. Structuring features of lake districts: landscape controls on lake chemical responses to drought. *Freshwater Biology* 43:499-515.
- Webster, K.E., T.K. Kratz, C.J. Bowser, and J.J. Magnuson. 1996. The influence of landscape position on lake chemical responses to drought in northern Wisconsin. *Limnology and Oceanography* 41:977-984.
- Wei, W.W.S. 1990. *Time Series Analysis*. Addison Wesley, Massachusetts.
- Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*. 3rd edition. Academic Press, San Diego, CA.

- White, E.P., P.B. Adler, W.K. Lauenroth, R.A. Gill, D. Greenberg, D.M. Kaufman, A. Rassweiler, J.A. Rusak, M.D. Smith, J.R. Steinbeck, R.B. Waide, J. Yao. 2006. A comparison of the species-time relationship across ecosystems and taxonomic groups. *Oikos* 112: 185-195.
- Williamson, C.E., W.K. Dodds, T.K. Kratz, and M. Palmer. In Press. Forecasting environmental change at regional to continental scales: lakes and streams as sentinels and integrators of terrestrial and atmospheric processes. *Frontiers in Ecology and the Environment*.
- Willis, T.V. and J.J. Magnuson. 2006. Response of fish communities in five north temperate lakes to exotic species and climate. *Limnology and Oceanography* 51: 2808-2820.
- Wilson, K. A., J. J. Magnuson, D. M. Lodge, A. M. Hill, T. K. Kratz, W. L. Perry, and T. V. Willis. 2004. A long-term rusty crayfish (*Orconectes rusticus*) invasion: dispersal patterns and community change in a north temperate lake. *Canadian Journal of Fisheries and Aquatic Sciences* 61:2255-2266.
- Wu, C.H. and H. Yuan. 2006. Efficiency and Accuracy of Non-hydrostatic modeling of free-surface flows, 434-447, *Estuarine and Coastal Modeling*, ASCE.
- Yan, N.D., and T.W. Pawson. 1997. Changes in the crustacean zooplankton community of Harp Lake, Canada, following invasion by *Bythotrephes cederstroemi*. *Freshwater Biology* 37:409-425.
- Yan, N.D., R. Girard, and S. Bourdreau. 2002. An introduced invertebrate predator (*Bythotrephes*) reduces zooplankton species richness. *Ecology Letters* 5:481-485.
- Yan, N.D., W.I. Dunlop, T.W. Pawson, and L.E. MacKay. 1992. *Bythotrephes cederstroemi* (Schoedler) in Muskoka lakes: First records of the European invader in inland lakes in Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 49:422-426.
- Yannarell, A.C., Kent, A.D., Lauster, G.H., Kratz, T.K., and Triplett, E.W. 2003. Temporal patterns in bacterial communities in three temperate lakes of different trophic status. *Microb. Ecol.* 46: 391-405.
- Yuan, H.L. 2007. Development of a non-hydrostatic model and its application to two lakes in Madison, Wisconsin. Ph.D., dissertation. University of Wisconsin-Madison.
- Yuan, H.L. and C.H. Wu. 2004a. A two-dimensional vertical non-hydrostatic sigma model with an implicit method for free-surface flows. *International Journal for Numerical Methods in Fluids* 44: 811-835.
- Yuan, H.L. and C.H. Wu. 2004b. An implicit 3D fully non-hydrostatic model for free-surface flows. *International Journal for Numerical Methods in Fluids* 46: 709-733.