Table of Contents

Project Summary

Lakes are conspicuous, ecologically-important, and socially-valued components of landscapes. Lakes collect water, energy, solutes and pollutants from the land and atmosphere, provide habitats and resources for organisms, and interact with diverse human activities. The North Temperate Lakes Long-Term Ecological Research program aims to understand the ecology of lakes in relation to relevant atmospheric, geochemical, landscape and human processes. Our overarching research question is "<u>How do biophysical setting, climate, and changing land use and cover interact to shape lake characteristics and dynamics over time (past, present, future)?</u>" We address this question through five inter-related goals:

1. Perceive long-term changes in the physical, chemical, and biological properties of lake districts

2. Understand the drivers of temporal variability in lakes and lake districts

3. Understand the interaction of spatial processes with long-term change

4. Understand the causes and predictability of rapid extensive change in ecosystems

5. Build a capacity to forecast the future ecology of lake districts

We examine patterns, processes, and interactions of lakes, landscapes and people at four spatial scales: individual lakes, small drainage systems with several lakes, entire lake districts, and the Western Great Lakes region of North America. Temporally, we consider scales from a fraction of a day to decades. We use multiple approaches of long-term observation, comparison across ecosystems, experimental manipulations, and process modeling. In this proposal, we specifically address decadal forecasts of ecosystem change, which become the hypotheses for future long-term research. Our interdisciplinary research group includes ecologists, hydrologists, climatologists, chemists, demographers, an economist, rural sociologists, and specialists in remote sensing and information management.

We expect our research to produce new conceptualizations of lake district dynamics. Among these are new insights on the dynamics and impacts of invasive species, understanding of the role of spatial location of lakes in landscape dynamics, the reflexive interactions of human and ecological processes, and the interactive effects of geomorphic setting, climate and human activity on long-term change in lake districts. The understanding of integrated landscape-lake-social systems developed through our LTER program will be useful in decisions of individuals and institutions concerned with the future of the Western Great Lakes region and the welfare of its residents.

Section 1. Results from Prior Support

Comparative Studies of a Suite of Lakes in Wisconsin
Grant # DEB9232863 Funding (1996-2002) = $6,000,000

The North Temperate Lakes Long-Term Ecological Research (NTL-LTER) program was established in 1981. Over the past 20 years we have designed and implemented a comprehensive study of seven lakes in a forested landscape within the Northern Highland Lake District in northern Wisconsin, and since 1994, an additional four lakes in the agricultural and urban catchments in southern Wisconsin. We have increased our understanding of long-term dynamics of lakes at spatial scales ranging from small sites within lakes to the northern hemisphere. We have published 243 peer-reviewed papers during the last six years (1996-2001, plus those in press; Fig. 1). A complete publication list is in the Supplementary Documentation section of this proposal.

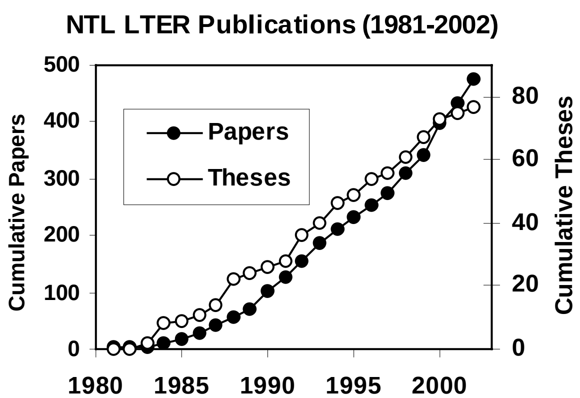


Fig. 1. Cumulative publications by year for the North Temperate Lakes LTER project from 1981 to present. Publications in press are counted as 2002. Popular articles and non-LTER related publications from the Center for Limnology are not included. Publication numbers are likely underestimated because we do not learn of every paper that uses our publicly-available data.

Below we describe some selected research, information management, and educational accomplishments of the past six years. For convenience we have grouped research results into four areas: in-lake dynamics, biotic invasions, regional analyses, and human-lake interactions. These four areas reflect the breadth of our program, but for brevity only a few representative research results are described. Each of these results relied on high-quality, well-managed, long-term data. Other examples can be found on our web page (http://www.limnology.wisc.edu/findings.html) or in our publications.

In-Lake Dynamics

Long-term patterns in water clarity. Analyses of long-term data for Lake Mendota show that food web dynamics, phosphorus runoff, and lake-mixing events interact in complex ways to determine water clarity (Lathrop et al. 1999). Food web dynamics that affect the grazing rate of *Daphnia* can dramatically influence algal densities, especially in the non-summer months when edible-sized algae dominate. Among-year variability in runoff events influences phosphorus loading which fuels algal blooms. Finally, fine-scale lake mixing events can influence nutrient distribution within the water column and alter water clarity (Soranno 1997). The combined effect of all of these processes is seen in the long-term data from NTL lakes.

Long-term dynamics of yellow perch in Crystal Lake. One of the most intriguing types of population fluctuation is that of regular cyclical change. Since 1981, we have observed three cases of cohort dominance of yellow perch in Crystal Lake in which two age-classes dominated the population for roughly 5 years (Fig. 2, Sanderson et al. 1999). Oscillations in young-of-the-year perch abundance were endogenously driven. Young-of-the-year fish were abundant primarily in years when reproductively mature fish were present, suggesting that the repeated oscillations are driven predominantly by pulses of abundant reproductive adult perch. As these young perch grow to juveniles, they exclude the possibility of survival by successive cohorts through cannibalistic and competitive interactions.

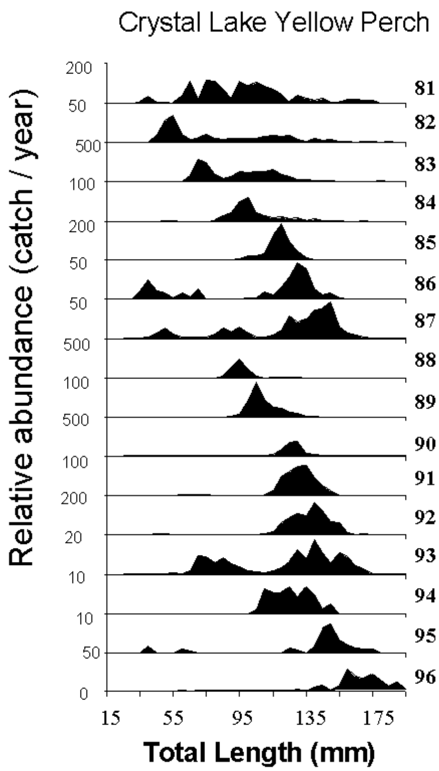


Fig. 2. Relative abundance (CPUE) of yellow perch (*Perca flavescens*) in Crystal Lake as a function of fish size for 1981-1996. Scales for each year differ and are indicated by the numbers on the left axis.

Instrumented buoys developed to measure lake metabolism. Whole-lake metabolism is an integrative process that is highly dynamic and difficult to measure. We developed a series of instrumented buoys and deployed them for several days on 32 lakes to measure diel dynamics of dissolved O_2 and CO_2 in the surface water of lakes. Changes in gas concentrations were used to calculate *in situ* rates of respiration (R), gross primary production (GPP) and net ecosystem production (NEP). O_2 was measured using a rapid pulse dissolved oxygen probe, and CO_2 was measured independently of O_2, using a custom-built gas equilibration chamber coupled with an infrared gas analyzer. R was positively correlated with dissolved organic carbon and chlorophyll concentrations, GPP was positively correlated with chlorophyll, and NEP was positively correlated with both chlorophyll and DOC. These short-term studies have laid the foundation for a more intensive long-term study of lake metabolism using instrumented buoys described in this proposal.

Biotic Invasions

Effects of introductions of exotic fish species. Long-term data revealed time lags in effects of invaders on lake communities. Rainbow smelt (*Osmerus mordax*) have invaded Crystal and Sparkling Lakes, two LTER primary lakes in northern Wisconsin. Each of these invasions has led to large shifts in fish community structure. Long-term data sets have been instrumental in allowing us to identify the mechanisms of inter-specific interaction, rates of decline, and extinctions of native species caused by the smelt invasions. Predation effects of smelt have led to the extinction of native cisco (*Coregonus artedi*) in Sparkling Lake over the span of approximately a decade and

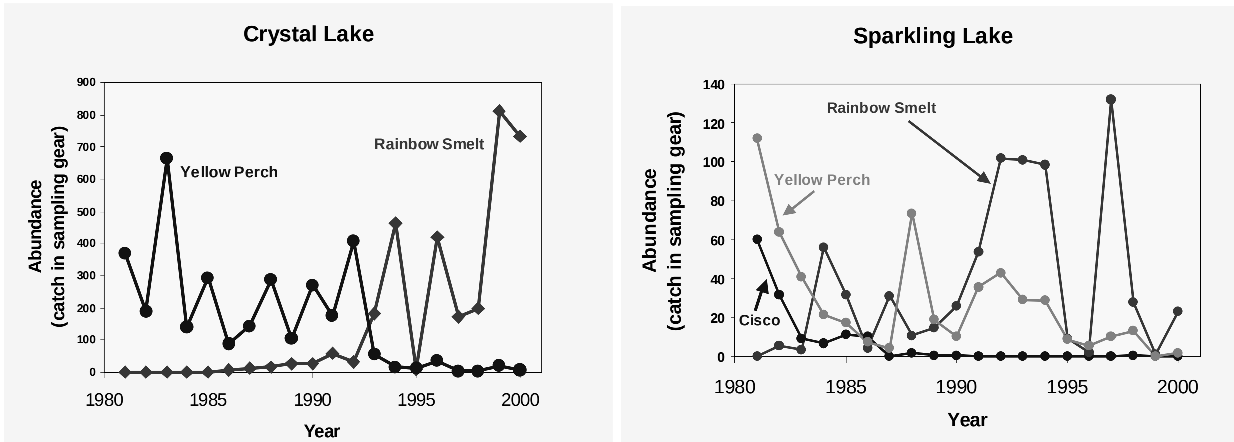


Fig. 3. Abundance of exotic Rainbow Smelt and native planktivorous fishes in Crystal and Sparkling Lakes.

competitive interactions have reduced a historically dominant yellow perch (*Perca flavescens*) population in Crystal Lake to a small component of the fish community (Fig. 3, Hrabik et al. 1998, Hrabik et al. 2001). Rainbow smelt is one of five invading species that NTL is studying. The others are rusty crayfish (*Orconectes rusticus*) which invaded many of the northern Wisconsin in the 1970s, zebra mussels which have recently been found in low numbers in the Madison area lakes, Eurasian milfoil which invaded the Madison area lakes in the 1960s, and *Cylindrospermopsis raciborskii*, an invasive and highly toxic cyanobacterium.

Lake District and Regional Analyses

Landscape Position, Groundwater, Lake Chemistry and Climate. The position of lakes within a hydrologic flow system determines many fundamental features of lakes. Lakes high in the flow system tend to be smaller, more dilute chemically, clearer, more susceptible to acidification, receive less groundwater input, have fewer fish species, and have less human use than lakes lower in the flow system (Kratz et al. 1997, Webster et al. 1996, Reed-Anderson et al. 2000a, Riera et al. 2000). Lake dynamics are also influenced by landscape position. Lake chemical responses to a prolonged drought were a function of a lake's landscape position (Fig. 4). Lakes moderately high in the landscape, where reversals in groundwater inflow are likely, lost cation mass during drought (Webster et al. 1996, 2000). Lakes low in the landscape, however, accumulated cations during the drought because their groundwater inputs are dominated by regional flowpaths, which are less responsive to climate shifts. Data from other lake districts such as the Experimental Lakes Area and the Dorset Research

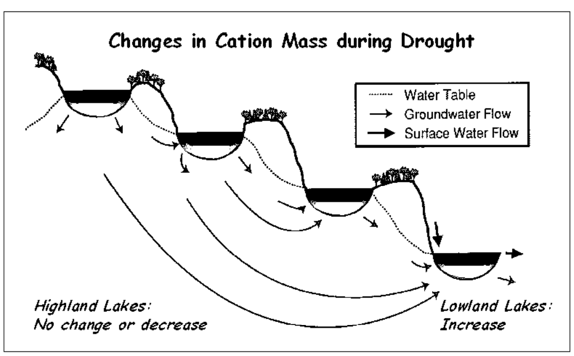


Fig. 4. Changes in cation mass of the NTL-LTER lakes during drought. Lakes are arranged along a landscape position gradient

Centre in Ontario suggest that landscape patterns of lake response to drought are complex but predictable across the Upper Midwest (Webster et al. 2000).

Ice phenology in the northern hemisphere. NTL researchers have led efforts to use changes in lake ice phenology as indicators of global climate change and variability. Duration of ice cover has decreased in the last 150 years in lakes throughout the Northern Hemisphere (Magnuson et al. 2000). El Niño influences (Robertson et al. 2002) and effects of interdecadal climatic shifts (Benson et al. 2002) are not uniformly distributed across the hemisphere. Interannual variation in freeze and thaw dates was larger from 1971-1990 than from 1951-1970 (Kratz et al. 2002a) but periods of high and low variation have occurred throughout the last 150 years.

Human/Lake Interactions

Predicting Blue-Green Algal Blooms in Lakes using Long-Term Data. Long-term records of phosphorus loading, in-lake P concentrations, and blue-green algal abundances were used to predict the probabilities that blue-green algae would exceed bloom thresholds of >2 and >5 mg L^{-1} as a function of P loading rate for Lake Mendota (Lathrop et al. 1998, Fig. 5). These analyses were used to set targets for P input reduction by the Lake Mendota Priority Watershed Project, which will commit over $16 million of state and local funds to improve water quality in the lake. The long-term P loading data were also used by Carpenter et al. (1999) to show that traditional deterministic lake models overestimated P input targets, if the goal of P management is to maximize the net economic benefits of all human activities using the lake and its watershed.

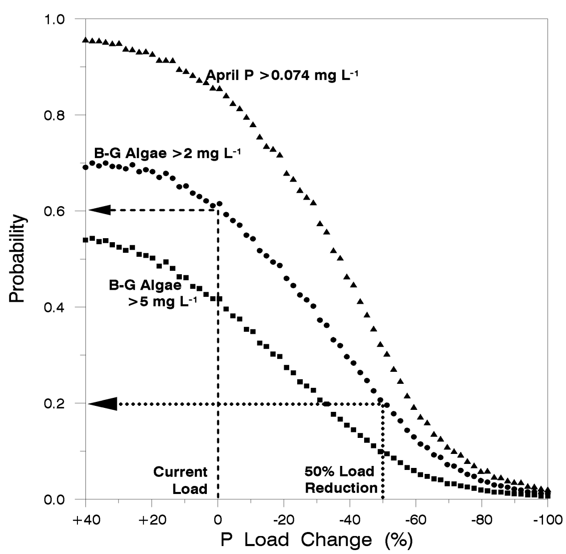


Fig. 5. Probabilities of summer blue-green algal bloom concentrations >2 and >5 mg L^{-1} and spring P concentrations >0.074 mg L^{-1} vs. change from current P loading rates. Arrows show current load and a proposed 50% reduction in P loading rates for Lake Mendota.

Ecological Economics of Lakes Subject to Regime Shifts. NTL interdisciplinary studies have calculated the net economic value of water quality, based on the economics of farming, value of housing near the lake, and the recreational economy derived from boating, fishing and so forth (Wilson and Carpenter 1999, Stumborg et al. 2001). These analyses suggest that the economically optimal loading of phosphorus to the lake (which maximizes net costs and benefits to society as a whole) is around one-third of the current loading rate. The long-term data also suggest that even the economically-optimal phosphorus loads may incur a high risk of shifting the lake into an irreversible eutrophic state (Carpenter et al. 1999, Carpenter 2001, Scheffer et al. 2001). This risk is related to the high variability in loading caused by variable climate. It also depends on the proportion of the watershed used for phosphorus-intensive agriculture such as dairy or meat production.

Cross-site science

We organized two large, international cross-site workshops: one on ice phenology across the Northern Hemisphere, which led to a special symposium at the SIL meeting in Dublin, Ireland, and the other on the ecological organization of lake districts, which led to a special issue of *Freshwater Biology*. In addition NTL scientists led or participated in a number workshops at the 2000 All-Scientists Meeting and NCEAS synthesis activities including workshops on Regional Comparison of Plankton Dynamics and Biodiversity and Productivity.

Long term, core data and their management

We collect and manage high-quality, comprehensive, long-term datasets on the physical, chemical, and biological properties and processes of the LTER lakes and the surrounding landscape (Magnuson and Bowser 1990, Kratz et al. 1986). All of these data are available electronically to LTER investigators and collaborators and data more than two years old are freely available to the public on the World Wide Web (Table 1, in Supplementary Documentation). The number of data requests and access history of our web page are summarized in Table 2 (in Supplementary Documentation). Data management at our site is described in Section 4: Information Management.

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 eight 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 14 Ph.D. theses based on LTER research were produced in the period 1996-2001.

Undergraduate education and undergraduate students were also both direct and indirect beneficiaries of LTER awards. In an average year 23 undergraduate students worked directly for our LTER project. Principal investigators routinely use recent results from LTER in their courses. We estimate that approximately 300 undergraduate students each year took classes taught by LTER PIs where LTER 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.

As part of the Schoolyard LTER program, we have partnered with several local elementary and high schools. We have worked with 3rd grade, 7th grade, and high school teachers and students to develop a curriculum for winter limnology projects that culminated in a day-long field trip where observations were made and hypotheses tested. More information about outreach appears in Section 5.

I. CONCEPTUAL FRAMEWORK

Lakes are foci of ecological, economic and social processes on many landscapes throughout the world. Small, inland lakes, such as those prominent throughout the Great Lakes region of North America, play a central role in regional hydrologic and biogeochemical cycles, ecological processes, and a wide range of human activities. Over the past two centuries, deforestation, fire suppression, agriculture, industrialization, tourism, and urbanization have transformed landscapes within the region and fundamentally altered the interactions between lakes and their surroundings. For the next century and beyond, the quality of life and the economies of the region will depend upon the quality of the lakes.

The North Temperate Lakes Long-Term Ecological Research (NTL LTER) program seeks to understand the long-term ecology of lakes and their interactions with terrestrial, atmospheric, and human processes. Our overarching question is:

***How do biophysical setting, climate, and changing land use and cover interact to shape lake characteristics and dynamics over time (past, present, future)*?**

Our conceptual framework considers lakes as interactive components of their environment. As collectors of water, energy, and solutes from the landscape and atmosphere, as habitats for aquatic biota, and as attractors of human activities, lakes affect and are affected by natural and human-induced changes in the local and regional landscape and atmosphere. Our perspective extends from analyses of the past (especially the past 150 years of recorded history but also including paleoecological records), through the present, to forecasts of the next 50 years of change in the landscapes and the lakes. We employ a nested set of spatial scales including individual lakes, multiple neighboring lakes, entire lake districts, the Upper Great Lakes region, and lakes of the northern hemisphere. Within the context of this conceptual framework, our program has five inter-related goals.

(1) Perceive long-term changes in the physical, chemical, and biological properties of lakes. This goal includes the collection and management of our core datasets. Most of the research we describe depends on these continually evolving, long-term datasets. We propose to add three new long-term core datasets: (i) land use and land cover change in the watersheds of our primary study lakes; (ii) human populations and socio-economic characteristics in these core watersheds; and (iii) daily archives of MODIS satellite imagery covering Wisconsin.

(2) Understand the drivers of temporal variability in lakes and lake districts. The growth of our long-term database has created several unique opportunities for understanding long-term change in lakes. Five topics have emerged as particularly promising at this stage of the project: (i) dynamics of algal blooms, (ii) patterns in ecosystem production and respiration, (iii) the association of productivity and diversity in lake plankton, (iv) long-term change in the balance of littoral and pelagic processes in lakes, and (v) patterns of fish recruitment.

(3) Understand the interaction of spatial processes with long-term change. Lakes are connected dynamically to surrounding landscapes. Long-term change in lakes may depend upon the spatial arrangement of these landscape mosaics. We address three questions in this area. (i) Over what scales of space and time are spatial dependencies important in determining lake characteristics and dynamics? (ii) How do climate, geologic setting, and land use/cover change influence water and solute loading to lakes? (iii) How does spatial positioning of lakes influence their value to humans?

(4) Understand causes and predictability of rapid, extensive change in ecosystems. Some ecological changes are rapid and extensive. Such big changes can be difficult to understand or anticipate. Yet understanding the mechanisms underpinning thresholds or regime shifts is a key need for forecasting future change. Our data sets have grown to the point where we can carefully evaluate certain types of big changes. We have selected three for analysis during this grant cycle: (i) eutrophication, (ii) ecosystem consequences of species invasion, and (iii) changes in angler-fish interactions as lakeshores switch between public and private ownership.

(5) Build a capacity to forecast the future ecology of lake districts. In coming decades, landscapes and lakes will exhibit complex responses to changes in climate, land use and cover, biota, and human activities such as riparian development and fishing. We will develop methods for forecasting changes in temperate lake districts, as both an emerging research frontier and as a mechanism to generate hypotheses for future long-term research. This research, which is a new theme for NTL LTER, will address two questions. (i) How might climatic, geochemical, ecological, and socio-economic drivers of the lake districts change in the next 50 years? (ii) How could these changes affect hydrology, biogeochemistry, and ecology of the lakes?

In addressing these five goals we use a variety of approaches including long-term observations, small- and large-scale experiments, comparative studies, and process modeling. In the next five sections, we elaborate on each of the five goals. We follow this with a concluding section describing the synthetic nature and significance of our proposed research program.

II. PERCEPTION OF LONG-TERM CHANGE

One of the basic goals of the NTL LTER program is the collection and management of ecologically relevant data that allow investigators to observe and analyze long-term changes in physical, chemical, and biological features of lakes. Long-term observations and analyses are crucial to understanding lake ecology. Natural phenomena, such as strong year-classes of long-lived predators, a series of drought years, or an invasion by an exotic species, 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). In addition, many human-induced pressures influencing lakes, such as eutrophication and climate change, operate over time scales of years to decades or longer. The accumulation of these effects can cause changes that are difficult to understand without a long-term context (Likens 1989, Holling 1995, Likens 2001). To provide such a context for our research, we collect and maintain a series of 'core' databases (Table 3). 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.

Background. Over the past 21 years we have designed and implemented a balanced and integrated data collection program (e.g. Kratz et al. 1986, Magnuson and Bowser 1990; online data catalog at http://lter.limnology.wisc.edu/catalog.html). 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.

We focus our data collection on two sets of lakes and their surrounding landscapes. One set is in the forested and tourism-dominated Northern Highland Lake District in northern Wisconsin, the other is in the agricultural- and urban-dominated landscape in and near Madison in southern Wisconsin (Fig. 6). Both regions have a substantial history of ecological research dating back to about 1900 (Frey 1963).

In northern Wisconsin, beginning in 1981, we focused on a suite of seven primary lakes and surrounding terrestrial areas linked through a common groundwater and surface water flow system and sharing a common climatic, edaphic, and biogeographic regime (Figs. 6 and 25). The lake set includes oligotrophic, dystrophic, and mesotrophic lakes (Table 4) chosen to represent marked differences in size, morphometry, habitat diversity, thermal and chemical features, species richness and assemblies, and position in the groundwater flow system. In 1994, we added four primary study lakes in southern Wisconsin (Table 4, Fig. 6). 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 these lakes (Brock 1985, Kitchell 1992, Lathrop et al. 1992, Watson and Loucks 1979). In addition to the primary lakes we also have a set of secondary lakes for which less complete information is collected. These lakes are used for comparisons with primary lakes on specific research questions. We also collaborate with two Canadian groups with similar data on two other lake districts, the Experimental Lakes Area in western Ontario and the Dorset Research Centre in eastern Ontario. Collectively, the data and research programs at these four lake districts afford a unique opportunity for analyses of the Western Great Lakes region.

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 3) 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, inorganic and organic carbon are sampled every two or four weeks, depending on the lake and the nutrient. Temperature, dissolved oxygen, chlorophyll *a*, light penetration, and zooplankton abundance are sampled every two weeks during the open-water season

Table 3. North Temperate Lakes LTER core parameters. More details on measurement protocols available at <http://lter.limnology.wisc.edu/catalog.html>
(* = measured at both the Madison Lake Area and Trout Lake Area; otherwise, Trout Lake Area only)

PARAMETER	FREQUENCY	LOCATION	METHOD
LOCAL MEASUREMENTS			
Weather Air Temperature* Relative Humidity* Wind Speed* Precipitation* Solar Radiation* Wind Direction* Soil Temperature* Evaporation Air Temperature Relative Humidity Wind Speed Water Temperature Precipitation Chemistry Other Weather Data*	 Hourly except half-hourly for Solar Radiation and 5 minute for rain gauge during rain events Weekly Daily	 Woodruff Airport, Sparkling Lake, Trout Lake and Madison NWS Woodruff Airport and Madison NWS Lake rafts on Sparkling Lake and Trout Lake Trout Lake NADP site 32 km radius	 Thermistor Campbell HMP 35c probe 3-cup anemometer Tipping Bucket Gauge Eppley Pyranometer (long and short wave) Electronic Wind vane Thermistor probes Thermistor Campbell HMP 35c probe 3-cup anemometers Thermistor array NADP protocols Weather Service Weather Stations
Hydrologic and Terrestrial Groundwater: Water Level Water Chemistry same as Chemical Limnology, except no total particulate matter	 Monthly Annually in autumn	 Selected wells near study lakes	 Tape and popper; chemistry same as lake samples
Physical Limnology Water Temperature* Vertical Light Attenuation Secchi Disk Depth* Dissolved Oxygen* Ice Thickness* Snow Depth on Lake* Ice Duration*	 Every two weeks during ice-free season Every six weeks during ice-covered season Annually	 Deepest part of lake; Quarter meter to one meter depth intervals depending on lake NTL lakes	 YSI 58, Campbell Dataloggers, LiCor Cosine Quantum Sensors, Meter Stick
Instrumented Buoys Water Temperature, Dissolved Oxygen, Chlorophyll, pH, PAR, Conductivity, Total Dissolved Gas Water Temperature, pCO2, Dissolved Oxygen, Chlorophyll	 Profiles several times per day Hourly	 Trout Lake at 1 meter intervals Selected study lakes	 Apprise Technology profiling buoy with YSI multiprobe sondes Custom designed buoys using probes and equilibration chambers

Chemical Limnology Total Nitrogen* Total Dissolved Nitrogen Nitrate, Ammonia* Total Phosphorus* Total Dissolved Phosphorus* Total Silica Dissolved Reactive Silica* Field pH* Air Equilibrated pH* Total Alkalinity Total Inorganic Carbon Dissolved Inorganic Carbon* Total Organic Carbon Dissolved Organic Carbon* Total Particulate Matter* Chloride*, Sulfate*, Calcium*, Magnesium*, Sodium*, Potassium*, Iron*, Manganese*, Specific Conductance*	Every four weeks during ice-free season Every six weeks during ice-covered season Quarterly at spring and fall mixis, summer and winter stratification	Deepest part of lake; top and bottom of epilimnion, midthermocline and top middle,and bottom of hypolimnion	Samples collected with peristaltic pump and in-line filtration. N by $K_2S_2O_8$ digestion and copper cadmium digestion and diazo complex; P by $K_2S_2O_8$ digestion and phospho-molybdate complex; Si by $NaHCO_3$ digestion and silica-molybdate complex; pH with meter; Alkalinity by Gran Titration; C by persulfate digestion; Anions by ion chromatography; Cations by atomic absorption
Biological Limnology Chlorophyll a* Primary Production Sedimentation Rate	Same as Physical Limnology	Deep part of lake; Chl at 2-9 discrete depths; Prod by thermal strata for euphotic zone	Chl by spectroscopy; Prod by C14 incubation and analysis of diurnal oxygen and pCO2; sediment traps
Macrophyte Distribution and Biomass*	Annually in August in Trout Lake and in summer in Madison lakes	Selected shoreline locations	Permanent line transects
Zooplankton Biomass*	Same as Physical Limnology	Deep part of lake; 2-9 depths per lake	2 meter long Schindler-Patalas trap; Wisconsin net
Crayfish Abundance*	Annually in August	Selected shoreline locations	Cylindrical traps baited with beef liver
Other Benthic Invertebrates	Annually in August and September	Deep part of lake and selected shoreline locations	Conical net for Mysis and Chaorborus; "Dendy" samplers
Fish*	Annually in August	Deep part of lake and selected shoreline locations	Vertical gill nets; Fyke nets; Trammel nets; Seines; Electroshocker; Acoustic Transects
Human Demography Housing Density	Each decade since 1940	Northern Highlands Lake District; partial block groups	U.S. Census

SPATIAL DATA: VECTOR NAME / THEME	**SCALE**	**SITE (MLA = Madison Lake Area, TLA = Trout Lake Area)**	**SOURCE**
Hydrography	1:24,000	Wisconsin	Wisconsin DNR
Bathymetry	1:24,000	Lake Mendota	NTL-LTER
Watersheds	1:100,000 1:24,000	Wisconsin TLA	Wisconsin DNR NTL-LTER
Soils	1:250,000 1:24,000 1:24,000	Wisconsin Vilas Co. Dane Co.	USDA Vilas Co. Dane Co.
Original Vegetation	1:100,000	Wisconsin	Wisconsin DNR
Historical Land Use/Cover	1:20,000	MLA /TLA 1930-1990s	NTL-LTER
Riparian Vegetation	1:24,000	Mendota Watershed	NTL-LTER
Building Locations	1:30,000	Vilas Co.	Vilas Co.
Roads	1:31,680	Vilas Co.	Vilas Co.
Wetlands	1:24,000	Vilas Co	Wisconsin DNR

SPATIAL DATA: RASTER (THEMATIC) NAME / THEME	DATE	SITE	SOURCE
WISCLAND Land Cover	1992 -1994	Wisconsin	Wisconsin DNR
Elevation	Variable	Wisconsin	USGS 7.5-minute DEMs
Digital Raster Graphs	Variable	TLA	Scanned USGS maps
Land Economic Inventory	1930	TLA	Scanned LEI maps

SPATIAL DATA: AERIAL PHOTOGRAPHS DATE	SCALE	SITE	COMMENTS
1930's	1:20,000	MLA & TLA	Black / White from statewide
1960's	1:20,000	MLA	Black / White
1960's	1:15,840	TLA	Black / White infrared
1986	1:10,000	TLA	Color /color infrared, shorelines
1993	1:40,000	MLA	Black / White from statewide
1996	1:31,680	TLA	Black / White, digital orthophotos
1997	1:9,000	MLA	Color infrared, from NASA ATLAS
1998	1:9,800	MLA & TLA	Color infrared, from NASA ATLAS

SPATIAL DATA: RASTER (DIGITAL IMAGES) NAME / SENSOR	**TYPE**	**RESOLUTION (m)**	**DATE (n=number of images if multiple) (MLA = Madison Lake Area, TLA = Trout Lake Area)**
Landsat MSS	M	80	TLA: 1972, 1986, 1991; MLA: 1975, 1986, 1990
Landsat TM	M,T	30 – 120	TLA: 1984, 1988, 1989 (2), 1991, 1992, 1993 (2), 2000; MLA: 1984 (2), 1986, 1987, 1988, 1989, 1990, 1991 (2), 1992 (2), 1994, 1995 (4)
Landsat ETM+	M,P,T	15 – 60	TLA: 1999; MLA: 1999 (3), 2000(2), 2001
Terra ASTER	M,P,T	30 – 90	TLA: 2000 (2)
Terra MODIS	M,T	250 – 1000	WI: 2000 (various dates), 2001 - present (daily)
SPOT HRV	M,P	10 – 20	TLA: 1988; MLA: 1986, 1988 (4), 1989
IKONOS	M,P	1 – 4	TLA: 2000; MLA: 2000
EO-1 ALI	M,P,T	10 – 30	MLA: 2001
EO-1 Hyperion	H	30	MLA: 2001
ATLAS	A,M,T	3	TLA: 1998; MLA: 1997, 1998
SIR-C	R	25	TLA: 1994 (3)
ERS-1	R	25	TLA: 1992 (2); MLA: 1992

Type codes: A = airborne, H = hyperspectral, M = multispectral, P = panchromatic, R = radar, T = thermal

Table 4. 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.

	TROUT LAKE AREA							MADISON LAKE AREA			
	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)	156	157	142	143	141	149	138		119	120	107
Water Temperature (°C)	19.9	18.0	20.8	20.9	20.9	21.2	19.9	23.9	24.3	23	25.2
Secchi Depth (m)	1.6	1.2	7.3	6.7	6.1	3.1	4.6	2.1	3.4	0.7	2.5
pH	5.1	4.8	6.0	7.3	7.3	7.5	7.6	8.3	8.2	9.4	8.2
ANC (μeq/L)	10	5	16	366	612	795	829	2873	3714	3723	3500
Conductivity (μS)	11	23	14	49	80	88	93	280	412	500	434
Total P (μg/l)	19.2	40.0	8.6	22.5	15.2	29.3	16.9	47.8	118.0	331	89.2
Total N (μg/l)	629	873	207	489	375	364	235	860	1080	930	1080
SiO2 (μg/l)	366	806	20	145	3582	6486	4311	550	1100		660
Chlorophyll (μg/l)	8.5	14.0	1.8	3.0	2.2	8.3	3.3	8.2	8.6	12.0	11.9
Number of fish species	1	3	23	30	30	38	39	24	43	26	38
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 SiO_2 from spring mixis; chlorophyll (surface) from open water season.

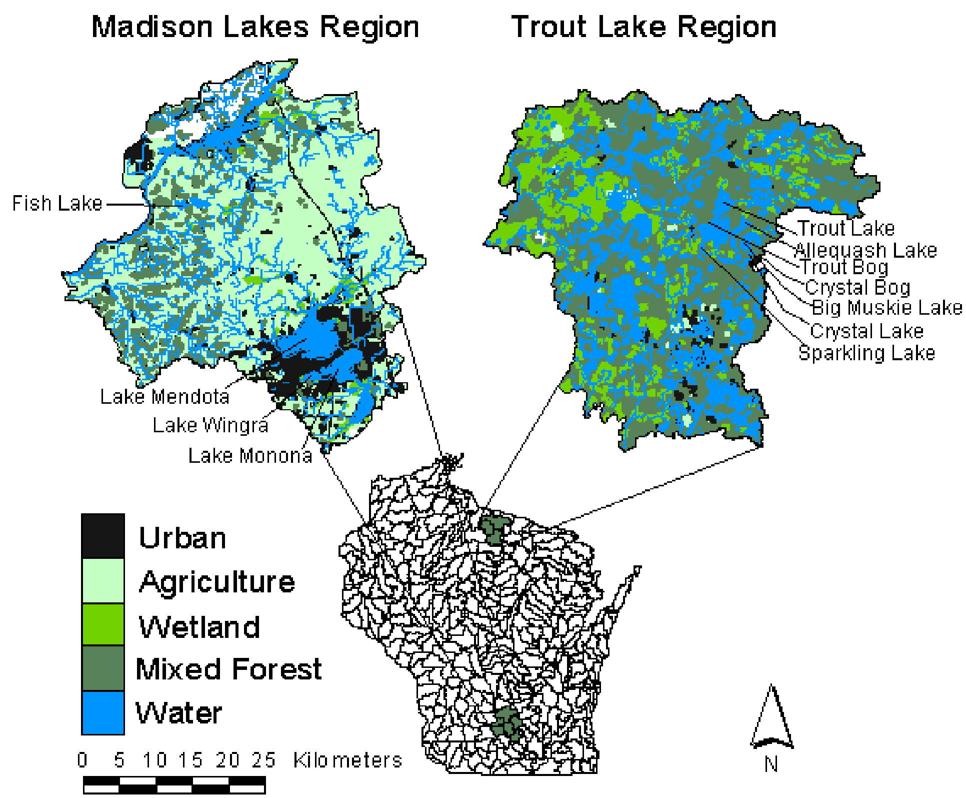


Figure 6. Hydrography and land use of the North Temperate Lakes LTER site. All data are copyright Wisconsin Department of Natural Resources. NTL-LTER core study lakes are labeled.

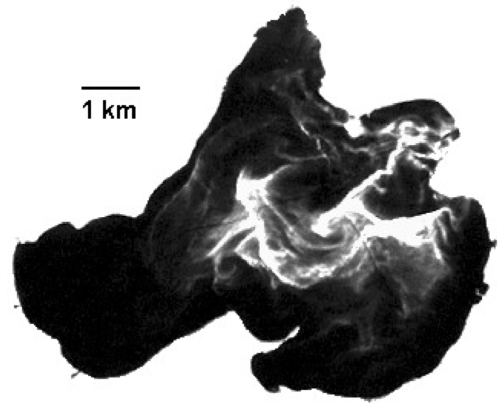


Figure 7. Landsat-7 near-infrared image showing swirling blue-green algal bloom in Lake Mendota, Wisconsin, 31 October 1999.

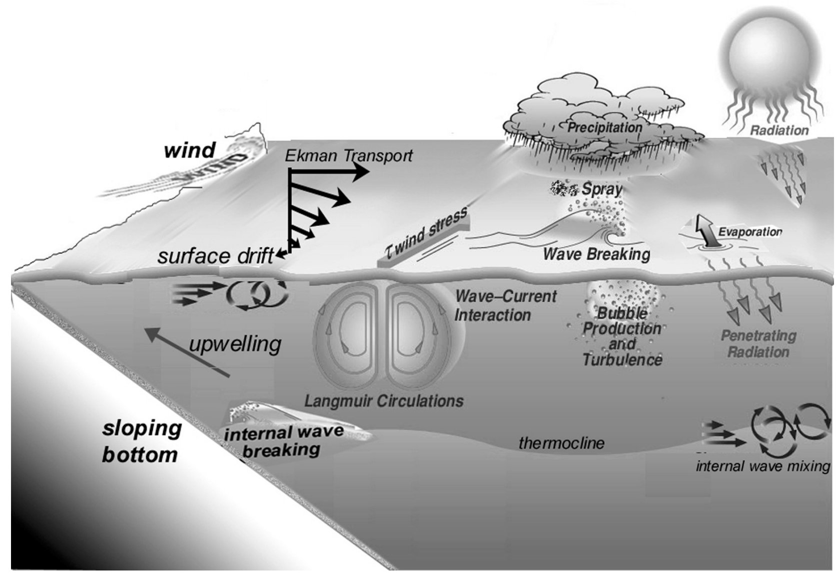


Figure 8. Hydrodynamic processes that affect the spatial pattern and movement of algal blooms.

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, biomass, 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.

We have a series of instrumented buoys on selected primary lakes, including a raft on Sparkling Lake for measurements of evaporation, wind stress, and high-resolution thermal structure, and an instrumented buoy on Trout Lake for vertical profiling. We plan to develop and deploy small buoys measuring pCO_2, oxygen, and water temperature for estimates of gross primary production, respiration, ecosystem productivity, and carbon flux to the atmosphere on each primary lake. In addition, we maintain an automated land-based weather station at the local airport 10 km from Trout Lake. We have access to National Weather Service data from the Madison airport.

In addition to providing comprehensive limnological data, this sampling program positions us to detect invading exotic species in our primary lakes. Potential new invaders include many European species that have reached the Laurentian Great Lakes (www.seagrant.umn.edu/exotics/index.html). These large lakes now act as a nearby source of colonists including fishes (ruffe, rainbow smelt, rudd, round goby, etc.), zooplankton (*Bythotrephes cederstroemi*, *Eurytemora affinis*, etc.), molluscs (zebra mussels, fingernail clams, and a variety of snails), a macrophyte (Eurasian watermilfoil), and a highly toxic cyanobacterium now invading North America (*Cylindrospermopsis raciborskii*). We have designed our sampling so that introductions of these or other invading species will be discovered early and we can implement specific research activities to understand consequences of these introductions (Turner et al. 2002).

To provide basic information about the terrestrial landscapes surrounding our study lakes, we have developed a geographic information system (Table 3) 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, large-scale historical land use/land cover databases from the 1930's, 1960's, and 1990's for watersheds or riparian zones of selected study lakes; and the statewide WISCLAND land cover database (Lillesand et al. 1998).

We maintain an extensive archive of airborne and satellite imagery for both the northern and southern lake regions (Table 3). The core of this archive consists of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images from 1984 to the present. Other image data sources available to researchers at the NTL site include the EO-1/Advanced Land Imager and Hyperion imaging spectrometer, high-resolution (1m to 4m) IKONOS images for the Madison and Trout Lake areas, 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 3).

Proposed New Core Datasets. The core datasets listed in Table 3 provide the foundation for addressing most of the research questions presented in this proposal. We will continue to collect and maintain these datasets. In addition we propose to add three new datasets: (i) a time series of land use and land cover for NTL core watersheds, (ii) U.S. census data configured for NTL core watersheds, and (iii) additional satellite imagery including daily archives of MODIS data.

Land use and land cover (LULC) patterns integrate many human activities that influence aquatic ecosystems. For example, the amount of impervious surface in the watershed affects runoff, the extent and location of agriculture influence nutrient sources, and the amount and continuity of natural riparian vegetation may control nutrient delivery to streams and lakes. We initiated development of a new core dataset on our primary study lakes under current funding, and this database development will be continued in the next funding cycle. For the Madison Lakes region, we mapped LULC for three watersheds (Lake Wingra and two subwatersheds of Lake Mendota) for the 1930's, 1960's and 1990's; a third subwatershed of Lake Mendota was also completed under EPA funding. For the Northern Highland area, mapping of LULC around 50 lakes is in progress using LTER and other funding. We will continue to update LULC patterns along with related data on population and building density at regular intervals for both study areas. These data will allow us to quantify important changes in the watersheds and will provide the foundation for forecasting future scenarios of LULC change.

We propose to add new demographic data sets to the NTL core data. The first two of these will provide the number of housing units and, by extension, housing density for the Northern Highland Lake District (encompassing Vilas and Oneida Counties). One of these housing data sets was developed under current funding and provides estimates of housing density for each decade from 1940 to 1990 at the neighborhood/community level, U.S. Census partial block groups (Hammer et al. in review, a). We propose to update these estimates to include the 2000 Census and to make projections to 2050 using a stochastic model. In addition, we will prepare a set of spatially more detailed estimates of housing density at the block level for 1990 and 2000. This second dataset will enhance the assessment of recent lakeshore development. The demographic data set that will be added to the core, will provide detailed demographic profiles of each of the watersheds within the Northern Highland Lake District for 1990 and 2000 with an assessment of the changes that occurred during the decade. This data set will be constructed using the methodology that was developed during the last project period, which uses road nodes to interpolate demographic characteristics from census geographies to watersheds (Hammer et al. in review, b).

Satellite imagery is an important tool in our efforts to understand long-term change at regional scales. Beginning with the summer 2001 season, we began collecting and archiving all MODIS imagery for Wisconsin on a daily basis to permit regional-scale, multi-temporal monitoring of large lakes (>400 hectares). We will investigate the viability of MODIS-derived estimates of a variety of biophysical parameters, such as transparency, chlorophyll *a*, and total suspended matter. Through the Wisconsin Satellite Lake Observatory Initiative (Lillesand et al. 2001), we have nearly completed a statewide database of Landsat-derived lake clarity estimates for 1999-2001, with one or more observations for over 7000 lakes. During the next six years we will extend this backward in time using historical satellite imagery and field observations. The ongoing acquisition of Landsat and MODIS data will provide an increasingly valuable tool for assessment of regional changes in lakes and watersheds.

III. UNDERSTANDING TEMPORAL VARIABILITY

Understanding how multiple drivers interact to affect the long-term dynamics of ecosystems is a central goal of the LTER program (Hobbie et al. 2002, Likens 1989, Magnuson 1990). In limnology, internal drivers, such as nutrient cycling and trophic interactions, and external drivers, such as changes in land use and climate, are important in determining ecological dynamics of lakes (Kalff 2001, Turner et al. 2001,Cushing 1997, Trenberth 2000). The rich data sets available for our primary study lakes allow us to address many fundamental questions of how internal and external drivers influence processes, status, dynamics, and potential futures of freshwater ecosystems. For this grant cycle, we propose work on five topics for which we are well-positioned to make significant advances. These topics address fundamental issues of limnology related to blooms of cyanobacteria; carbon cycling; plankton diversity and productivity; cross-habitat interactions; and fish recruitment. Each proposed study depends on long-term data sets as well as other types of information.

Temporal and spatial dynamics of cyanobacterial blooms

Blooms of cyanobacteria (blue-green algae) are conspicuous but highly variable features of eutrophic lakes (Reynolds 1997). Because blue-green algae are often buoyant, hydrodynamic processes create spatial pattern in blooms within lakes (Fig. 7).

Physical, chemical, and biological factors that drive the growth and movement of different species of blue-green algae are still poorly understood. The interaction of physical hydrodynamic processes (Fig. 8) such as Ekman transport, wind-induced surface waves, Langmuir circulation, and internal breaking waves are responsible for algal spatial patchiness (Verhagen 1994, Bees 1998, Olsen et al. 2000, Azumaya et al. 2001, Franke et al. 1999, Ennet et al. 2000, Litchman and Klausmeier 2001, Huisman et al. 1999, Araujo et al. 2001, DeSilva et al. 1997, Etemad-Shahidi and Imberger 2001). Chemical drivers such as excessive nutrients can increase algal biomass and primary production (Paerl 1997, Pinckney et al. 1999), and blooms may develop in response to nutrient pulses into surface waters that arise from hydrodynamic processes linked to wind stress and temperature (Kononen et al. 1996, Soranno 1997, Stauffer 1987). Finally, grazing by zooplankton can suppress competitors of blue-green algae, recycle nutrients, and thereby contribute to blooms (Kasprzak et al. 1999).

How do physical, chemical, and biotic factors affect the timing and location of cyanobacterial blooms? This question will be addressed by intensive, spatially-detailed sampling of algal blooms and their drivers during summer. In addition to sampling for nutrients, phytoplankton and zooplankton, we will measure velocity and temperature profiles using acoustic Doppler profilers and thermistor chains to assess hydrodynamic processes. To detect community responses to chemical and physical changes, we will use molecular characterization of cyanobacterial taxa (Honda et al. 1999). We will examine archived and contemporary samples for the highly toxic *Cylindrospermopsis raciborskii*, an invasive cyanobacterium associated with climate change (Chorus et al. 2000, Baker et al. 2001).

This study will use several remote sensing technologies to quantify the spatial/temporal dynamics of bloom development. We will employ a remote controlled model aircraft with a high-precision CCD camera to sample individual lakes. At the lake district scale, we will employ remote sensing systems described in Table 3 to study blooms on lakes >1.5 ha in area. We will track bloom development on 100 large lakes (>400 ha) in Wisconsin on a daily basis using the UW's real-time reception facilities for MODIS data (Lillesand et al. 2001). Our aim is to compare bloom development across lakes and assess synchronicity of blooms among lakes within a region. High synchronicity would indicate the importance of regional processes in controlling bloom development.

Patterns and controls of temporal variability in lake metabolism

Lake metabolism, the balance between gross primary production (GPP) and respiration (R), integrates lake ecosystem processes, including influences of the surrounding landscape (Kling et al. 1991, 1992, del Giorgio and Peters 1993, Cole et al. 1994, Raymond et al. 1997, del Giorgio et al. 1997, Dillon and Molot 1997, Cole and Caraco 2001). R and GPP are closely coupled (Fig. 9). Some drivers of ecosystem metabolism, such as nutrient input, are expected to change R and GPP in the same direction. Other factors, such as dissolved organic carbon loading, are not. For example, R exceeds GPP in lakes with dissolved organic carbon concentrations above about 10 mg L^{-1}. Is this change in the R versus GPP relationship simply a result of external forcing by dissolved organic carbon, or are there also changes in a lake's microbial community that amplify ecosystem respiration? There is some evidence that pelagic microbial communities can change rapidly in response to allochthonous dissolved organic carbon inputs (Hessen 1992, Jones 1992, Triplett et al. unpublished).

We will test the hypothesis that shifts in the balance of R and GPP in lakes can be explained by changing dissolved organic carbon and microbial community structure. To determine the components of lake metabolism we will measure diel cycles of O_2, CO_2, pH, temperature, and wind speed using in situ buoys, which will provide estimates of GPP, R, and total CO_2 flux to the atmosphere. Examples of metabolism measurements by our buoy systems are presented on <144.92.62.239/buoy/results/metabolism.htm>. Zooplankton and phytoplankton communities are measured by our routine monitoring program. Microbial communities will be measured in collaboration with the Microbial Observatory project (<microbes.limnology.wisc.edu>). Bacterial communities will be determined by molecular methods (Bowman et al. 2000). Bacterial respiration and production will be measured directly (Roland and Cole 1999). Substrate specific utilization arrays (Bertilsson and Polz 2001) coupled with planktonic respiration

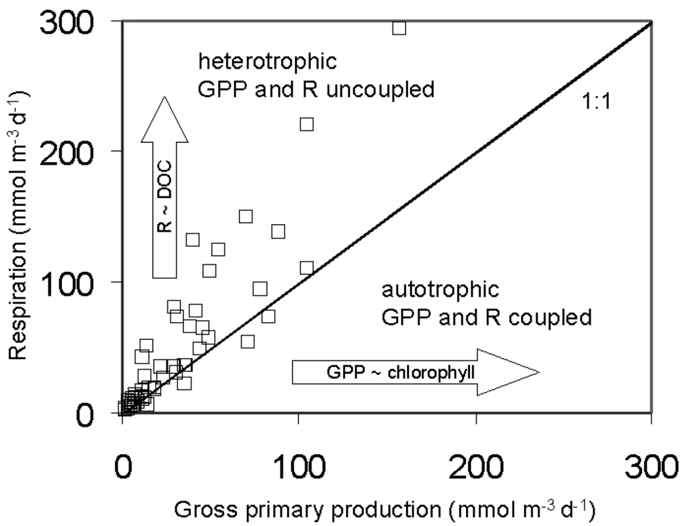


Figure 9. The heterotrophic status of 32 north temperate lakes surveyed in the summer of 2000. Lakes ranged in dissolved organic carbon (DOC) from 2-25 mg L^{-1} and in chlorophyll from 2-57 g L^{-1}. Most lakes fall above the 1:1 line, indicating that they are net heterotrophic. This is especially true for lakes with DOC above about 10 mg $L^{-1,}$ consistent with the findings of Jansson et al. (2000)."

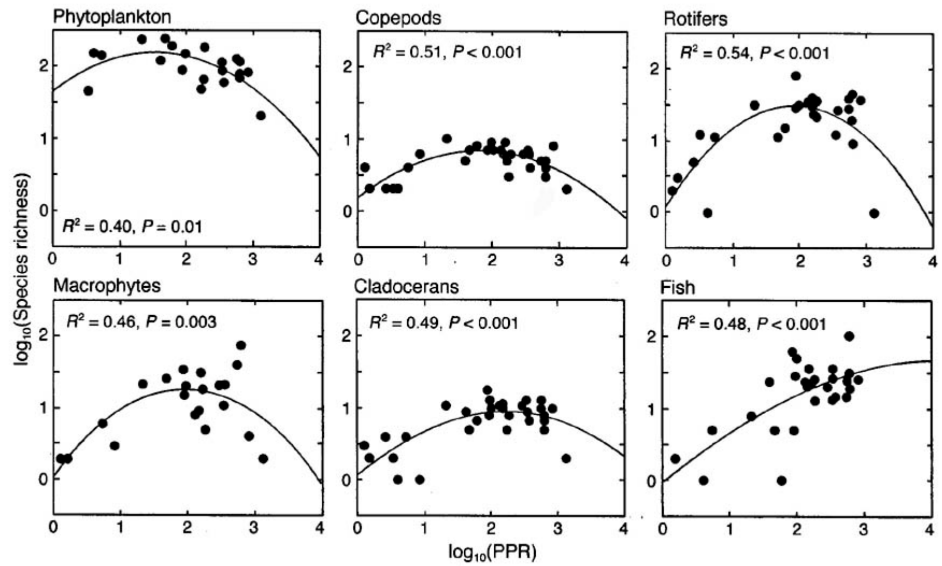


Figure 10. A regression analysis of log (species richness) as a function of log (PPR) for phytoplankton, copepods, rotifers, macrophytes, cladocerans and fish. (Dodson et al, 2001)

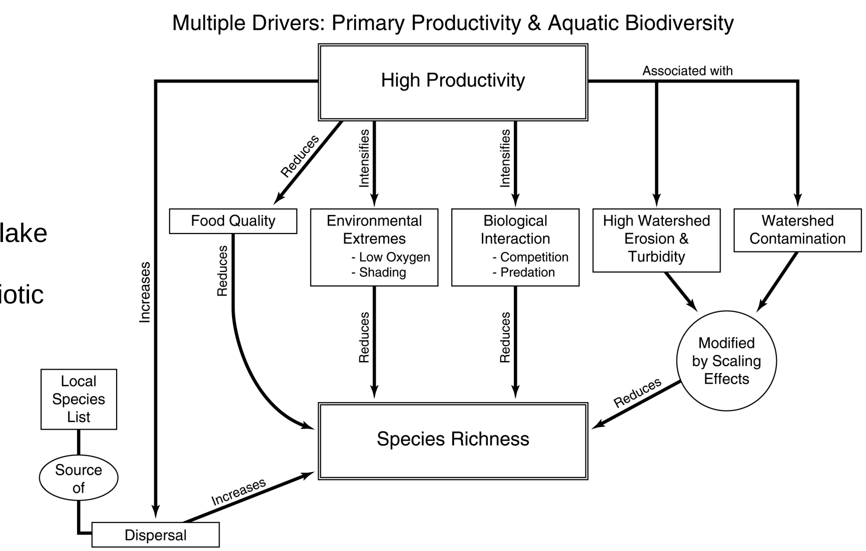


Figure 11. Linkages between lake productivity and biodiversity through multiple abiotic and biotic drivers.

measurements will allow us to connect allochthonous and autochthonous substrate dynamics to bacterial activity and whole lake metabolism.

Productivity – diversity relationships in lakes

Aquatic biodiversity is related to lake productivity (Fig. 10, Dodson et al. 2001). Multiple drivers (Fig. 11) have been suggested as being responsible for this observed relationship. Many of the hypotheses offered to explain aquatic diversity vs. productivity relationships invoke competitive and predator-prey interactions which reduce diversity at extreme levels of productivity (Leibold 1999, Dodson et al. 2001). Others invoke physical-chemical changes associated with eutrophication. Assessment of the various hypotheses is complicated by variability in measures of diversity related to the duration of a study (Arnott et al. 1998), apparent species turnover (Arnott et al. 1999) and time delays in biotic responses to changes in productivity (Dodson et al 2001). Resolution of this debate has been difficult because the drivers operate at different time scales and display varying degrees of correlation over time (Waide et al. 1999, Loreau et al. 2001).

We will characterize changes in the relationship between diversity and productivity in lakes as a function of the temporal scale of analysis. We hypothesize that the strength and direction of the relationship (i.e., positive or negative) may depend upon the time scale over which measurements are made and interpreted. Furthermore, factors contributing to lake condition, such as climate, land use and cover, lake size, physical mixing, and water chemistry, may also influence the diversity-productivity relationship. Therefore, our analysis will also consider these important covariates.

Littoral habitat: connections to fish community structure and dynamics

Macrophytes and coarse woody debris (CWD) are central components of the littoral zone structure, which provides habitat and refuge from predation for a variety of species (Persson et al. 1996). Furthermore, littoral and benthic habitats are highly productive, and provide a central food resource for a variety of fishes (Vander Zanden and Vadeboncoeur 2002). Changes in macrophytes occur seasonally and from year to year, while natural changes in CWD occurs at a multi-decadal time scale. We plan to examine how changes in littoral habitat structure affect benthic invertebrate community structure and productivity, and the implications for fish growth, fish recruitment dynamics, and community composition.

Past changes in littoral habitat of our core lakes have been driven by eutrophication, species invasion, and human removal of CWD. Lake eutrophication shifts primary and secondary production from benthic to pelagic habitats, potentially contributing to a decline in macrophyte cover due to shading by phytoplankton (Vadeboncoeur et al. 2001, 2002). Exotic species, particularly rusty crayfish and Eurasian milfoil, have driven many littoral changes in NTL core lakes, specifically the reduction of macrophyte diversity and abundance (Nichols et al. 1992, Lodge et al. 2000, Wilson 2001). In undisturbed lakes, rates of accumulation and degradation of CWD are much slower than for macrophytes, with processes of input and decay requiring centuries

(Christensen et al. 1996). However, humans can rapidly disrupt CWD dynamics, resulting, for example, in depletions of CWD in lakes surrounded by houses (Christensen et al. 1996, Kratz et al. 2002). We are engaged in two experimental whole-lake manipulations of CWD in a collaborative project with separate funding from NSF (http://biocomplexity.limnology.wisc.edu).

Long-term time-series data for fishes, invertebrates, and macrophyte cover will be used to test for changes in fish growth, recruitment, and community structure associated with the observed changes in littoral zone structure. Dietary and stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) will be used to assess reliance on littoral resources. Cross-lake, comparative analyses and in-lake manipulations of CWD and macrophytes will be used to quantify the importance of CWD for zoobenthic productivity and fish growth and the consequences for recruitment.

Is variability in fish recruitment correlated among lakes?

Fish recruitment is among the most variable ecological phenomena (Forney 1980, Ricker 1954), and our lakes are no exception. The dynamic patterns of variation in fish year classes and assemblages within and among the Northern Wisconsin LTER lakes are likely related to both internal and external drivers (Magnuson et al. 1994, Hrabik et al. 1998, Sanderson et al. 1999). Between 1981 and 2001, large variations occurred in temperature (Trenberth 2000), ice cover (Magnuson 2002), and precipitation (Webster et al. 1996), and several species invasions were recorded (Hrabik et al. 2001, Wilson 2001). Air temperature, storms, and precipitation are external drivers of lake conditions that affect fish year class strength (Shuter and Post 1990, Van Winkle et al. 1997, King et al. 1999, Steinhart et al. 2001) (Fig. 12b,c). Internal factors include predation, cannibalism, and competition for resources (Hrabik et al. 1998, Sanderson et al. 1999, Jackson et al. 2001a, Hrabik et al. 2001, Wilson 2001). The introduction of an exotic species originates from outside the lake but can influence the internal dynamics for many years (Hrabik et al. 1998, Sanderson et al. 1999, Wilson 2001).

High correlation or coherence (Magnuson et al. 1990, Baines et al. 2000, Magnuson and Kratz 2000) in fish year-class dynamics between time series (Fig. 12a) would indicate that regional drivers such as climate have coordinated impacts on fish year classes. Low coherence, would suggest that internal lake-specific drivers might be more important. We hypothesize that changes in climatic factors and the invasion of exotics the largest drivers of variability in fish year classes and assemblages in the NTL LTER site. We will use the NTL database to address the following specific questions: (i) How coherent are fish year classes among the LTER lakes? (ii) How well do external and internal drivers explain fish year-class dynamics? and (iii) How general are the explanatory variables for species and guilds among lakes? Analyses will employ coherence measures for time series as well as multivariate methods.

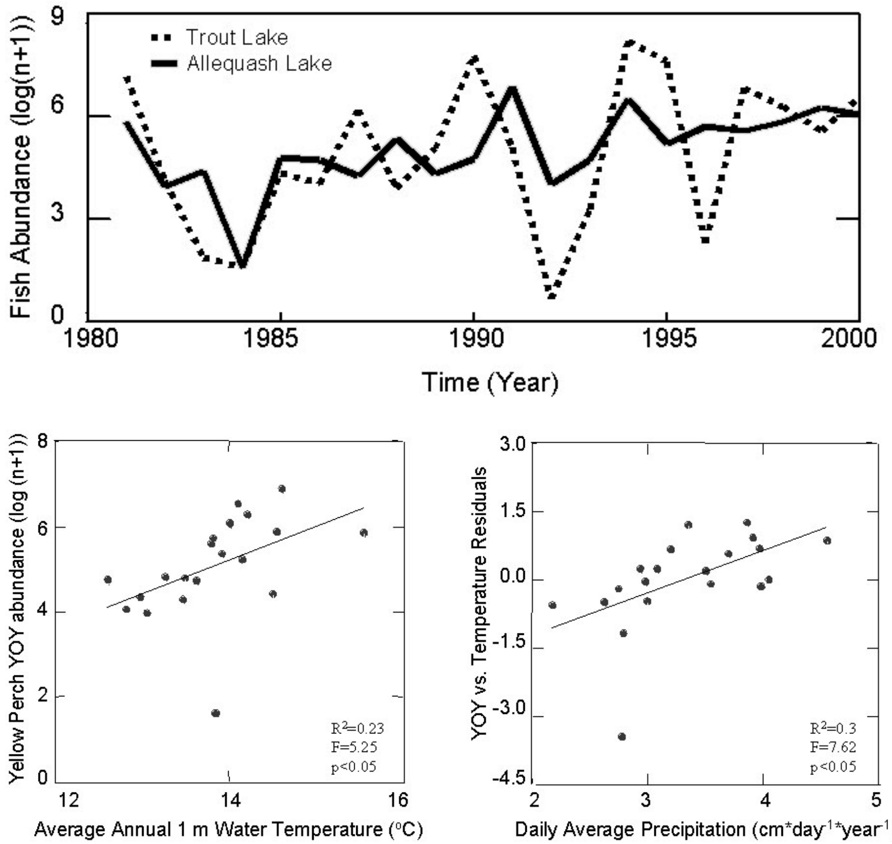


Figure 12. The coherence in year class strength for yellow perch between two NTL-LTER lakes, Trout and Allequash (a), are significant and positive (r=0.56, p=0.01). Explanatory models for yellow perch abundance in Allequash Lake were tested using stepwise linear regression. Water temperature accounted for 23% (p<0.05, F=5.3, df=19) of the annual variation in young-of-year yellow perch abundance (b), and precipitation accounted for 30% (p<0.05, F=7.6, df=19) of the remaining variation (c). The year 1984 is an outlier in both plots, and if removed the new regression explains 67% (p<<0.001, F=15.9, df=18) of the annual variation in young-of-year yellow perch abundance with the same two explanatory variables.

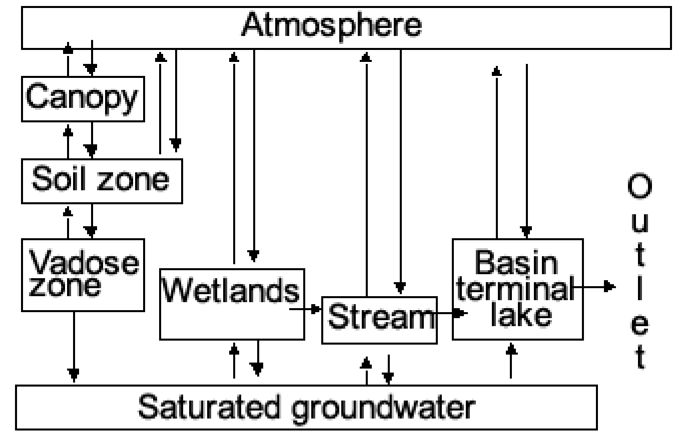


Figure 13. Hydrologic connections between lakes and their surroundings.

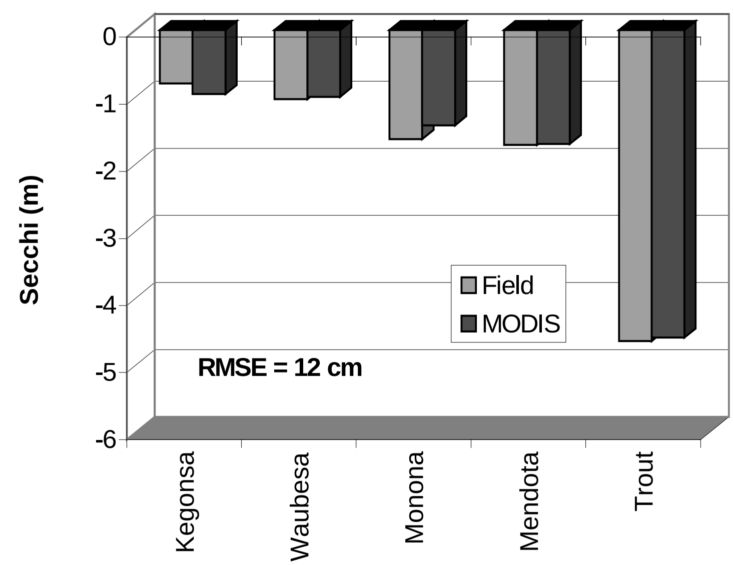


Fig 14. Accuracy of MODIS satellite-derived estimates of summer 2001 seasonal mean lake transparency, shown in comparison to NTL-LTER field observations.

IV. SPATIAL DEPENDENCIES AND LONG-TERM CHANGE

Lake ecosystems do not exist in isolation. They are connected spatially and functionally to streams, wetlands, and their watersheds (Wetzel 1983, Likens 1985, Soranno et al. 1999, Kling 2000, Kalff 2001, Fig. 13), and are affected by long-term change in their surrounding environment. Building on the foundation of our previous work, we propose to investigate spatial dependencies of lake ecosystems and the role of long-term changes in factors such as climate and land use/land cover. Spatial dependencies can be defined as situations in which the outcome of an ecological process or phenomenon is dependent upon the spatial arrangement of component parts. Thus, for example, we anticipate that the answer to the question of "How does land use change influence nutrient loading to a lake?" will depend upon how and where land conversions are occurring within the watershed. The specific studies that we are proposing are grouped into three general questions: (i) Over what scales of space and time are spatial dependencies important in determining lake characteristics and dynamics? (ii) How do climate, geologic setting, and land use and cover change influence water and solute loading to lakes? and (iii) How does spatial positioning of lakes influence their value to humans? The answers to these questions will provide new insights into the effects of spatial and temporal context on lake ecosystems.

Over what scales of space and time are spatial dependencies important in determining lake characteristic and dynamics?

Understanding the spatial and temporal scales at which spatial dependencies are important informs us about the relative roles that local and regional processes play in influencing lake dynamics (Magnuson and Kratz 2000). There is strong evidence that spatial dependencies can be important within lake districts (Baines et al. 2000, Kling et al. 2000, Kratz et al. 1997, Riera et al. 2000, Soranno et al. 1999), suggesting that processes occurring at that scale, such as hydrologic transport of solutes across the landscape, are important. For example, lakes that are positioned higher in the hydrologic flow system tend to be smaller, clearer, less diverse, more susceptible to acidification, and less used by humans than lakes positioned lower in the landscape (Riera et al. 2000). Similarly, spatial positioning of lakes within the landscape has been shown to be an important influence on the degree of among-year synchrony of a variety of limnological properties (Webster et al. 1996, 2000, Baines et al. 2000). Over the next six years we will examine spatial dependencies occurring across an expanded set of temporal and spatial scales, ranging from days to decades and from within-lakes to across continents. We will emphasize the following two topic areas.

How is the magnitude of temporal coherence of lakes affected by the temporal and spatial scale of analysis? Temporal coherence of lakes is the degree to which two or more lakes vary synchronously (Magnuson et al. 1990). Understanding how temporal coherence varies as a function of scale is crucial to developing a better understanding of the scales at which important drivers of lake dynamics operate. We will focus on time scales of hours to decades and spatial scales of individual lakes to continents. Four evolving datasets will be used for these analyses. (i) We will use the existing core physical, chemical, and biological data collected over the past 21 years (and counting) at biweekly to annual frequencies (Table 3). (ii) The new data on lake metabolism that we propose to measure using automated buoys on multiple lakes (see Section III. Understanding Temporal Variability) will provide important physical, chemical and biological data at sub-daily time scales. (iii) Data on ice phenology we assembled for 749 waterbodies across the Northern Hemisphere, covering more than 100 years in some cases, will allow analyses at continental and century scales. In particular, these data will allow us to analyze how interannual variability is related to large-scale climate dynamics such as the El Niño Southern Oscillation, the North Atlantic Oscillation, variations in the Aleutian Low, or volcanic eruptions (Robertson 1989, Anderson et al. 1996, Benson et al. 2001, Livingstone 2001, Robertson et al. 2001), and to a long-term warming trend apparent in ice phenology records (Magnuson et al. 2000). (iv) Satellite observations of lake conditions over large spatial extents, including Landsat-derived estimates of lake clarity for over 7000 lakes and daily MODIS imagery from which estimates of water transparency (Fig. 14), chlorophyll a, and total suspended matter can be made for all lakes in Wisconsin larger than 400 hectares, will allow analysis of water clarity patterns over extended spatial scales. Collectively, these data sets provide a rich resource for investigating the scales over which a variety of limnological drivers operate.

How does a lake's landscape position influence its biotic community composition and diversity? Preliminary work in the Northern Highland Lake District showed that diversity of fish, macroinvertebrates, and macrophytes was influenced more by lake position in the regional groundwater flow system than by the presence or absence of stream connections (http://www.limnology.wisc.edu/lppbite.html). We propose to extend this analysis to other lake districts in the western Great Lakes region such as the Experimental Lakes Area and the Dorset Research Centre, where the hydrology is more heavily influenced by surface water rather than groundwater and we expect stream connections to be a more important determinant of species richness.

How do climate, geologic setting, and land use/cover change influence water and solute loading to lakes?

Climate, geologic setting, and patterns of land use/land cover may all control the loading of water and solutes to lakes (Naiman and Turner 2000). At a regional scale, climatic variability has significant effects on the water budget of the central US (Lenters et al. 2000). The geologic setting and landscape position of lakes further influence water balance and solute loading, because lakes high in the landscape receive most of their water from precipitation, whereas lakes lower in the landscape receive significant amounts of water from ground or surface waters (Kratz et al. 1997). Finally, the distribution of land cover types within a watershed and their management are important determinants of water and solute loading because of their influences on surface runoff, evapotranspiration, groundwater recharge, and water quality (Detenbeck et al. 1993, Hunsaker and Levine 1995, Johnson et al. 1997, Wear et al. 1998). Long-term landscape changes occurring in the NTL LTER study region are correlated with significant alterations in lake level response to storms and nutrient loading (Wegener 2001, Soranno et al. 1996). These findings prompt us to investigate the linkages of geologic setting, climate, and land use/cover change that affect flux of water, C, N and P to our study lakes. Using a combination of long-term, comparative, and modeling approaches, we will address the following four topic areas.

What are the roles of landscape position and geologic setting in controlling loadings of water and solutes to lakes? To predict solute flux in a watershed (and hence inputs to lakes) it is important to understand the source of the water and the flowpath it takes through the watershed (Fig. 15). Even in the relatively simple geologic setting of the Trout Lake watershed, refining a groundwater flowpath can be quite challenging (Bullen et al. 1996, Kim et al. 1999). To improve our understanding of the geologic setting and its effects on water and solute loadings, we will use the results from recharge studies and coupled groundwater/surface-water models (Dripps in prep.), along with samples collected along various flowpaths for verification and refinement.

What are the functional roles of streams and wetlands in our watersheds, and how do they interact with lakes? Water may pass through wetlands and streams, where diverse biogeochemical reactions occur, before entering a lake (Fig. 13). For example, wetlands in the Allequash Creek system are important in methylation of mercury (Krabbenhoft et al. 1995) and can influence DOC export of stream systems that later drain into lakes (Elder et al. 2000). Similarly, the extent of wetland surrounding northern lakes is correlated with lake DOC concentration (Gergel et al. 1999). Thus, understanding how solutes are transported through a watershed to lakes requires knowledge of system hydrology, and how flow paths interact with reactive “hot spots” such as streams and wetlands. We will investigate the functional roles of streams and wetlands in shaping lake characteristics by examining biogeochemical dynamics of C, N and P and interannual fluctuations in chemistry within these systems. To address these questions we will combine a variety of approaches, including process-based measures of C, N and P dynamics in stream-wetland sites, continuation of a growing time series of chemistry of streams draining wetlands, examination of long-term lake chemistry and USGS flow records, and models linking hydrology and lake chemistry.

What is the role of climate variability in water and solute input to lakes? Our previous work has shown that the central US has strong seasonal and inter-annual variations in precipitation, evapotranspiration, and soil moisture (Lenters et al. 2000). There is a need to understand how this climate variability impacts water flow and solute delivery into lakes. For example, in recent decades the Upper Mississippi River basin has seen increased discharge, which has resulted in a large increase in nitrogen transport in addition to that caused by increased fertilizer application (Donner et al. 2002). We will investigate the extent to which both the magnitude and the timing of precipitation impact solute loading at scales ranging from individual rainfall events to inter-annual patterns of wet and dry years.

What is the role of land use/land cover in discharge and solute concentration of streams entering lakes, and how are long-term changes in land use/land cover affecting lakes? We have recently completed a time series of spatial databases covering 60 years of land use/land cover change for watersheds in the Madison Lakes region. During the

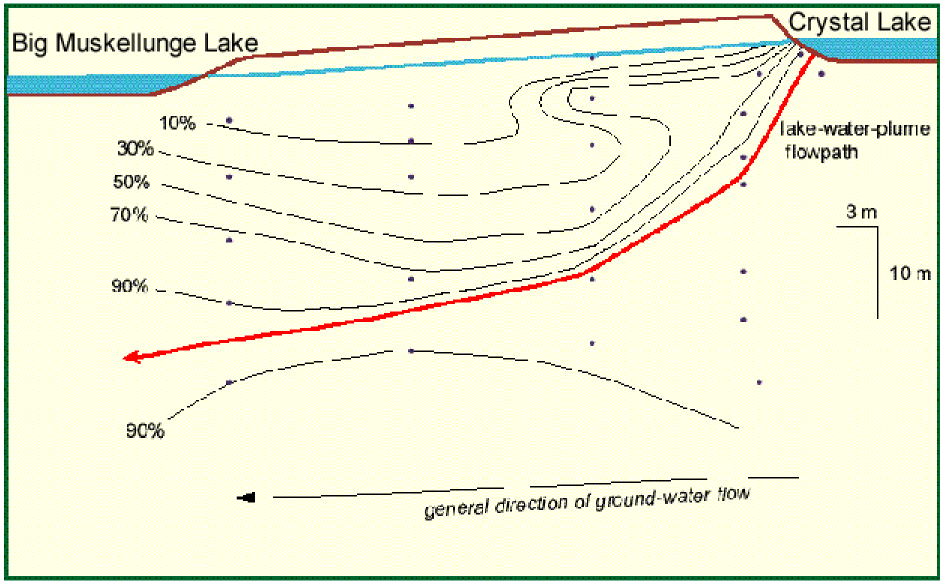


Figure 15. Groundwater flow between Crystal Lake and Big Muskellunge Lake, in the Trout Lake watershed. Groundwater beneath the isthmus between the two lakes is a mixture of Crystal Lake water and precipitation recharged through the isthmus. Contours shown represent percent lake water based on a simple mixing model using stable isotopes of water (^{18}O and ^{2}H). The flowpath shown is one likely flowpath of Crystal lakewater through the isthmus.

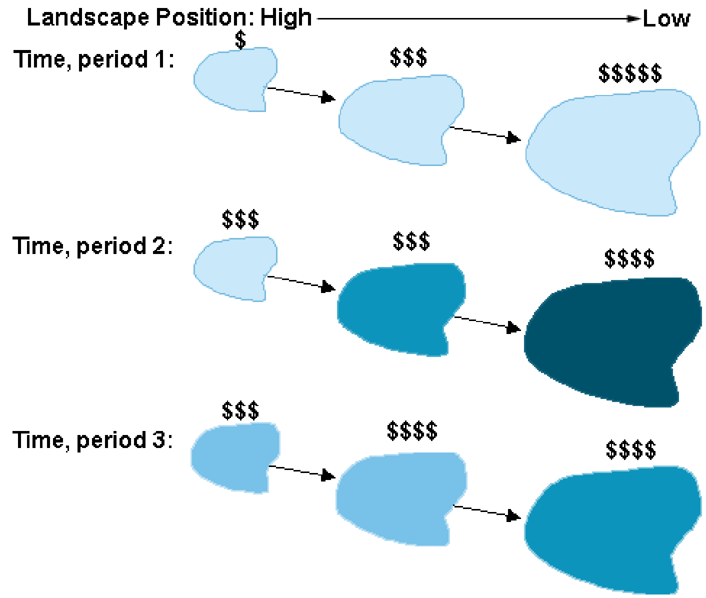


Figure 16. Hypothetical interaction between landscape position and change in lakeshore property value. The direction of hydrologic flow is indicated by the arrows; water moves from small lakes with a high landscape position to larger lakes with a low landscape position. The relative value of property along lakes is indicated by the number of dollar signs ($). Loss of environmental quality is indicated by the shades of blue; the darker the blue, the lower the environmental quality. In Period 1, all lakes are relatively undeveloped, and so environmental quality for all lakes is high. Property values on lakes with a low landscape position are relatively high, reflecting the hypothesis that people prefer the environmental goods and services associated with larger lakes to those associated with smaller lakes. In Period 2, heavier initial development on low-position lakes causes environmental quality on these lakes to diminish, thereby reducing the price differentials between lake types. Possibly this leads to action to preserve/recover environmental quality on low-position lakes, as shown in Period 3; this feedback alters again the price differentials among lakes.

next six years, we will complete development of a historical land cover database for riparian zones in the Trout Lake region. At the same time, we will examine the effects of agricultural practices and urbanization on the quantity and quality of water entering the lakes in the Madison region, and the role of long-term changes in these factors. We will use a coupled ecosystem and hydrologic model to answer questions such as: 1) how have historical changes in land use/land cover impacted the water and solute input to lakes in the last 60 years; 2) to what extent do individual land use types (urban, cropping, forest, fallow) contribute to the observed water and nutrient balance; and 3) how do individual crops (corn, wheat, soybean, and alfalfa), their respective management practices (fertilizer application amount and timing), and landscape position contribute to the total solute and water budget?

How does spatial positioning of lakes influence their value to humans?

In examining the relationships between socioeconomic and ecological systems, the focus is usually on how social systems affect ecology. The reverse question – how lake features affect social systems – has received less attention. We have documented variation in lakeshore building density based on lake attributes (Schnaiberg et al. 2002). We now turn to the effect lake characteristics have on lakefront property values (Wilson and Carpenter 1999, Spalatro and Provencher 2001, Poor et al. 2001). We hypothesize that lakefront property values are a function of a lake's landscape position (Fig. 16) and will use price differentials as indicators of preferences for some lakes over others. As the ecology of lakes change (in part due to human settlement), this price differential changes over time, and perhaps even changes direction (Fig. 16).

To examine this question, we propose a hedonic valuation study (Rosen 1974) in which lakefront property value is cast as a bundle of property and lake characteristics (such as the size of the property, lake water quality, the quality of fishing, and many other characteristics of the lake and property), and the market price of the property is regressed on these characteristics in a statistical analysis to determine the marginal contribution to the property price of each observed characteristic (see Palmquist 1991 for a description of hedonic valuation). Periodic estimation of the hedonic model will reveal how social preferences for different lake types change over time, with implications for feedbacks between social and lake systems.

V. THRESHOLDS AND REGIME SHIFTS

Ecological change need not be continuous in time. Many researchers, including NTL scientists, have documented periods of substantial change, in which ecosystems appear to cross thresholds from one dynamic regime to another (Peterson 2002, Carpenter 2001, Jackson et al. 2001b, Scheffer et al. 2001, Steele 1998). Assessments of rapid, extensive ecosystem change are crucial for understanding the past and anticipating the future. NTL long-term observations provide a strong foundation for the investigation of such change. Over the next six years, we will focus research effort on three types of massive, rapid change that are ecologically significant and well represented at our sites: eutrophication, species invasions, and change from public to private ownership of lakeshores.

Hysteresis in Eutrophication

When lake eutrophication is mitigated by pollution control, are the changes in ecosystem processes simply the reversal of those that occurred when eutrophication was created? Or is eutrophication hysteretic, i.e., changes during reversal of eutrophication are not just the opposite of those that occurred during its onset?

Eutrophication may be hysteretic, according to models based on many case studies (Carpenter et al. 1999, Dent et al. 2002). Relatively drastic reductions in P input are needed to control eutrophication, in comparison to P inputs that trigger eutrophication (Fig. 17). The causes of hysteresis may include individual farmers' decisions about fertilizer and manure application (Nowak and Korsching 1998, Nowak et al. 1998), excess P buildup in soils (Bennett et al. 1999, 2001), and effective recycling of P from sediments (Nürnberg 1984, Smith 1998, Carpenter et al. 1999).

The ongoing restoration of Lake Mendota is a long-term experimental test of the hysteresis hypothesis. Numerous long-term and retrospective studies have documented the changes that occurred during eutrophication of the lake beginning in the 1880s, and since restoration began about 1960. State and County officials are now engaged in aggressive control of nonpoint pollution aimed at reducing nonpoint P inputs to Lake Mendota 50% by 2008 (Betz et al. 1997). We will focus LTER research on three mechanisms that could create hysteresis in ecosystem response. (1) Does the interaction of management institutions with farmers achieve goals for soil P input rates in a smooth linear way as planned, or are changes in fertilizer and manure practices delayed? (2) Are the existing pools of soil P drawn down quickly, or do they persist and delay recovery of the lake? (3) Does recycling of P from sediment decrease, or does it persist and support algal blooms?

Species Invasions and Ecosystem Change

Introductions of invasive species are common in freshwater ecosystems (Kolar and Lodge 2000, 2001; Lodge 2001, Ricciardi and MacIsaac 2000) and the NTL primary lakes have experienced several such introductions. The common carp (*Cyprinus carpio*) was introduced to the Madison lakes in the 1880's and many other non-native fishes were stocked in the following century (Lathrop et al. 1992). Eurasian water milfoil (*Myriophyllum spicatum*) arrived in the Madison lakes in the early 1960s (Andrews 1986) and continues to dominate the macrophyte community (Nichols et al. 1992). Since the inception of the NTL LTER in 1981, lakes in northern Wisconsin have been invaded by both the rusty crayfish (*Orconectes rusticus*) (Lodge et al. 1986, Lodge and Lorman 1987, Wilson 2001), and the rainbow smelt (*Osmerus mordax*) (Hrabik et al. 1998), with impacts on many native species (Figs. 3 and 18).

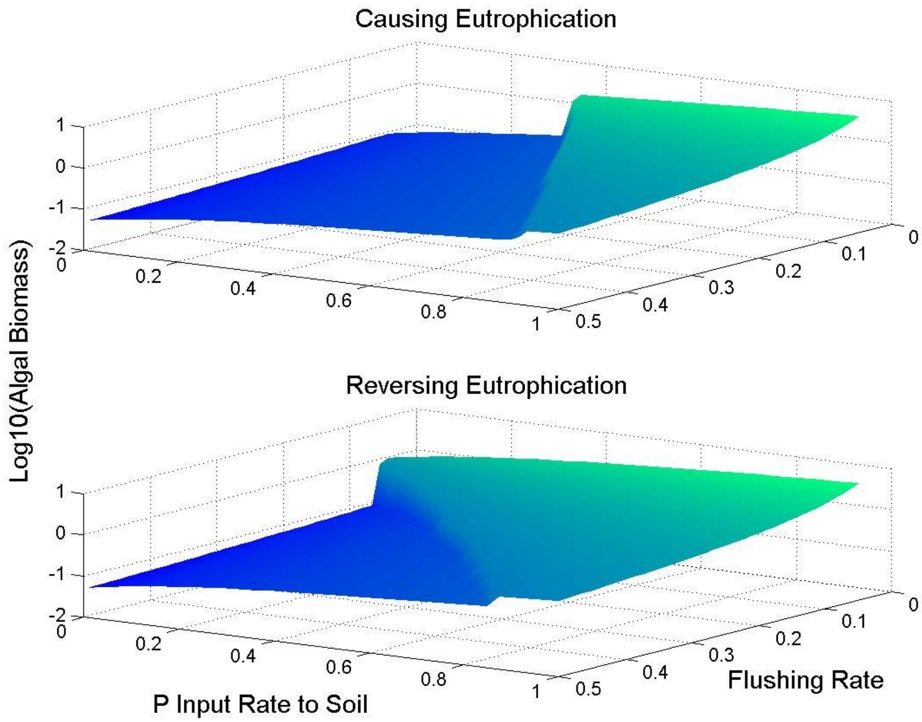


Figure 17. Hysteresis in eutrophication: Algal biomass (log10 scale) versus rate of P input to soil (from manure and inorganic fertilizers, g m^{-1} y^{-1}) and hydraulic flushing rate of the lake (y^{-1}) during the creation of eutrophic conditions (upper panel) and during the reversal of eutrophication (lower panel). For a given flushing rate, the onset of high algal biomass does not occur until P flux to soil is relatively high (upper panel). However, return to low algal biomass requires that P flux to soil be decreased to relatively low levels (lower panel). This difference between forward and backward pathways is hysteresis (Dent et al. 2002).

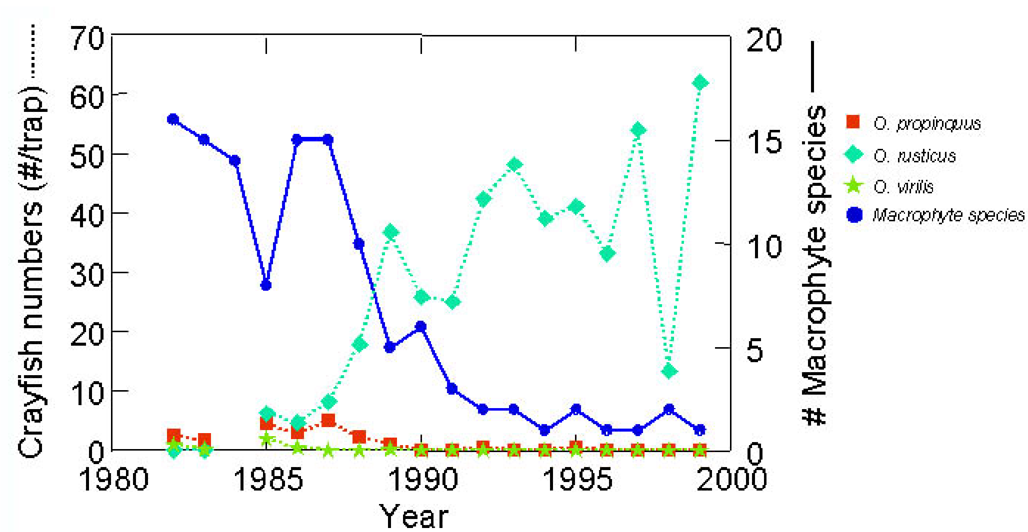


Figure 18. Invasion of rusty crayfish (*O. rusticus*) in one area of Trout Lake. Rusty crayfish have nearly eliminated the native crayfish, and reduced macrophyte species richness (Wilson 2001).

In 2001, adult zebra mussels (*Dreissena polymorpha*) were found in Lake Monona, heralding the arrival of yet another invader in NTL LTER lakes. Zebra mussels often exert dramatic and ecosystem-altering impacts on lakes and rivers (Ludyanskiy et al. 1993, MacIsaac 1996, Strayer et al. 1999). With a zebra mussel invasion on the horizon, the NTL database provides an opportunity to test model predictions for zebra mussel impacts in the Madison lakes (Reed-Anderson et al. 2000b). This invasion is predicted to drive Lake Mendota from a system dominated by pelagic production and processes, to one dominated by benthic production (Strayer et al. 1999, Rutherford et al. 1999, MacIsaac 1996). Such a shift may have tremendous consequences for species and community composition, energy flow through the food web, trophic dynamics, and fisheries (MacIsaac 1996). We are poised to determine the effects of zebra mussel invasion in the Madison lakes to assess ecosystem change, test model predictions, and evaluate changes in benthic and pelagic processes.

Private vs. Public Lakes: Angler Heterogeneity and Fish Community Change

Increasingly, public policy reflects the economic perspective that privatization of ecological goods and services assures their stewardship and beneficial allocation ("privatization" is defined as the replacement of an allocative regime by one in which benefits and costs of an action accrue directly to the decision maker). The future likely will bring an increase in environmental privatization, yet the ecological changes associated with changes in resource management regimes are poorly understood. This raises a number of important research questions about the impact of ownership (public versus private) on lake ecology and its interactions with human activity.

Potential differences in the ecology of public and private lakes have implications for human use (Fig. 19). The illustration emphasizes an important aspect of privatization: ecological variables (such as game fish) with economic value captured by lake "owners" become the drivers of the ecological system, in the sense that the levels of other ecological variables depend on their relationship to the "valuable" variables lake users manipulate. While a growing literature addresses questions of angler choice in open-access recreational fisheries (Beard et al. in review, Carpenter and Gunderson 2001, Cox et al. 2002, Hunt and Ditton 1997, Miranda and Freese 1991, Radomski et al. 2001), we do not have a good understanding of the potential impacts of privatization on freshwater fish communities.

We propose research to explore ecological implications of public vs. private ownership. The study will involve (1) comparisons of fish population structure on selected private and public lakes; and (2) analysis of behavioral and motivational heterogeneity among anglers using public and private lakes, with an emphasis on how angler behavior evolves over time in response to changing economic and ecological conditions (in particular, changes in the levels of lake privatization, and attendant changes in lake ecology). Recently developed econometric methods for modeling heterogeneity in consumer choice will be used to test for behavioral differences among anglers (Provencher et al. 2001, Provencher and Bishop 2001, Train 1999, Boxall and Adomowicz 1999, Chen and Coslett 1998).

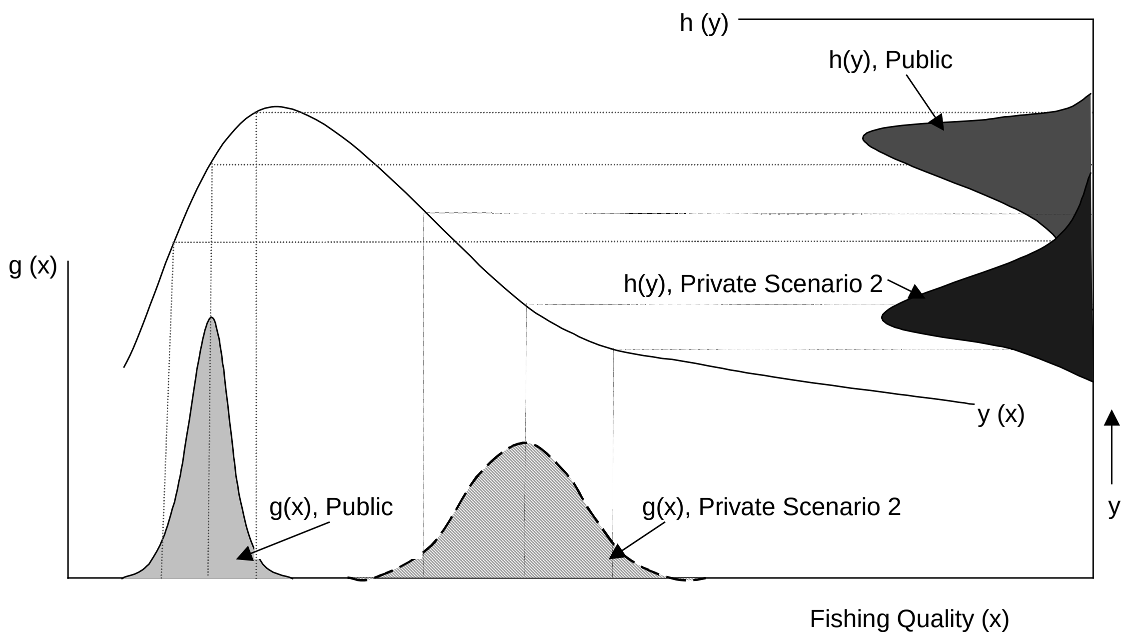


Figure 19. Hypothetical cross-sectional frequency distributions of fishing quality as perceived by anglers (x) and fish population density, public vs. private lakes. A mobile subset of expert, avid anglers effectively “flatten” fishing quality across lakes (Beard et al. 2001, Cox et al. 2001). This suggests an outcome in which the frequency distribution of fishing quality across lakes is lower and “tighter” for public lakes than for private lakes, because the subset of mobile, avid anglers more easily exploit public lakes than private lakes. Given a specified relationship between variables x and y, the frequency distribution of y for public and private lakes can be mapped from the frequency distributions for x.

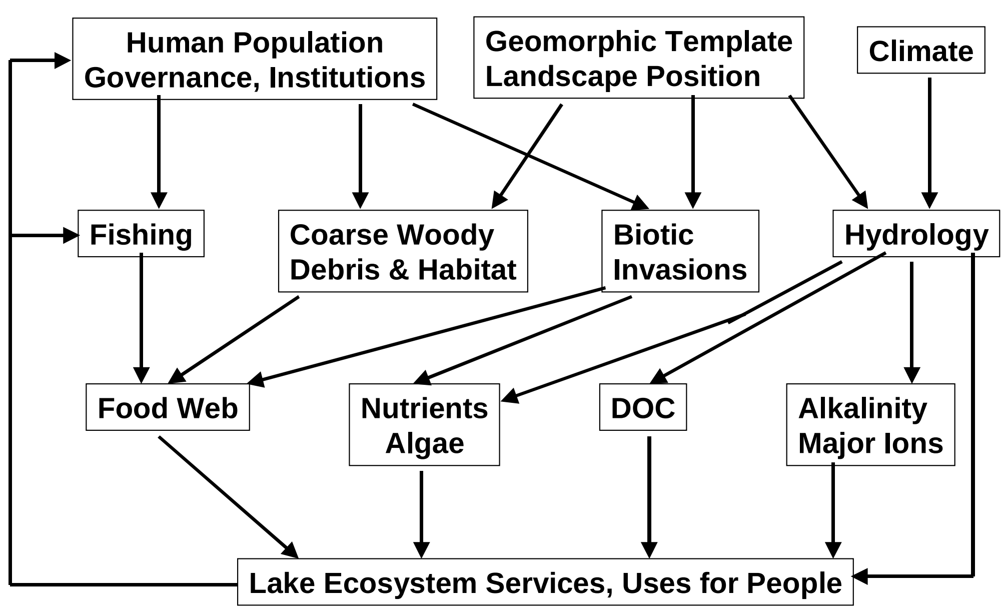


Figure 20. Major interactions hypothesized to affect long-term change in North Temperate Lake districts.

VI. FORECASTING LONG-TERM CHANGE

Multi-scale ecological observations, combined with emerging capabilities in coupled systems modeling, will rapidly accelerate our ability to forecast ecosystem change in the future. In addition to being an important research frontier, ecological forecasting offers managers and policymakers a capacity to anticipate potential environmental changes (Clark et al. 2001, Carpenter 2002). With this proposal, we introduce ecological forecasting as a new component of NTL LTER. It is natural for a program focused on long-term change to look forward as well as into the past. Conceptual frameworks and models developed to forecast will integrate and synthesize our long-term research, and the forecasts become hypotheses to be tested by future long-term research.

Over the next 50 years, the freshwater and terrestrial ecosystems of temperate lake districts may exhibit complex responses to several driving forces, including climatic variability, climate change, CO_2 fertilization (through the effects on C and water cycles), nutrient fertilization (through atmospheric deposition, and fertilizer input), land use and cover change, fishing, and lakeshore management. To some extent, we have already embedded forecasting in our research. We have developed forecasts of blue-green algal bloom frequency (Lathrop et al. 1998), dynamics of CWD (Turner 2002), impacts of invasive species (Reed-Anderson et al. 2000b, Hrabik and Magnuson 1999), and potential effects of climate change on lakes (DeStasio et al. 1996). All of these efforts have focused on selected, specific drivers and responses. However, no systematic, integrated evaluation of future change has yet been attempted for our lake districts.

We will develop and apply methods for forecasting changes in hydrological and biogeochemical processes of temperate lake districts. These changes derive from a complex web of interactions that involve both biogeophysical and socio-economic drivers and responses (Fig. 20). Over the next six years, we will focus on three objectives: (1) developing and testing integrated models for projecting hydrologic and biogeochemical changes; (2) creating scenarios for plausible future trajectories of important demographic and biogeophysical drivers; and (3) combining these to generate forecasts and hypotheses for long term change in our lake districts.

Integrated Models: Development and Testing

Forecasts involve synthesis of observations using models. We will build a new integrated regional environmental modeling system to evaluate large-scale changes in regional hydrological processes (including changes in terrestrial water balance, surface- and ground-water flows, and lake water budgets), and biogeochemical cycles (including regional-scale flows of carbon, nitrogen, and phosphorus). This system will link existing models of terrestrial ecosystems, surface hydrology, and groundwater transport and will include representations of human activity (e.g., land use, lake management practices) and changing environmental driving conditions (e.g., climate, climatic variability, atmospheric CO_2 concentration).

The modeling system (Fig. 21) will couple the IBIS terrestrial ecosystem model (Foley et al. 1996, Kucharik et al. 2000, Lenters et al. 2000), the HYDRA surface hydrology model (Coe 2000, Coe and Foley 2001, Donner et al. 2002, Fig. 26), and an analytic-element groundwater transport model (Hunt et al 1998, Walker and Krabbenhoft 1998, Fig 22) together with specific solute transport modules (Donner et al. 2002). These models will form the biophysical and ecological basis of the regional modeling system. Next, we will develop a human activity module to characterize management practices (e.g., lakeshore management, land cover change, fertilization and tillage practices, and crop and forest rotation practices). Finally, these sub-models will be linked through a common environmental change module, which will characterize changes in climate and atmospheric chemistry. We will use this modeling system to examine the sensitivity of lake districts to multiple environmental and social drivers, including changes in climate, climate variability, land cover and land use. Examples of results from preliminary model runs include monthly simulated water balance for the Trout Lake watershed (Fig. 23), crop yield and soil water balance for an agricultural field (Fig. 24), and simulated spatial dynamics of water recharge in the Trout Lake watershed from two models, a water balance model (Fig. 25 upper) and IBIS ecosystem model (Fig. 25 lower).

In order to test our regional modeling system, we will examine how human and environmental drivers have affected terrestrial and aquatic ecosystem processes during the last two decades recorded in NTL LTER data. Specifically, we will drive the integrated modeling system with historical data representing changes in climate, atmospheric CO_2 concentration, lake management practices, land cover, and land use practices (tillage practices, fertilizer use, irrigation, urbanization). This exercise will contribute to our understanding of these systems, and allow us to test our ability to meaningfully diagnose changes in hydrological and biogeochemical processes with available data.

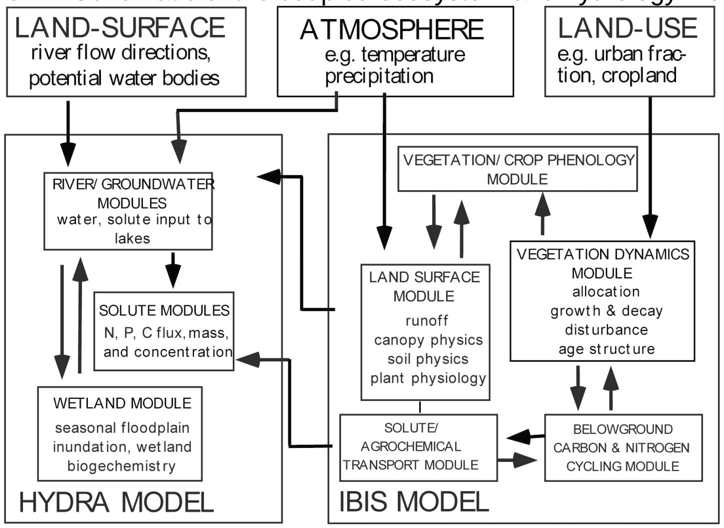
In order to improve our understanding of temperate lake districts, and how they may respond in the future, we must examine their sensitivity to various drivers. We will conduct a thorough sensitivity analysis with the regional modeling system. This analysis will consider effects of changing combinations of driving factors, nonlinearities, and threshold responses.

Scenarios for Demographic and Biogeophysical Drivers

We will focus on selected drivers for which quantitative scenarios can be constructed during the next six years: human population and settlement patterns, and changes in climate related to changes in atmospheric chemistry.

Past and future extent of residential development: For Madison-area watersheds, historical and current patterns of land development are available from our own core data and county land-use planners (Table 3, Bennett 2002). NTL researchers and county governments have developed projections of future development which will be used in scenario analyses (e.g. Soranno et al. 1996).

Figure 21. Schematic of the coupled ecosystem and hydrology models.



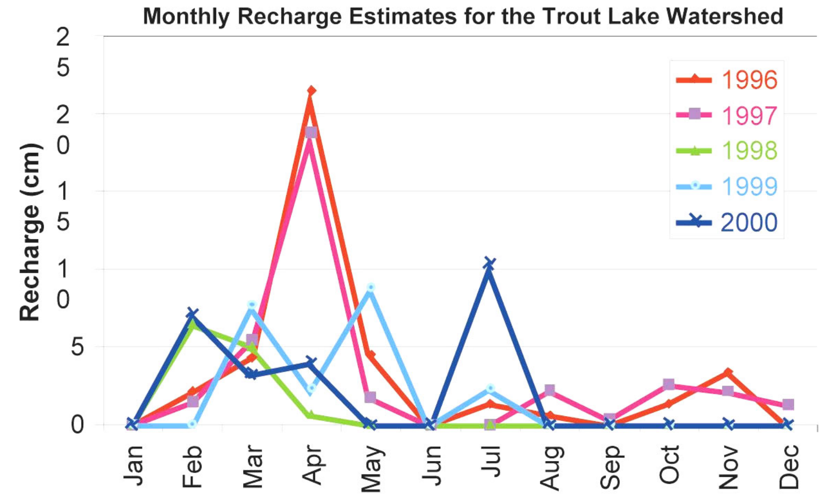


Figure 23. Monthly simulated soil water balance. Average recharge estimates for Trout Lake watershed (in cm).

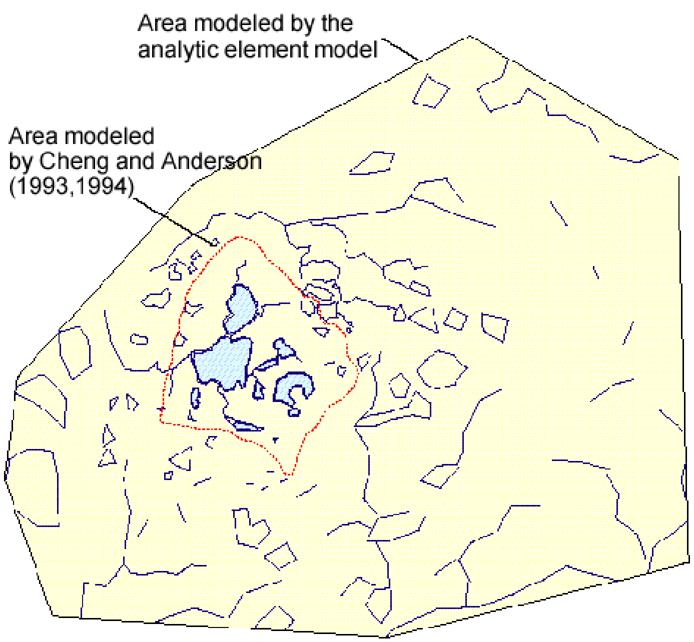


Figure 22. Example of the area analytic approach to groundwater modeling. The area of basin simulated with traditional groundwater model is shown in red dotted watershed (Cheng and Anderson 1993,1994). The efficient model architecture of the analytic model allows for much greater simulated area. This technique will be incorporated into our existing ecosystem/surface hydrology model.

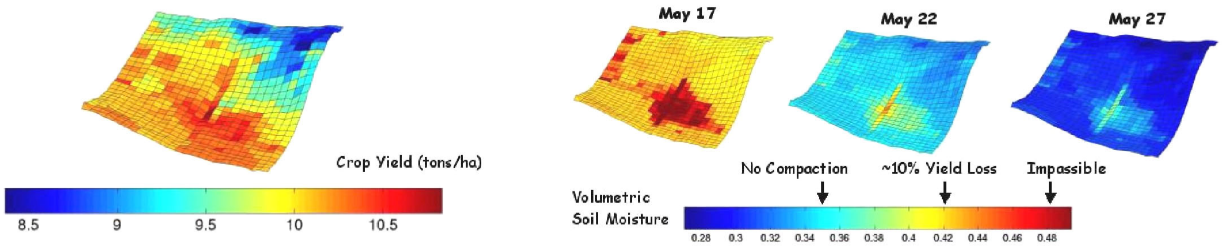


Figure 24. Illustration of IBIS simulations at very high resolution. IBIS simulated maize yield (left) and changes in May soil moisture (right figures) in 1999 for an individual field (125 m x 125 m) at the Arlington Agricultural Research Station in Arlington, Wisconsin. Each grid cell represents a 5 m x 5 m area. Gridded information such as texture, topography, and depth of a horizon were used as model inputs. Hourly micrometeorological data were used to drive the model.

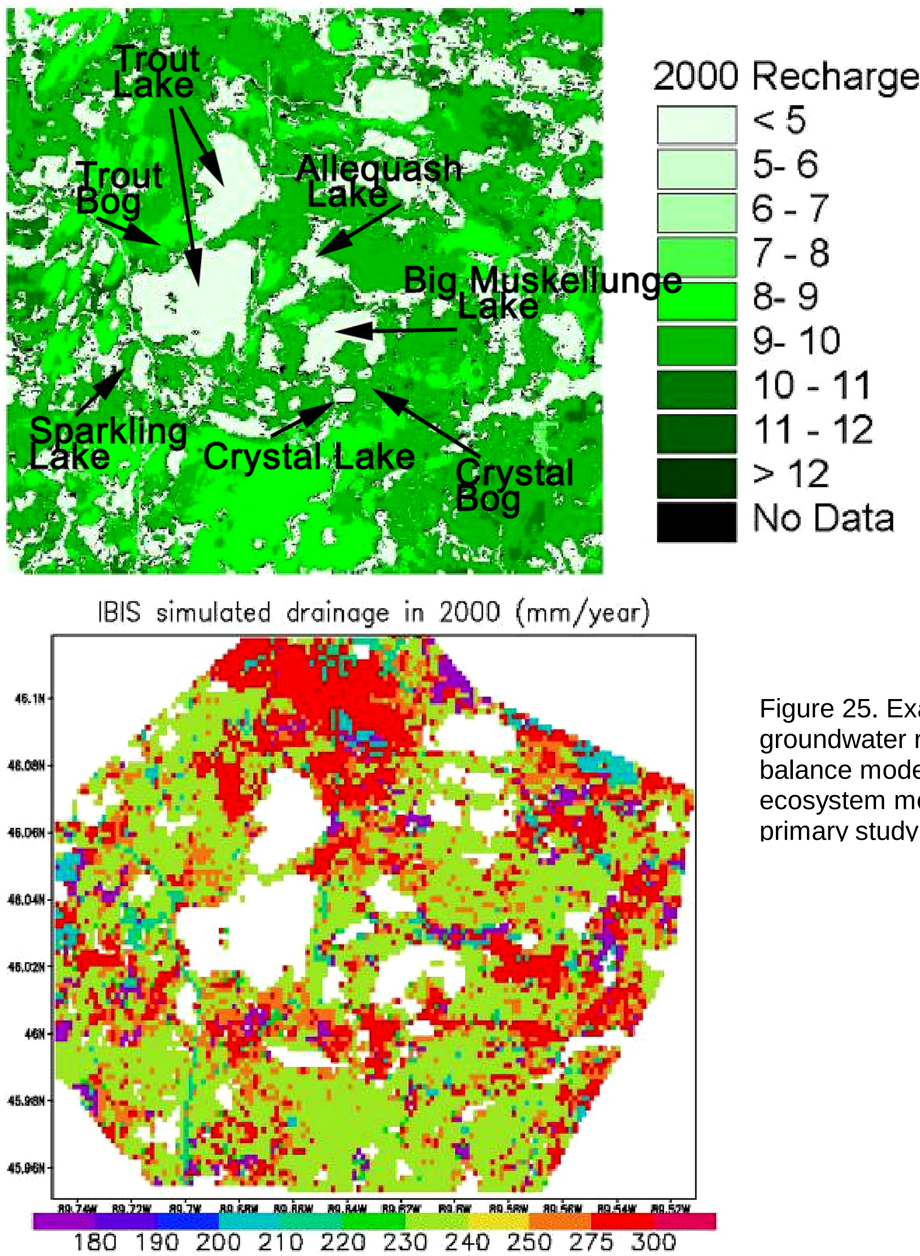


Figure 25. Example of simulated groundwater recharge from water balance model (top) and IBIS ecosystem model (bottom). The primary study lakes are labeled.

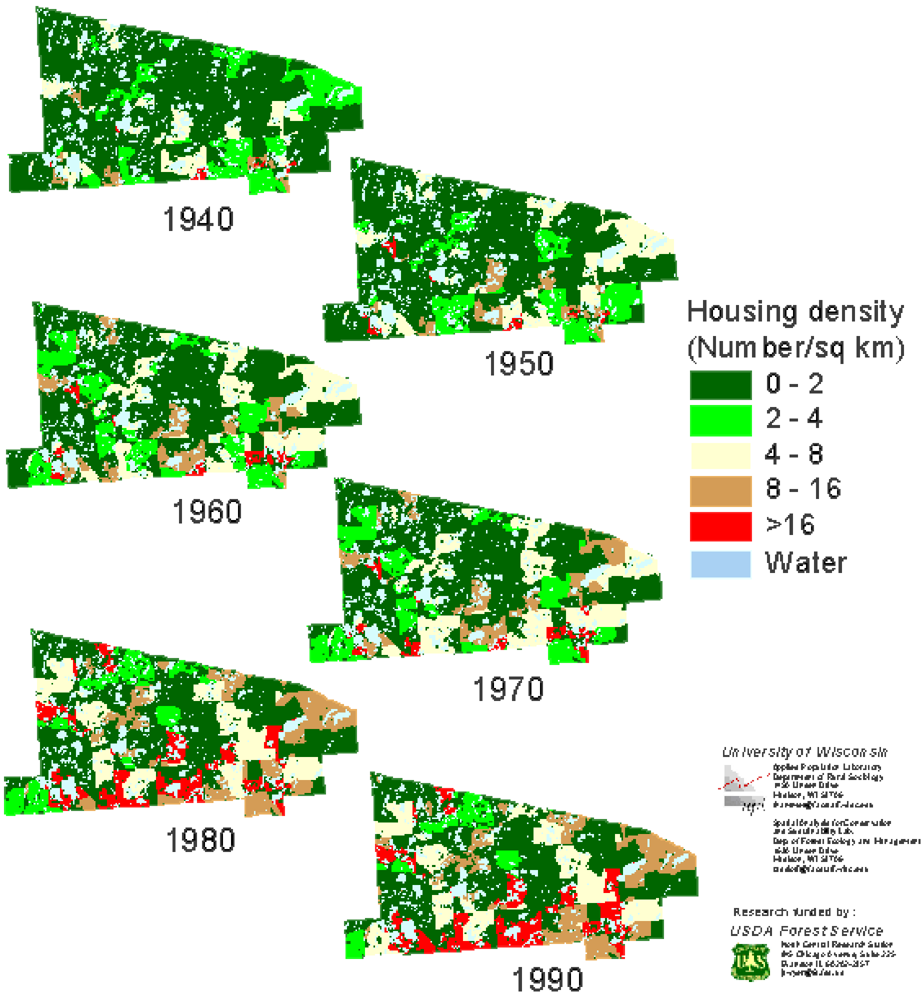


Figure 26. Housing density in Northern Highland Lake District, Vilas County, Wisconsin, 1940-1990. DO NOT CITE OR REPRODUCE.

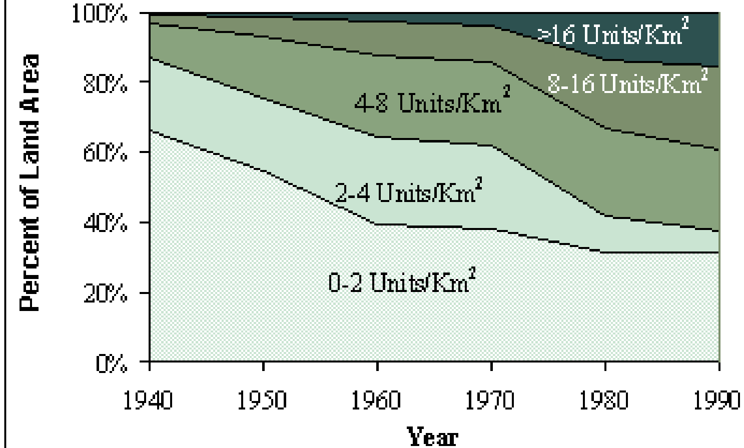


Figure 27. Percent of land area by housing density (units/square kilometer), 1940-1990 Vilas County, Wisconsin.

In the Trout Lake region, we will build on work of Schnaiberg et al. (2002) and Hammer et al. (in review,a). In 1990, the southern tier of Vilas County and the adjacent communities in Oneida County represented the largest consolidated cluster of high housing density (≥ 8 housing units km^{-2}) in the northern portion of the state. During the period from 1940 to the present, Vilas County experienced a distinctive pattern of growth, especially in areas proximate to large lakes and chains of lakes (Fig. 26). Between 1940 and 1990, the land area in Vilas County with eight to sixteen housing units per square kilometer increased nearly 10 fold, while the area with greater than 16 housing units per square kilometer increased nearly 20 fold (Fig. 27). In the next phase of this project, we will update these housing density estimates to include the 2000 Census and make projections of housing density to 2050. Projections will be a component of the integrated regional modeling system. We will also prepare finer-grained (i.e. Census Block Level) estimates of housing density for 1990 and 2000, to facilitate the assessment of lake-front development that occurred during the decade.

Past and Future Climate of the Lake Districts: We will generate future climate scenarios for temperate lake districts by combining the predictions of climate simulations by General Circulation Models (GCM) from the National Center for Atmospheric Research (NCAR) and the UK Hadley Center, along with historical climate data over our region. By blending historical climate data and GCM simulations, we will create a 50-year dataset of meteorological drivers (including temperature, precipitation, and solar radiation). The atmospheric concentration of CO_2 has a direct impact on plant physiology and ecosystem processes (in addition to its role as a greenhouse gas). Therefore, hypothesized increases in atmospheric CO_2 concentrations to 500-700 ppmv by 2050 will also be used.

A continued increase in the concentration of greenhouse gases in the atmosphere may result in an increase in frequency and severity of extreme weather events (IPCC 2001). A number of studies have noted that a substantial proportion of nitrate leaching from the terrestrial system occurs during heavy precipitation and flood events (e.g. Creed and Band 1998a,b). In our work, we will explore changes in climatic variability and extreme events such as prolonged droughts (Webster et al. 1996, 2000), on simulated hydrological and biogeochemical processes.

Forecasts and Hypotheses for Long-Term Change

We will use the regional modeling system to derive simple regional environmental indicators to diagnose and document large-scale changes in hydrologic and biogeochemical processes across temperate lake districts. For example, changes in the proportions of rainwater, groundwater, and surface water entering a lake are important clues to biogeochemical change (Webster et al. 2000). Such indicators will be used to diagnose locations where terrestrial and aquatic systems may be undergoing significant changes. In addition, we will conduct several more detailed case studies, where we will validate our modeling approaches with detailed datasets.

For our lake districts, we will develop a set of quantitative scenarios of future hydrologic conditions. The scenarios will be designed to span the range of possible outcomes based on plausible ranges of drivers and quantified uncertainties in the model. By formalizing these scenarios, we will be able to evaluate them against our database as it evolves. The forecasting component of NTL LTER is one of “learning by doing.” Our capacity to forecast can be improved only by constructing forecasts, criticizing them rigorously in light of data, and then creating improved models and procedures for a new cycle of learning.

VII. SYNTHESIS AND SIGNIFICANCE

The research we propose will address key challenges in ecology that are of global importance. We focus especially on how four of the most important changes of global significance (climate, land use/land cover, introduction of species and biotic mixing, and movement of materials and solutes from terrestrial to aquatic ecosystems) will influence north temperate lake ecosystems. These drivers are ubiquitous. We address them at a variety of levels of organization, over a wide range of spatial and temporal scales, and in lakes in a rural, forested setting and in a rapidly changing agricultural/urban landscape (Fig. 28). Our basic understanding of how ecosystems respond to change will be integrated in forecasts of future ecosystem states. We also will consider key questions that represent important research frontiers in ecology—for example, understanding the linkage of community structure and biodiversity to ecosystem function, the complex dynamics of the integrated hydrosphere, the spatial and temporal scales over which spatial dependencies are important, and the ecological effects of species invasions.

In addition to generating new understanding about lake ecosystems, we will make innovative conceptual contributions that are of broad relevance to ecology. The National Academy of Sciences identified eight “Grand Challenges” for environmental science (NRC 2001). Research proposed here is directly relevant to six of the eight Grand Challenges: biogeochemical cycles; biodiversity and ecosystem functioning; climate variability and its consequences for ecosystems; hydrologic forecasting; institutions and resource use; and land use dynamics. Forecasting future scenarios is another innovative objective of our proposal (Clark et al. 2001). With our focus on understanding the conditions that may produce qualitative changes in lake districts, the proposed research will enhance understanding of threshold dynamics, feedbacks, spatial dependencies and disproportionalities at many scales. The potential for small changes to produce surprising and large responses is of particular importance for constructing and analyzing scenarios of future change.

High-quality, long-term datasets have been intimately connected to past scientific advances at our site, and are directly involved in our future plans (Fig. 29). The length and quality of the observational record affords new insights about lake dynamics at scales ranging from individual lakes to large regions. Ecosystems are complex systems in which change derives from multiple factors acting across a range of spatial and temporal scales. Disentangling cause and effect requires long-term data, and we will

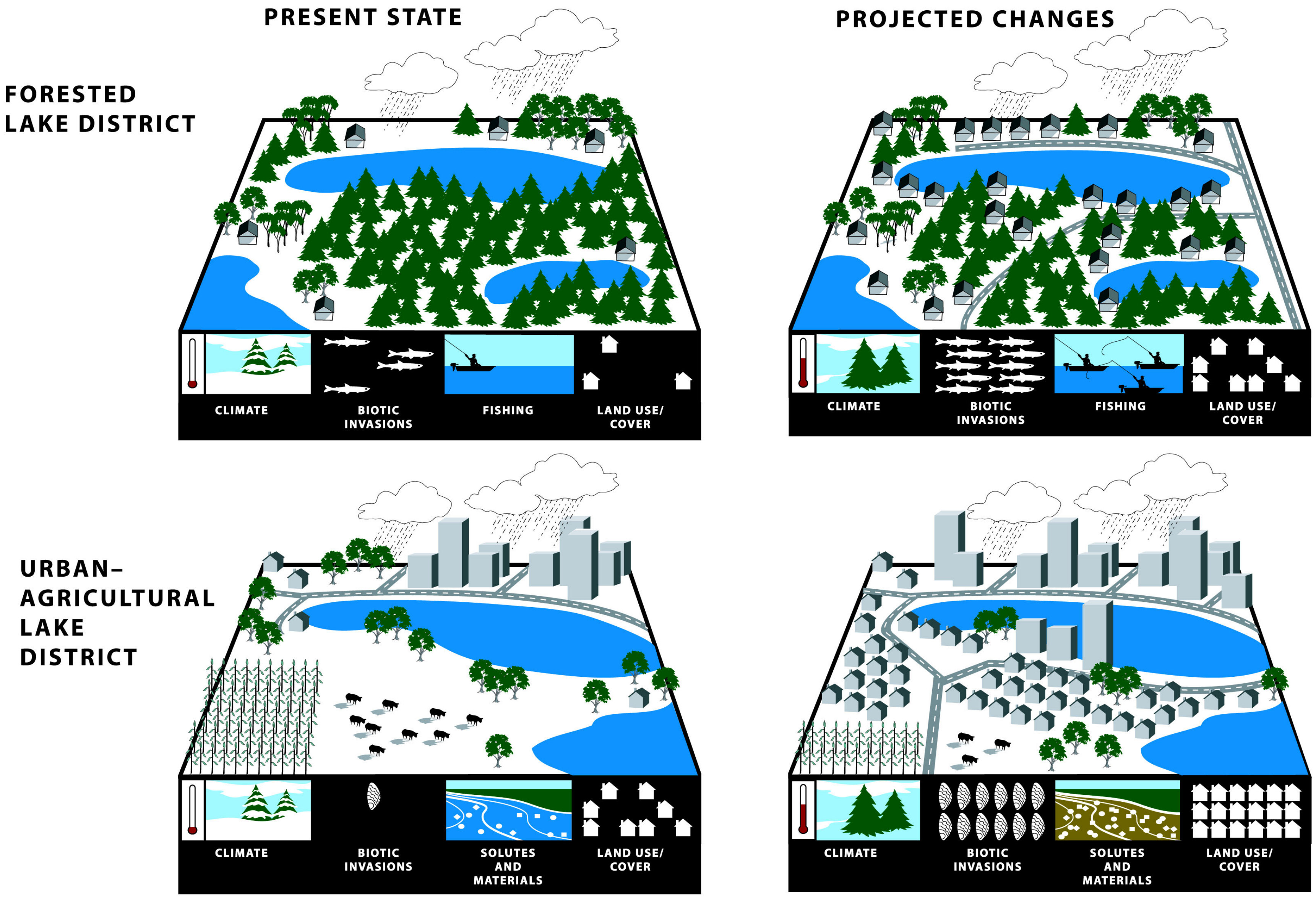


Figure 28. Present state and projected changes in the forested northern and agricultural/urban southern study landscapes.

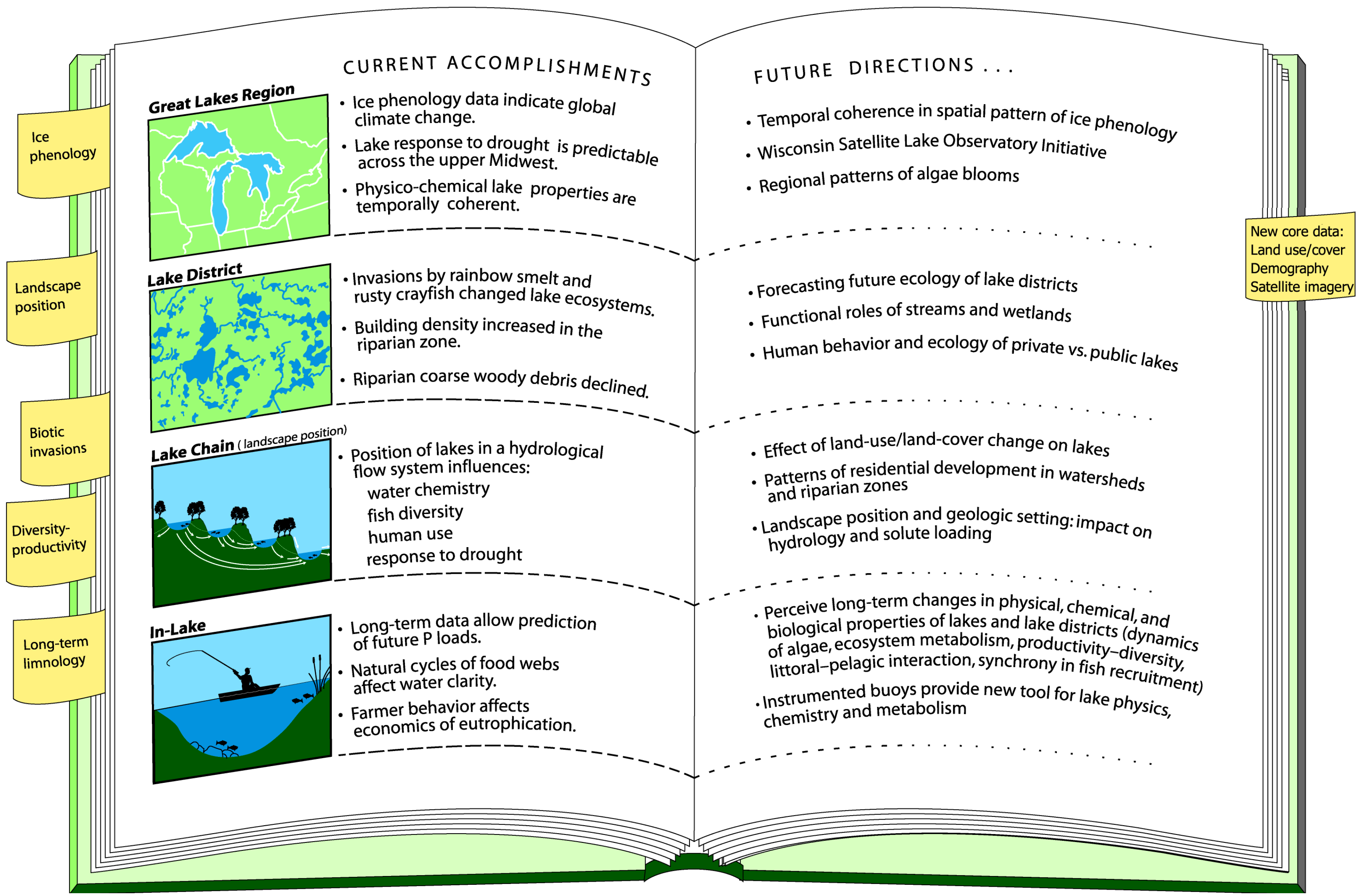


Fig. 29. Current and future chapters of the NTL-LTER program summarized for regional, lake-district, lake-chain, and in-lake spatial scales, with tabs denoting a few key data sets.

continue to build and use our long-term database. Our long-term research provides an opportunity for studying natural experiments through analysis of regional variability, historic data, and both episodic and chronic events. The core data sets will also be augmented to include new variables that reflect the interdisciplinary work we initiated during the current grant cycle. In addition, we will use new technologies (e.g., instrumented buoys and advances in remote sensing) to improve and expand measurements of key limnological variables.

The work at the NTL LTER site has been characterized by multiple approaches to question-driven science, including observational or comparative studies, experimental studies, modeling, and development of theory. Long-term observations and cross-system comparisons are a hallmark of LTER research. We are engaged in a major management experiment on eutrophication of Lake Mendota. We are also collaborating on three whole-lake manipulations under separate NSF funding. A core LTER lake, Sparkling Lake, is the site of a whole-ecosystem experiment on exotic species removal. We are also collaborating in whole-lake manipulations of littoral habitat in two lakes near Trout Lake Station. Finally, modeling for synthesis and ecosystem forecasting is a new major feature of this proposal.

Interdisciplinary studies are strongly developed at our site. We have a well-integrated approach that considers biophysical setting, climate, and land-cover change. In particular, we have effectively considered how humans interact with aquatic ecosystems at many scales. For example, understanding LULC patterns, changes and effects on aquatic ecosystems; community- and ecosystem-level effects of fishing; and forecasting future scenarios require fundamental contributions from both natural and social sciences. We will continue in this tradition, as we recognize the unique contributions of each approach and from different disciplines. Furthermore, we will continue to conduct our research across a range of temporal and spatial scales—from within-lake analyses to the Great Lakes region, and from short- to long-term dynamics (Fig. 29).

NTL research has been and will continue to be directly relevant to management and policy. 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. We actively collaborate with staff in state and federal agencies and participate in joint experiments (e.g., P reduction in Lake Mendota) and monitoring programs (e.g., USGS groundwater monitoring). In addition to these pragmatic activities, LTER research will continue to address fundamental issues in the theory of ecosystem management (e.g. www.consecol.org/vol3/iss2/art4).

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 (Fig. 29). 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 research.

Section 3. Project Management

Project Governance: Direction of NTL-LTER is provided by Carpenter with the participation of the Principal Investigators, research staff, and students. We have no formal executive committee, although on certain issues Carpenter consults with a subgroup of relevant PIs. All PIs meet monthly for an hour to plan and advise on program, personnel, and budget decisions; minutes are taken. We normally operate by consensus with Carpenter acting on hard choices. The entire group of researchers meets monthly for two hours to discuss scientific results, concepts, and plans. In addition, subgroups of researchers meet frequently to work on projects, both on the Madison campus and at Trout Lake Station.

Our PIs are involved in LTER Network activities including the Executive Committee (Kratz 97-01), the Steering Committee for Information Management (Benson), and Committee on Scientific Initiatives (Carpenter, Magnuson). Many PIs have attended network meetings on various specialized topics. More than 25 NTL researchers participated in the LTER All-Scientists meeting in 2000.

Project Administration: The project is administered through the Center for Limnology (College of Letters and Sciences, University of Wisconsin-Madison). The Center has field stations at both primary sites (Trout Lake Station in northern Wisconsin, and the Laboratory of Limnology in Madison). Both sites have a LTER site manager (Kratz in the north, Lathrop in the south) and LTER field technicians. Information Management (led by Benson) is concentrated in Madison, at the Laboratory of Limnology. Spatial analyses and modeling also occur in Madison, in the Environmental Remote Sensing Center (directed by Lillesand), 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 Laboratory of Limnology and adjacent Water Chemistry Laboratory. PIs (Table 5) are based at Trout Lake or around the Madison campus in three colleges and 11 departments. Two PIs are agency personnel based in Madison: Lathrop (Wisconsin Department of Natural Resources, the state management agency) and Walker (U.S. Geological Survey). Most graduate students receive degrees in Limnology and Marine Science, Zoology, Water Chemistry, Environmental Monitoring, or Rural Sociology, but degrees can come from any academic unit as our project evolves.

Project operations come from Carpenter, Sarah Carter (fiscal officer), Barbara Martinez (project officer) and secretarial staff in Madison and at Trout Lake.

The College of Letters and Sciences provides substantial direct costs annually for Center management, operations, and general building services which directly benefit LTER. Half of Carpenter's academic year salary is covered by an endowment which represents a substantial subsidy to LTER. Additional college funding exercises provide support for capital equipment, remodeling, and facilities upgrades. When direct costs paid by the college, endowment funds, equipment and remodeling monies are accounted for, the actual overhead rate on the LTER grant was –6% (i.e. a net subsidy) from 1997-2001. This rate was calculated as 100 * (NSF indirect cost – total UW contribution) / NSF direct cost.

PI Additions: The PI roster (Table 5) has some new names. Emily Stanley (biogeochemistry) has assumed leadership of the NTL-LTER chemistry lab. We have added two social scientists, Roger Hammer (demography) and Bill Provencher (economics) to bolster our interdisciplinary capabilities. We have added a physical limnologist (Chin Wu). In May 2002, Dr. James Rusak will join the project, bringing his expertise in plankton ecology, paleolimnology, and multivariate statistics.

Coordination with other Projects: NTL-LTER is the central axis of a portfolio of grants with interlocking groups of PIs. These include NSF grants for IGERT on Integrated Social and Aquatic systems (lead PI Nowak), Microbial Observatory (lead PI Triplett), and BioComplexity (lead PI Carpenter); an EPA award for research on subwatersheds of Lake Mendota (lead PI Lathrop); and a USGS Water, Energy, and Biogeochemical Budgets project based at Trout Lake (led by Walker). We collaborate regularly with staff from the state management agency (Wisconsin Department of Natural Resources). We have maintained an active collaboration with other research groups focused on lake districts in Canada, Germany, and Japan.

We encourage others to use our LTER site by posters and talks at national and international meetings; an informative web page (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 waive user fees 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 5. Principal Investigators and senior staff involved in NTL-LTER.

PI	Department	Specialty Area
Timothy Allen	Botany	Complex systems, hierarchy theory
Mary Anderson	Geology and Geophysics	Hydrogeology
David Armstrong	Water Science & Engineering	Biogeochemistry
Barbara Benson	Limnology	Ecoinformatics
Carl Bowser	Geology & Geophysics	Geochemistry
Steve Carpenter	Zoology	Ecosystem studies, social-ecological modeling
Jonathan Chipman	Environmental Remote Sensing Center	Satellite remote sensing/landcover imaging
Stanley Dodson	Zoology	Community ecology, toxicology
Jonathan Foley	Atmospheric & Ocean Sciences	Regional hydrologic and biogeochemical models
Linda Graham	Botany	Eukaryotic aquatic microbiology
Paul Hanson	Limnology	Computing systems, wireless data acquisition
Roger Hammer	Rural Sociology	Population growth, residential development
Thomas Heberlein	Rural Sociology	Environmental attitudes, behaviors
Tim Kratz	Limnology	Lake landscape ecology
Dick Lathrop	Wisconsin Department of Natural Resources	Lake and watershed management
Tom Lillesand	Environmental Remote Sensing Center	Remote sensing
John Magnuson	Zoology	Fish ecology, Limnology
Pete Nowak	Rural Sociology	Agricultural systems
Robert (Bill) W. Provencher	Agricultural & Applied Economics	Economics
Emily Stanley	Zoology	Biogeochemistry, river ecology
Eric Triplett	Agronomy	Microbial ecology/function in lakes
Monica Turner	Zoology	Landscape ecology
Jake Vander Zanden	Zoology	Aquatic food web dynamics
Paul Voss	Rural Sociology	Demographic, migration modeling
John Walker	US Geological Survey	Hydrology
Chin Wu	Civil & Environmental Engineering	Physical limnology

Section 4. Information Management

Philosophy and Goals

Information management is an integral part of our research process. The NTL LTER data and information 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 ecosystems we study. Primary goals are to (1) maintain database integrity, (2) create a powerful and accessible environment for the retrieval of information, and (3) facilitate linkages among diverse data sets.

Information Management Infrastructure

NTL LTER has computer facilities at the Lake Mendota Laboratory, the Trout Lake Station, the Environmental Remote Sensing Center, and other associated laboratories. Specific details on networking, the web and database servers, backup protocols, and other components of the infrastructure are presented in Table 6 and the Facilities section of this proposal.

Personnel

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, Jonathan Chipman, has a Ph.D. in remote sensing and is appointed jointly at the Center for Limnology and the Environmental Remote Sensing Center (ERSC). A laboratory manager maintains the LAN and computers at the Center for Limnology. Two persons with backgrounds in computer science assist the information manager.

Data Sharing

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. Thus, at our site, getting researchers to contribute data to the LTER database is not an issue. Meteorological and 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 sooner.

We encourage collaborative explorations of our data (Table 2, Supplementary Documents Section). Our policy is to provide all core data prior to the most recent two years on-line on the web. Meteorological data are placed on-line as soon as they have been incorporated into the LTER database (Table 1, Supplementary Documents Section, shows the status of data availability). Our data access policy is available on the

NTL home page. Researchers who wish to access additional data or information must contact Steve Carpenter directly.

NTL Database

Most of the core data collected by NTL (Table 3) reside in the Oracle database. Other data are maintained in text or spreadsheet format. NTL spatial data are stored on file systems at ERSC and the Center for Limnology and are fully accessible to NTL researchers. Core data are available to all NTL researchers as soon as the data are entered and quality screened. 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).

Data are entered, updated and maintained in the Oracle database using scripts and applications on the Sun Sparc Ultra2 workstation as well as through use of an application installed on networked Windows workstations. Some data are entered into the Oracle database directly through an application installed on the NTL web site. Data from the Oracle database are made available for viewing and/or downloading over a network connection by several methods (see Table 6). 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).

Data Access and Analysis

The client/server environment provides researchers with the powerful search and linkage capabilities of a relational database together with an end-user query tool for simple, direct access. Currently, most researchers use an end-user query tool with a point-and-click interface. 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. An alternative way to access data is through text files available on the NTL web site (lter.limnology.wisc.edu) (Table 1). Links to on-line data are found within the on-line data catalog that also supplies the supporting metadata.

Information management staff provides support by developing data acquisition tools for technicians and data analysis for researchers. To speed data acquisition and reduce data entry errors, custom software has been written for recording fish field data, counting zooplankton, and analyzing fish scales. 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). Views are created within the Oracle database to provide researchers with useful joins of the Oracle tables.

Metadata

Metadata are a crucial part of our information system. Each on-line data set has associated header information including data set title, document update date, investigators, contact person, temporal and spatial resolution, descriptive abstract, study areas, variable description and units of measurement, variable codes, and file format. Metadata for spatial data include copyrights, map scale, thematic and map accuracy, and data lineage information. Field and lab methods are documented for each core data set and available on-line for most data sets.

We are restructuring the metadata associated with the NTL core data sets to be compliant with emerging standards, in particular, Ecological Metadata Language (EML), a metadata standard based on the emerging XML Schema specification. EML is the standard adopted by the LTER Network. The restructured NTL metadata will reside in Oracle and will be retrieved in conjunction with dynamic database access through the web.

Quality Control

A number of different 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 about the ratio of 1:10 (replicate:sample). Quality control in the chemical results is checked by ion balances, calculation of critical parameters from a redundant data set, and visual verification. Error checking occurs in the data entry software and proofreading. Data sets have a system of flags to indicate quality conditions such as non-standard routine or equipment used.

Intersite Information Management Contributions

The NTL information manager is a member of IMExec, the steering committee for the LTER Information Managers, and the LTER Network Information System working group. For the 2000 LTER All Scientists Meeting, she was chair of the Organizing Committee for Information Management Workshops and co-organizer of a workshop entitled “Partnership between Long-term Ecological Research and Information Management: Successes and Challenges” and a follow-up working group, “Advancing the Sharing and Synthesis of Ecological Data: Guidelines for Data Sharing and Integration”, (June 2001).

Future Directions and Challenges

We anticipate a long-term commitment to providing data sets on the NTL web site. The universal access of the web makes our web site the main entry point for external data distribution. We have constructed a prototype interface between the web and the Oracle database to add query functionality to data on the web site. This prototype also contains a form for users that will allow us to track data use. We propose a full implementation of this prototype.

Table 6. North Temperate Lakes LTER Information Management Infrastructure

Local Area Networks (LAN)	Windows NT LAN supporting Macintosh and Windows-based microcomputers at the Lake Mendota Laboratory and Trout Lake Station, Sun workstation, laser and color printers, slide maker, scanner *
Connection to WANs	Lake Mendota Laboratory LAN linked by a 10baseT connection to the campus-wide WAN; Trout Lake Station connected via a T1 land line
Web Server	Apache web server running on the Sun Sparc Ultra2 workstation (Solaris 7 operating system)
Database	Oracle 8.1.7 RDBMS installed on the Sun Sparc Ultra2 workstation
Data Retrieval	Oracle Browser application installed on networked Windows workstations; ODBC connections on networked workstations with installed Oracle Clients; text-formatted data on the NTL web site; dynamic query of the database through the NTL website (meteorological data).
System Backup	Daily backups of the Sun workstation to DAT tape; daily Oracle database exports; regular backups to tape of data on microcomputers; backups of spatial data to CD-ROM
Wireless Communication	Serial to field equipment/sensors; Ethernet for computers and some sensor systems
Video Conferencing Equipment	PC with Microsoft NetMeeting software, video camera, computer projector, document scanner, electronic tablet
Remote Sensing	Space Science and Engineering Center (SSEC) X-band satellite receiving antenna and ingest capability

* Computer facilities at the Center for Limnology are described at limnology.wisc.edu/Lake_Mendota_Lab/computerroom.htm

Section 5: Outreach

NTL-LTER personnel have engaged in many important outreach and professional service activities, and will continue to do so. In this section we describe our educational and public activities, media interactions, and implications of our research to policy and management.

The main focus of our educational activities is and will continue to be graduate student training. Graduate students are an intrinsic component of NTL-LTER research who figure prominently throughout our proposal. LTER funds supported 30 M.S. and Ph.D. students over the past six years who produced a total of 28 theses. These LTER-students have been highly successful in research productivity, in obtaining additional non-NTL-LTER support, and in obtaining post-graduate positions. The contribution of graduate students to NTL-LTER is highly valued and will always be encouraged.

Our program provides undergraduate students with extensive and rewarding first-hand research experiences. We involve 3-5 Research Experience for Undergraduate (REU) students every year in our summer LTER and related activities. We employ undergraduates as hourly workers to assist with summer field and laboratory work. We solicit applications for these positions from around the US and Canada. Our summer crews typically include an internationally diverse group. Many of our summer undergraduates continue on to graduate work in environmental science; we recruited several of these undergraduates to our own graduate programs. We encourage University of Wisconsin-Madison undergraduates to apply for university sponsored, summer environmental fellowships for independent research projects. Their projects often result in publishable papers. A large number of graduate students and recent Ph.D.'s trace their roots to early experiences with the NTL-LTER program. In addition to undergraduates involved directly with research, an additional 300 undergraduates each year take classes taught by NTL-LTER principal investigators and featuring NTL-LTER data. NTL-LTER data published on the web are also used by faculty at other universities in support of their teaching.

Our Schoolyard LTER program partners with six elementary and middle schools in the Trout Lake and Madison areas. Called "Limnology Explorers", the program provides hands-on lab and field experience for third and seventh graders as well as teacher training with an emphasis on winter limnology (Figure 30). These activities are led by NTL-LTER staff in partnership with the UW-Madison Center for Biology Education and the UW-Madison School of Education Outreach Saturday Enrichment Program. From participant evaluation surveys, we know that parents and students are enthusiastic about the program. Schoolyard LTER funds have been leveraged with a Dwight D. Eisenhower Professional Development Program grant awarded to Dr. Robert Bohanan at the Center for Biology Education to develop SchoolYard Science: Inquiry-Based Workshops and Research Experiences for Middle School Teachers (SYS). This program is closely allied with our Schoolyard LTER and has provided summer research experiences, curriculum development, and pedagogy workshops for practicing teachers as well as undergraduates majoring in Education.

We are also heavily involved in informal education activities. We participate annually in community activities such as leading popular nature walks; making public presentations on limnology and ecology to service organizations, lake associations and local governmental bodies; working with local to national print media to develop stories related to limnology; giving presentations to Elderhostel groups; and participating in a Northern-Highland-wide lake fair, where local residents and visitors are exposed to a variety of aquatic organisms and processes. We have open houses at the Trout Lake Station where homeowners from individual lakes are invited to discuss "their" lake and the research we are doing. NTL scientists appear on local and statewide radio and television shows to discuss water-related issues. NTL science has been featured prominently in each of the Madison Magazine's monthly "Lake Effect" columns since its inaugural issue in January 2001. NTL research was highlighted on the Wisconsin Public Television show *Weekend*. The roughly six-minute clip showed LTER field sampling and discussed important research findings. These activities will continue.

We have deployed a sophisticated, state-of-the-art, instrumented buoy on Trout Lake. Real time data from this buoy (30 second updates) are available to the general public via the world wide web. In addition, almost all of our core data sets two years or older are publicly available via our web page.

NTL-LTER researchers participate in a wide range of professional activities such as service to National Research Council committees, the Millennium Ecosystem Assessment, State of Wisconsin Department of Natural Resources committees, the Nature Conservancy, and the Leopold Memorial Reserve. NTL-LTER personnel are active in national and international professional societies, particularly the Ecological Society of America, the American Society of Limnology and Oceanography, and the North American Lake Management Society. NTL scientists have briefed local, state, and federal elected officials on water-related issues. We are frequent reviewers of grant proposals to the National Science Foundation and other funding agencies and routine participants on review panels. Many other such activities could be listed.

Understanding the long-term dynamics of lakes allows us characterize the natural variability that lakes exhibit. Individuals and institutions can use this information to assess effects of existing or proposed changes in reference to the bounds of natural variability. Project scientists have interacted with various local, state, and federal policymakers to discuss how NTL-LTER results are useful in formulation of policy. Examples include interacting with the local County Board to explain the utility of our science to local resource management and the local economy, interacting with state agencies to develop sound policies towards exotic species, and communicating with congressional staff on issues of water resource management.

In the next six years we will continue and expand upon our education and outreach activities.

Section 6. Literature Cited

Anderson, W.L., D.M. Robertson, and J.J. Magnuson (1996). Evidence of recent warming and El Nino-related variation in ice breakup of Wisconsin lakes. Limnology and Oceanography 41(5): 815-21.

Andrews, J. (1986). Nuisance vegetation in the Madison lakes; current status and options for control. Committee Report, printed by the Institute for Environmental Studies & Center for Limnology, University of Wisconsin-Madison.

Araujo, M., D. Dartus, P. Maurel, and L. Masbernat (2001). Langmuir Circulations and enhanced turbulence beneath wind-waves, Ocean Modeling, 3(1-2): 109-126.

Arnott, S. E., N.D. Yan,J.J. Marnuson and T.M. Frost (1999). Interannual variability and species turnover of crustacean zooplankton in Shield lakes. Canadian Journal of Fisheries and Aquatic Sciences 56: 162-172.

Arnott, S. E., J.J. Magnuson and N.D. Yan (1998). Crustacean zooplankton species richness: single-and multiple-year estimates. Canadian Journal of Fisheries and Aquatic Sciences 55: 1573-1582.

Azumaya, T., Y. Isoda and N. Shinichiro (2001). Modeling of the spring bloom in Funka Bay, Japan. Continental Shelf Research 21: 473-494.

Baines, S. B., K. E. Webster, T. K. Kratz, S. R. Carpenter and J. J. Magnuson (2000). Synchronous behavior of temperature, calcium and chlorophyll in lakes of northern Wisconsin. Ecology 81:815-825.

Baker P.D., D.A. Steffensen, A.R. Humpage, B.C. Nicholson, I.R. Falconer, B. Lanthois, K.M. Fergusson, C.P. Saint (2001). Preliminary evidence of toxicity associated with the benthic cyanobacterium Phormidium in South Australia. Environmental Toxicology 16(6): 506-511.

Beard, T.D., S. Cox and S.R. Carpenter (in review). Impacts of bag limit regulations on angler effort responses in Wisconsin walleye lakes and implications for management. North American Journal of Fisheries Management.

Bees, M.A. (1998). Planktonic communities and chaotic advection in dynamical models of Langmuir circulation. Applied Scientific Research 59(2-3): 141-158.

Bennett, E.M., T. Reed-Andersen, J.N. Houser, J.R. Gabriel and S.R. Carpenter (1999). A phosphorus budget for the Lake Mendota watershed. Ecosystems 2: 69-75.

Bennett, E.M., S.R. Carpenter and N.F. Caraco (2001). Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience 51: 227-234.

Bennett, E. M. (2002). Patterns in Soil Phosphorus: Variability and Concentrations in an Urbanizing Agricultural Watershed. PhD Thesis. Limnology and Marine Sciences. University of Wisconsin-Madison.

Benson, B.J., J.J. Magnuson, R.L. Jacob and S.L. Fuenger (2002). Response of lake ice breakup in the Northern Hemisphere to the 1976 interdecadal shift in the North Pacific. Verh. Int. Ver. Limnol. 27: in press.

Bertilsson, A., and M. Polz (2001). Application of a diversity array to study specific substrate utilization in individual populations of aquatic heterotrophic bacteria. Presented at the 9th International Symposium on Microbial Ecology, Amsterdam, The Netherlands.

Betz, C.R., M.L. Lowndes, and S. Porter (1997). Nonpoint source control plan for the Lake Mendota Priority Watershed Project. Project Summary, Wis. Dep. Nat. Resour. Publ. No. WT-481-97.

Bowman, J.P., S.A. McCammon, S.M. Rea and T.A. McMeekin (2000). The microbial composition of three limnologically disparate hypersaline Antarctic lakes. FEMS Microbiol. Lett. 183:81-88.

Boxall, P.C. and W.L. Adamowicz (1999). Understanding Heterogeneous Preferences in Random Utility Models: The Use of Latent Class Analysis. Staff Paper no. 99-02, Department of Rural Economy, University of Alberta.

Brock, T.D. (1985). A eutrophic lake: Lake Mendota, Wisconsin. New York, Springer-Verlag.

Bullen, T.D., D.P. Krabbenhoft and C. Kendall (1996). Kinetic and mineralogic controls on the evolution of groundwater chemistry and 87sr/86sr in a sandy silicate aquifer, northern Wisconsin. Geochim. et Cosmochim. Acta 60: 1807-1821.

Carpenter, S.R. (2001). Alternate states of ecosystems: Evidence and its implications. Ecology: Achievement and Challenge. M.C. Press, N. Huntly and S. Levin. London, Blackwell: 357-383.

Carpenter, S.R. (2002). Ecological futures: building an ecology of the long now. Ecology: in press. Available on the internet: http://www.limnology.wisc.edu/macarthur/ecofutures.pdf

Carpenter, S.R. and L.H. Gunderson (2001). Coping with collapse: Ecological and social dynamics in ecosystem management. BioScience 51: 451-458.

Carpenter, S.R., D. Ludwig and W.A. Brock (1999). Management of eutrophication for lakes subject to potentially irreversible change. Ecological Applications 9: 751-771.

Carpenter, S.R. and P.R. Leavitt (1991). Temporal Variation in a Paleolimnological Record Arising From a Trophic Cascade. Ecology 72:277-285.

Chen, H.Z. and S.R. Coslett (1998). Environmental Quality Preference and Benefit Estimation in Multinomial Probit Models: A Simulation Approach. American Journal of Agricultural Economics 80: 512-520.

Cheng, X. and M. P. Anderson (1993). Numerical simulation of ground-water interaction with lakes allowing for fluctuating lake levels. Ground Water 31: 929-33.

Cheng, X. and M. P. Anderson (1994). Simulating the influence of lake position on groundwater fluxes. Water Resources Research 30(7): 2041-9.

Chorus, I., I.R. Falconer, H.J. Salas, and J. Bartram (2000). Health risks caused by freshwater cyanobacteria in recreational waters. Journal of Toxicology and Environmental Health-Part B-Critical Reviews 3(4): 323-347.

Christensen, D. L., B. R. Herwig, Schindler D.E. and S.R. Carpenter. (1996). Impacts of lakeshore residential development of coarse woody debris in north temperate lakes. Ecological Applications 6(4): 1143-1149.

Clark, J.S., S.R. Carpenter, M. Barber, S. Collins, A. Dobson, J.A. Foley, D.M. Lodge, M. Pascual, R. Pielke Jr., W. Pizer, C. Pringle, W.V. Reid, K.A. Rose, O. Sala, W.H. Schlesinger, D.H. Wall, and D. Wear (2001). Ecological Forecasts: An Emerging Imperative. Science 293(5530):657-660.

Cole, J. C. and N.F. Caraco (2001). Carbon in catchments: connecting terrestrial carbon losses with aquatic metabolism. Mar. Freshwater Res. 52: 101-110.

Cole, J. J., N.F. Caraco, G.W. Kling and T.K. Kratz (1994). Carbon dioxide supersaturation in the surface waters of lakes. Science. 265: 1568-1570.

Coe, M.T. (2000). Modeling terrestrial hydrologic systems at the continental scale: Testing the accuracy of an atmospheric GCM. Journal of Climate 13: 686-704.

Coe, M.T. and J.A. Foley (2001). Human and natural impacts on the water resources of the Lake Chad basin. Journal of Geophysical Research (Atmospheres) 106 (D4): 3349-3356.

Cox, S.P., T.D. Beard and C.J. Walters (2002). Harvest control in open access sport fisheries: hot rod or asleep at the reel? Bulletin of Marine Science: in press.

Creed I.F. and L.E. Band (1998a). Exploring functional similarity in the export of nitrate-N from forested catchments: A mechanistic modeling approach. Water Resources Research 34(11): 3079-3093.

Creed I.F. and L.E. Band (1998b). Export of nitrogen from catchments within a temperate forest: Evidence for a unifying mechanism regulated by variable source area dynamics. Water Resources Research 34(11): 3105-3120.

Cushing, C.E. (1997). Freshwater ecosystems and climate change in North America, a regional assessment. Advances in Hydrological Processes. New York, John Wiley & Sons. or Hydrological Processes-An International Journal 11:819-1067.

del Giorgio, P. A., J.J. Cole and Andre Cimbleris (1997). Respiration rates in bacteria exceed phytoplankton production in unproductive aquatic systems. Nature. 385: 148-151.

del Giorgio, P. A. and R.H. Peters (1993). Balance between phytoplankton production and plankton respiration in lakes. Can. J. Fish. Aquat. Sci. 50: 282-289.

Dent, C.L., G.S. Cumming and S.R. Carpenter (2002). Multiple states in river and lake ecosystems. Philosophical Transactions of the Royal Society, Series B: in press.

DeSilva, I.P.D., Imberger J. and Ivey G.N. (1997). Localized mixing due to a breaking internal wave ray at a sloping bed. Journal of Fluid Mechanics 350:1-27.

De Stasio, J., Bart T. , D. K. Hill, J. M. Kleinhaus, N. P. Nibbelink and J. J. Magnuson (1996). Potential effects of global climate change on small north-temperate lakes: physics, fish, and plankton. Limnology and Oceanography 41(5): 1136-49.

Detenbeck, N., C. A. Johnston, and G. Niemi. 1993. Wetland effects on lake water quality in the Minneapolis/St. Paul metropolitan area. Landscape Ecology 8:39-61.

Dillon, P. J. and L.A. Molot (1997). Dissolved organic and inorganic carbon mass balances in central Ontario lakes. Biogeochemistry. 36: 29-42.

Dodson, S.I. S.E. Arnott and C.L. Cottingham (2001). The Relationship in Lake Communities between Primary Productivity and Species Richness. Ecology 81:2662-2679.

Donner, S.D., M.T. Coe, J.D. Lenters, T.E. Twine and J.A. Foley (2002). Modeling the impact of hydrologic changes on nitrate transport in the Mississippi River basin from 1955-1994. Global Biogeochemical Cycles: in press.

Dripps, W. R. In preparation (expected May 2002). The Spatial and Temporal Variability of Natural Groundwater Recharge, PhD. University of Wisconsin – Madison, Department of Geology and Geophysics.

Elder, J.F., N.B. Rybicki, V. Carter and V. Weintraub (2000). Sources and Yields of Dissolved Carbon in Northern Wisconsin Stream Catchments with Differing Amounts of Peatland: Wetlands 20(1): 113-125.

Ennet, P., H. Kuosa and R. Tamsalu (2000). The influence of upwelling and entrainment on the algal bloom in the Baltic Sea. Journal of Marine Systems 25(3-4) 359-367.

Etemad-Shahidi, A. and J. Imberger (2001). Anatomy of turbulence in thermally stratified lakes. Limnol. Oceanogr 46 (5): 1158-1170.

Foley, J.A., I.C. Prentice, N. Ramankutty, S. Levis, D. Pollard, S. Sitch, and A. Haxeltine (1996). An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. Global Biogeochemical Cycles 10(4), 603-628.

Forney,J.L. (1980). Evolution of a management strategy for the walleye in Oneida Lake, New York. N. Y. Fish Game J. 27: 105-141.

Franke, U., K. Hutter and K. Johnk (1999). A physical-biological coupled model for algal dynamics in lakes. Bulletin of Math. Biology 61(2): 239-272.

Frey, D.G. (1963). Limnology in North America. Madison, University of Wisconsin Press.

Gergel, S.E., 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.

Hammer, Roger B., Paul R. Voss and Volker C. Radeloff. (in review, a). Approximating Geographic Patterns of Residential Development from 1940 to 1990 in Wisconsin's North Woods. Rural Sociology.

Hammer, Roger B., David D. Long and Paul R. Voss. (in review, b). When Census Geography Doesn't Work: Using Ancillary Information to Improve the Spatial Interpolation of Demographic Data. Society and Natural Resources.

Hessen, D.O. (1992). Dissolved organic carbon in a humic lake: effects on bacterial production and respiration. Hydrobiologia 229: 115-123.

Hobbie, J., S. Carpenter, N. Grimm, J. Gosz and T. Seastedt (in review). The U.S. Long-Term Ecological Research program. BioScience.

Holling, C.S. (1995). Investing in research for sustainability. Ecol. Appl. 3:552-555.

Honda D., A.Yokota, and J. Sugiyama (1999). Detection of seven major evolutionary lineages in cyanobacteria based on the 16S rRNA gene sequence analysis with new sequences of five marine Synechococcus strains. Journal of Molecular Evolution 48: 723-739.

Hrabik, T.R., M.P. Carey and M.S. Webster (2001). Interactions between young-of-the-year exotic rainbow smelt and native yellow perch in a northern temperate lake. Transactions of American Fisheries Society 130:568-582.

Hrabik, T.R. and J.J. Magnuson (1999). Simulated dispersal of exotic rainbow smelt (Osmerus mordax) in a northern Wisconsin lake district and implications for management. Canadian Journal of Fisheries and Aquatic Sciences 56(1):35-42.

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.

Huisman, J., P. van Oostveen and F.J. Weissing (1999). Critical depth and critical turbulence: Two different mechanisms for the development of phytoplankton blooms, Limnol. Oceanogr. 44 (7): 1781-1787.

Hunsaker, C. T., and D. A. Levine. 1995. Hierarchical approaches to the study of water quality in rivers. Bioscience 45:193-203.

Hunt, K.M. and R.B. Ditton (1997). The social context of site selection for freshwater fishing. North American Journal of Fisheries Management 17: 331-338.

Hunt, R.J., M.P. Anderson, and V.A. Kelson (1998). Improving a complex finite-difference ground water flow model through the use of an analytic element screening model. Ground Water 36(6): 1011-1017.

IPCC (2001). Climate Change 2001: The Scientific Basis. Cambridge, England, Cambridge University Press.

Jackson, D., P. Peres-Neto and J. Olden (2001a). What controls who is where in freshwater fish communities - the roles of biotic, abiotic, and spatial factors. Canadian Journal of Fisheries and Aquatic Sciences 58:157-170.

Jackson, J.B.C. and 18 co-authors (2001b). Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629-638.

Jansson, M., A.K. Bergstrom, P. Blomqvist and S. Drakare (2000). Allochthonous organic carbon and phytoplankton/bacterioplankton production relationships in lakes. Ecology 81(11): 3250-3255.

Johnson, L. B., C. Richards, G. Host, and J. W. Arthur. 1997. Landscape influences on water chemistry in Midwestern streams. Freshwater Biology 37:193-208.

Jones, R. I. (1992). The influence of humic substances on lacustrine planktonic food chains. Hydrobiologia 229: 73-91.

Kalff, J. (2001). *Limnology*. Prentice-Hall, New Jersey.

Kasprzak P., R.C. Lathrop and S.R. Carpenter (1999). Influence of different-sized *Daphnia* species on chlorophyll concentration and summer phytoplankton community structure in eutrophic Wisconsin lakes. J. Plankton Res. 21:2161-2174.

Kim, K., M.P. Anderson and C.J. Bowser (1999). Model calibration with multiple targets: a case study. Groundwater 37: 345-351.

King, J., B. Shuter and A. Zimmerman (1999). Empirical Links between Thermal Habitat, Fish Growth, and Climate Change. Transactions of the American Fisheries Society 128:656-665.

Kitchell, J.F. (1992). Food web management: a case study of Lake Mendota. New York, Springer-Verlag.

Kling, G.W., G.W. Kipphut, and M.C. Miller (1991). Arctic lakes and streams as gas conduits to the atmosphere: Implications for tundra carbon budgets. Science. 251: 298-301.

Kling, G. W., G.W. Kipphut, and M.C. Miller (1992). The flux of CO2 and CH4 from lakes and rivers in arctic Alaska. Hydrobiologia. 240: 23-36.

Kling, G. W., G.W. Kipphut, M.M. Miller, and W.J. O'Brien. 2000. Integration of lakes and streams in a landscape perspective: the importance of material processing on spatial and temporal coherence. Freshwater Biology 43:477-498.

Kolar, C. and D.M. Lodge (2000). Freshwater nonindigenous species: interactions with other global changes. Invasive Species in a Changing World. H.A. Mooney and R.J. Hobbs. Washington D.C., Island Press: 3-30.

Kolar, C. and D.M. Lodge (2001). Progress in invasion biology: predicting invaders. Trends in Ecology and Evolution 16: 199-204.

Kononen, K., J. Kuparinin, K. Makela, J. Laanemts and J. Pavelson (1996). Initiation of cyanobacterial blooms in a frontal region at the entrance to the Gulf of Finland, Baltic Sea. Limnol. Oceanogr. 41:98-112.

Krabbenhoft, D.P., J.M. Benoit, C.L Babiarz, J.P. Hurley and A.W. Andren (1995), Mercury Cycling in the Allequash Creek Watershed, Northern Wisconsin: Water, Air, and Soil Pollution 80:425-433.

Kratz, T. K., B. P. Hayden, B. J. Benson and W. Y. B. Chang (2002a). Patterns in the interannual variability of lake freeze and thaw dates. Verh. Internat. Verein. Limnol. 27: in press.

Kratz, T. K., D. W. Bolgrien, S. Giblin, and J. O'Leary. (2002b). Human iInfluences on the spatial distribution of coarse woody debris in lakes in northern Wisconsin, USA. Verh. Internat. Verein. Limnol.: in press.

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: 209-17.

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 Research Program. Rationale for Sampling and Interpretation of Ecological Data in the Assessment of Freshwater Systems. B.G. Isom. Philadelphia, ASTM STP 894 American Society for Testing and Materials: 22-33.

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(3):795-825.

Lathrop R.C., S.R. Carpenter, C.A. Stow, P.A. Soranno, J.C. Panuska (1998). Phosphorus loading reductions needed to control blue-green algal blooms in Lake Mendota. Canadian Journal of Fisheries and Aquatic Sciences 55(5): 1169-1178.

Lathrop, R.C. and S.R. Carpenter (1992). Phytoplankton and their relationship to nutrients. Food web management: a case study of Lake Mendota, Wisconsin. J.F. Kitchell. New York, Springer-Verlag: 99-128.

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(1): 137-46.

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.

Leibold, M.A. (1999). Biodiversity and nutrient enrichment in pond plankton communities. Evolutionary Ecology Research, 1: 73-95.

Lenters, J.D., M.T. Coe, and J.A. Foley (2000). Surface water balance of the continental United States, 1963-1995: regional evaluation of a terrestrial biosphere model and the NCEP/NCAR reanalysis. Journal of Geophysical Research-Atmospheres 105 (D17): 22393-22425.

Likens, G. E. 1985. An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag. New York. 516pp.

Likens, G.E. (1989). *Long-Term Studies in Ecology*. Springer-Verlag, NY.

Likens, G.E. (2001). Ecosystems: energetics and biogeochemistry. A New Century of Biology. W.J. Kress and G.W. Barrett. Washington, Smithsonian Institution Press: 53-88 .

Lillesand, T.M., J. Riera, J. Chipman, J. Gage, M. Janson, J. Panuska and K. Webster. (2001). Integrating multi-resolution satellite imagery into a satellite lake observatory. Proceedings of the Annual Meeting of the American Society for Photogrammetry and Remote Sensing (ASPRS), St. Louis, MO.

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.

Litchman, E. and C.A. Klausmeier (2001). Competition of phytoplankton under fluctuating light, American Naturalist 157(2): 170-187.

Livingstone, D.M. (2002). Large-scale climatic forcing detected in historical observations of lake ice breakup. Verh. Int. Ver. Limnol. 27: in press.

Lodge, D.M. (2001). Lakes. Pages 277-313 in F.S. Chapin III, O.E. Sala and E. Huber-Sannwald (editors), Global Biodiversity in a Changing Environment: Scenarios for the 21st Century. Springer-Verlag, NY.

Lodge, D.M., C.A. Taylor, D.M. Holdich and J. Skurdal (2000). Nonindigenous crayfishes threaten North American freshwater biodiversity: lessons from Europe. Fisheries 25: 7-20.

Lodge, D.M. and J.G. Lorman (1987). Reductions in submersed macrophyte biomass and species richness by the crayfish *Oronectes rusticus*. Canadian Journal of Fisheries and Aquatic Sciences 44:591-597.

Lodge, D.M., T.K. Kratz and G.M. Capelli (1986). Long-term dynamics of three crayfish species in Trout Lake, Wisconsin. Canadian Journal of Fisheries and Aquatic Sciences 43:993-998.

Loreau, M., S. Naeem, P. Inchausti, J. Bengtsson, J.P. Grime, A. Hector, D.U. Hooper, M.A. Huston, D. Rafaelli, B. Schmid, D. Tilman and D.A. Wardle. 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294: 804-808.

Ludyanskiy, M.L., D. McDonald, and D. MacNeil (1993). Impact of the zebra mussel, a bivalve invader. BioScience 43:533-544.

MacIsaac, H.J. (1996). Potential abiotic and biotic impacts of zebra mussels on the inland waters of North America. American Zoologist 36:287-299.

Magnuson, J. J. (2002). Signals from Ice Cover Trends and Variability. in Fisheries in a Changing Climate. Special Publication, American Fisheries Society, Washington D.C.: in press.

Magnuson, J.J. and T. Kratz (2000). Lakes in the landscape approaches to regional limnology. Verh. Internat. Verein. Limnol. 27:74-87.

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., B.J. Benson and A.S. McLain (1994). Insights on species richness and turnover from long-term ecological research: Fishes in north temperate lakes. American Zoologist 34:437-451.

Magnuson, J.J. (1990). Long-term ecological research and the invisible present. Bioscience 40:495-501.

Magnuson, J.J. and C.J. Bowser (1990). A network for long-term ecological research in the United States. Freshw. Biol. 23:137-143.

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 23:145-59.

Miranda, L.E. and W. Freese (1991). Can fishery scientists predict angler preferences? American Fisheries Society Symposium 12: 375-379.

Naiman, R. J. and M. G. Turner. 2000. A future perspective on North America's freshwater ecosystems. Ecological Applications 10:958-970.

National Research Council. 2001. Grand Challenges in the Environmental Sciences. National Academy Press, Washington DC.

Nichols, S.A., R.C. Lathrop and S.R. Carpenter (1992). Long-term vegetation trends: a history. Food Web Management – A Case Study of Lake Mendota. Kitchell, J.F. New York, Springer-Verlag: 151-172

Nowak, P. and P. Korsching (1998). The human dimension of soil and water conservation: a historical and methodological perspective. Advances in Soil and Water Conservation. F. J. Pierce and W. W. Frye. Chelesa, MI, Ann Arbor Press: 159-84.

Nowak, P.F. Madison and R. Shepard (1998). Farmers and manure management: a critical analysis. Animal Waste Utilization: Effective Use of Manure as a Soil Resource. J. Hatfield and B. Stewart. Chelesa, MI, Ann Arbor Press: 1-32.

Nürnberg, G. (1984). Prediction of internal phosphorus load in lakes with anoxic hypolimnia. Limnology and Oceanography 29: 135-145.

Olsen, N.R.B., R.D. Hedger and D.G. George (2000). 3D numerical modeling of Microcystis distribution in a water reservoir. Journal of Environmental Engineering 126(10): 949-953.

Paerl, H.W. (1997). Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. Limnol Oceanogr. 42 (5): 1154-1165.

Palmquist, R.B. (1991). Hedonic Methods. Measuring the demand for environmental quality. J.B. Braden and C.D. Kolstad. New York, Elsevier: 77-120.

Persson, L., J. Bengtsson, B.A. Menge, and M.E. Power (1996). Productivity and consumer regulation-concepts, patterns and mechanisms. Food webs: integration of patterns and dynamics. G. A. Polis and K. O. Winemiller. New York, Chapman and Hall.

Peterson, G.D. (2002). Contagious disturbance, ecological memory, and the emergence of landscape pattern. Ecosystems 5: in press.

Pinckney, J.L., H.W. Paerl and M.B. Harrington (1999). Responses of the phytoplankton community growth rate to nutrient pulses in variable estuarine environments. J. Physiology 35(6): 1455-1463.

Poor, P. J., K. J. Boyle, L.O. Taylor and R. Bouchard (2001). Water clarity in hedonic property value models. Land Economics 77: 482-493.

Provencher, B. and R.C. Bishop (2001). Using Static Recreation Demand Models to Forecast Angler Responses to Interseasonal Changes in Catch Rates. Manuscript, University of Wisconsin, Madison. Available on the internet: http://www.aae.wisc.edu/provencher.

Provencher, B., K. Baerenklau and R.C. Bishop (2001). A Finite-Mixture, Markov-Logit Model of Recreational Angling with Serially-Correlated Random Utility. Manuscript, University of Wisconsin, Madison. Available on the internet: http://www.aae.wisc.edu/provencher.

Radomski, P.J., G.C. Grant, P.C. Jacobson and M.F. Cook (2001). Visions for recreational fishing regulations. Fisheries 26: 469-480.

Raymond, P.A., N.F. Caraco and J.J. Cole (1997). Carbon dioxide concentration and atmospheric flux in the Hudson River. Can. J. Fish. Auat. Sci. 20(2): 381-390.

Reed-Andersen, T., E. M. Bennett, B. S. Jorgensen, G. Lauster, D. B. Lewis, D. Nowacek, J. L. Riera, B. L. Sanderson and R. Stedman (2000a). Distribution of recreational boating across lakes : do landscape variables affect recreational use? Freshwater Biology 43: 439-48.

Reed-Andersen, T., S.R. Carpenter, D.K. Padilla and R.C. Lathrop (2000b). Predicted impact of zebra mussel (*Dreissena polymorpha*) invasion on water clarity in Lake Mendota. Canadian Journal of Fisheries and Aquatic Sciences 57:1617-26.

Reynolds, C.S. (1997). Vegetation Processes in the Pelagic: A Model for Ecosystem Theory. Ecology Institute, Oldendorf/Luhe, Germany.

Ricciardi, A. and H.L. MacIsaac (2000). Recent mass invasion of the North American Great Lakes by Ponto-Caspian species. Trends in Ecology and Evolution 15: 62-65.

Ricker, W. E. (1954). Stock and Recruitment. Journal of the Fisheries Research Board of Canada. 11:559-623.

Riera J.L., J.J. Magnuson, T.K. Kratz, and K.E. Webster (2000). A geomorphic template for the analysis of lake districts applied to the Northern Highland Lake District, Wisconsin, USA. Freshwater Biology 43(3):301-318.

Robertson, D.M., R.H. Wynne, and Y.B. Chang (2002). Influences of El Nino on lake and river ice cover in the Northern Hemisphere from 1990 to 1997. Verh. Int. Ver. Limnol. 27: in press.

Robertson, D.M. (1989). The use of lake water temperature and ice cover as climatic indicators. Ph.D. University of Wisconsin - Madison.

Roland, F., and J.J. Cole (1999). Regulation of bacterial growth efficiency in a large turbid estuary. Aquatic Microbial Ecology 20(1): 31-38.

Rosen, S. (1974). Hedonic prices and implicit markets: product differentiation in pure competition. Journal of Political Economy 82:34-55.

Rutherford, E.S., K.A. Rose, E.L. Mills, J.L. Forney, C.M. Mayer, and L.G. Rudstam (1999). Individual-based model simulations of a zebra mussel (*Dreissena polymorpha*) induced energy shunt on walleye (*Stiostedion vitreum*) and yellow perch (*Perca flavescens*) populations in Oneida Lake, New York. Canadian Journal of Fisheries and Aquatic Sciences 56:2148-2160.

Sanderson, B., T. Hrabik, J. Magnuson and D. Post (1999). Cyclic dynamics of a yellow perch (Perca flavescens) population in an oligotrophic lake: evidence for the role of intraspecific interactions. Canadian Journal of Fisheries and Aquatic Sciences 56:1534-1542.

Scheffer, M., S. R. Carpenter, J. Foley, C. Folke and B. Walker (2001). Stochastic events can trigger large state shifts in ecosystems with reduced resilience. Nature 413: 591-596.

Schnaiberg, J., J. Riera, M. G. Turner and P. R.Voss (2002). Explaining human settlement patterns in a recreational lake district: Vilas County, Wisconsin, USA. Environmental Management: In press.

Shuter, B. and J. Post (1990). Climate, population viability, and the zoogeography of temperate fishes. Transactions of the American Fisheries Society 119:314-336.

Smith, V.H. (1998). Cultural eutrophication of inland, estuarine and coastal waters. Successes, Limitations and Frontiers in Ecosystem Science. M.L. Pace and P.M. Groffman. New York, Springer-Verlag: 7-49.

Soranno, P.A., K.E. Webster, J.L. Riera, T.K. Kratz, J.S. Baron, P. Bukaveckas, G.W. Kling, D. White, N. Caine, R.C. Lathrop and P. Leavitt (1999). Spatial variation among lakes within landscapes: ecological organization along lake chains. Ecosystems 2:395-410.

Soranno, P.A. (1997). Factors affecting the timing of surface scums and epilimnetic blooms of blue-green algae in a eutrophic lake, Can. J Fish. Aquat. Sci., 54 (9): 1965-1975.

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 pattern of land use. Ecological Applications 6: 865-878.

Spalatro, F. and B. Provencher (2001). An analysis of minimum frontage zoning to preserve lakefront amenities. Land Economics 77: 469-481.

Stauffer, R. E. (1987). Vertical nutrient transport and its effects on epilimnetic phosphorus in 4 calcareous lakes. Hydrobiol 154: 87-102.

Steinhart, G., R. Stein and E. Marschall (2001). Weathering the storm: synergistic effects of storms, angling, and predators on largemouth bass nest success. Ecological Society of America 86th Annual Meeting, Madison, WI, Ecological Society of America.

Strayer, D.L., N.F. Caraco, J.J. Cole, S. Findlay, and M.L. Pace (1999). Transformation of freshwater ecosystems by bivalves. BioScience 49:19-27.

Steele, J.H. (1998). Regime shifts in marine ecosystems. Ecological Applications 8: S33-S36.

Stumborg, B. E., K. A. Baerenklau and R. C. Bishop. (2001). Nonpoint source pollution and present values: a contingent valuation of Lake Mendota. Review of Agricultural Economics, 23(Spring/Summer): 120-132.

Train, K.E. (1999). Mixed Logit Models for Recreation Demand. Valuing Recreation and the Environment: Revealed Preference Methods in Theory and Practice. J.A. Herriges and C.L. Kling. Edward Elger : 121-139.

Trenberth, K.E. (2000). Stronger Evidence of Human Influences on Climate. Environment 43:8-19.

Turner, M. G. (2002). Modeling for synthesis and integration: forests, people and riparian coarse woody debris. Understanding ecosystems: the role of quantitative models in observation, synthesis and prediction. C. Canham and W. Lauenroth. Princeton New Jersey, University Press: In press.

Turner, M.G., S. Collins, A. Lugo, J. Magnuson, S. Rupp and F. Swanson (in review). Long-term ecological research on disturbance and ecological response. Submitted to BioScience.

Turner, M.G., R.H. Gardner and R.V. O'Neill (2001). Landscape Ecology in Theory and Practice. Springer-Verlag, NY.

Vadeboncoeur, Y., M. J. Vander Zanden, et al. (2002). Putting the lake back together: Reintegrating benthic pathways into lake food webs. BioScience: in press.

Vadeboncoeur, Y., D.M. Lodge and S.R. Carpenter (2001). Whole-lake fertilization effects on the distribution of primary production between benthic and pelagic habitats. Ecology 82: 1065-1077.

Van Winkle, W., K. Rose, B. Shuter, H. Jager and B. Holcomb (1997). Effects of climatic temperature change on growth, survival, and reproduction of rainbow trout: Predictions from a simulation model. Canadian Journal of Fisheries and Aquatic Sciences 54:2526-2542.

Vander Zanden, M. J. and Y. Vadeboncoeur (2002). Fishes as integrators of benthic and pelagic food webs in lakes. Ecology: in press.

Verhagen, J.H.G. (1994). Modeling the photoplankton patches under the influence of wind-driven-currents in Lakes, Limnol. Oceanogr. 39(7): 1551-1565.

Waide, R.B., M. R. Willig, C. F. Steiner, G. Mittelbach, L. Gough, S. I. Dodson, G. P. Juday, and R. Parmenter (1999). The relationship between productivity and species richness. Annual Review of Ecology and Systematics 30: 257-300.

Walker, J.F. and D.P. Krabbenhoft (1998). Groundwater and surface-water interactions in riparian and lake-dominated systems. Isotope tracers in catchment hydrology. J.J. McDonnell and C. Kendall. Amsterdam, The Netherlands, Elsevier: 467-488.

Watson, V.J. and O.L. Loucks (1979). An Analysis of Turnover Times in a Lake Ecosystem and Some Implications for System Properties. Theoretical Systems Ecology. E. Halfon. New York, Academic Press: 355-383.

Wear, D. N., M. G. Turner, and R. J. Naiman (1998). Institutional imprints on a developing forested landscape: implications for water quality. Ecological Applications 8:619-630.

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, J.J. Magnuson, W.J. Rose (1996). The influence of landscape position on lake chemical responses to drought in northern Wisconsin. Limnology and Oceanography 41(5): 977-984.

Wegener, M. (2001). Long-term land use/cover change patterns in the Madison Lakes area and their impacts on runoff volume to Lake Mendota. M.S. Thesis. University of Wisconsin, Madison.

Wetzel, R. G. (1983). Limnology 2nd Ed. Saunders College Publishing. Philadelphia. 767pp.

Wilson, K.A. (2001). Community impacts of the invasive rusty crayfish (*Orconectes rusticus*) in northern Wisconsin lakes. PhD. Department of Zoology. Madison, University of Wisconsin. 160pp.

Wilson, M.A. and S.R. Carpenter (1999). Economic valuation of freshwater ecosystem services in the United States, 1977-1997. Ecological Applications 9: 772-783.

Facilities, Equipment & Other Resources

Laboratory:

Laboratory of Limnology (U.W. Madison campus)

The LTER Water Chemistry laboratory includes a 604 ft^2 lab in the Laboratory of Limnology and 248 ft^2 lab in the Water Science and Engineering building. Both labs contain fume hoods. Refrigerators, freezers, drying ovens, a muffle furnace, and balances are also available in one or both spaces.

The LTER wet lab is 502 ft^2 in the basement of the Laboratory of Limnology with 70 ft^2 of storage space. The wet lab is used for cleaning equipment and occasionally for processing samples. Laboratory 101 at the Laboratory of Limnology is a 538 ft^2 lab space which is used for storage, water sample processing, and zooplankton counting. There also is a 52 ft^2 chlorophyll lab space used to process chlorophyll samples on the fluorometer and for equipment storage.

Trout Lake Station

The Trout Lake Station has a complex of buildings located on the shore of Trout Lake in northern Wisconsin. Most are operated year-round. These include a main laboratory, Juday House, four year-round cabins and several service buildings. Although the actual physical property of the station is only 20 ha, we provide access to the more than 2500 lakes in our region.

Our all-season laboratory is a two-story structure with more than 7,500 ft^2 of space. The upper floor contains a chemistry laboratory and five well-equipped research laboratories. One laboratory is designed for super-clean conditions necessary for trace metal sample processing. The upper floor also contains a library/conference room, eight offices, a lunchroom and a computer room. The lower floor of the station provides space for field gear storage, sample processing, aquarium facilities, and a primary production incubation lab. Light and temperature conditions can be controlled in the three aquarium rooms and a set of five incubators. Specialized laboratories are available for microscopy, high performance liquid chromatography, gas chromatography, and radio-isotope work. Critical equipment at the laboratory is serviced by an auxiliary power plant. Five service buildings at the station provide facilities for equipment and vehicle storage.

Year-round housing at the station provides space for 29 people. During the period from May until October, non-winterized cabins provide an additional 12 spaces. Housing at the station is provided only for short-term stays (<1 year). Permanent employees provide their own housing off station.

Computer facilities include a central fileserver linked to computers in the main laboratory and the five all season residences via ethernet. Multiple general use computers are available for use by visiting scientists. The Trout Lake Station has a T1 connection to the internet. We are in the process of developing wireless internet connectivity to automated rafts and buoys located on key study lakes.

Environmental Remote Sensing Center (ERSC)

ERSC occupies approximately 4800 ft^2 on the 12th floor of the Atmospheric, Oceanic, and Space Sciences Building, 1225 W. Dayton Street, Madison, Wisconsin 53706. The LTER-ERSC Research Associate Office is located in Room 1201, and includes one dedicated Windows workstation. Other components of ERSC that are widely used for NTL-LTER research include the Integrated Remote Sensing Resource Center (IRSRC) and the Instructional Laboratory (Room 1253).

Established as part of a NASA Centers of Excellence grant in 1997, the purpose of the IRSRC is to provide UW with a state-of-the-art computing facility for high-end spatial research needs. The NTL-LTER site is one of the primary users of the Center. The IRSRC hardware environment consists of a high-speed network, a Terabyte file server, a central research facility at ERSC (Room 1249), and remote nodes at research venues scattered across the university campus. The network component of the IRSRC consists of Fast Ethernet networks linked via a campus Asynchronous Transfer Mode (ATM) backbone. Data storage consists of a 4-way Pentium Pro 200 file server with 62 - 18 Gigabyte hard drives configured as RAID 5 virtual disks. The formatted capacity of the data store is 985 Gigabytes. The central research facility consists of 5 high performance Windows workstations, support computers, and other peripheral hardware.

The facilities of the ERSC Instructional Laboratory are available for use by NTL-LTER researchers and graduate students. These include fifteen high performance Windows workstations and two Calcomp digitizing tables. Other computational resources at ERSC include three Linux servers, a slide scanner, several flatbed scanners (including one UMAX large-format scanner suitable for the creation of high-resolution digital orthophotos from aerial photographs), laser and color inkjet printers, a slide maker, a large format inkjet plotter, CD-ROM writers, and other peripherals.

Major image processing and analytical software packages at ERSC include ESRI products (ArcGIS and ArcView), ERDAS Imagine, IDL, and ENVI. A number of software products developed in-house for teaching have also been used in NTL-LTER projects, and they include WiscImg, Softcopy, and OrthoMapper.

Center for Sustainability and the Global Environment (SAGE)

Most of the new modeling proposed here will be conducted at SAGE on the U.W. Madison campus. SAGE has extensive computing and laboratory facilities for the analysis of environmental data, as well as developing complex simulation models of the Earth's climate system and biosphere. Currently, SAGE uses a combination of Unix and Macintosh computing equipment: 4 multiprocessor Silicon Graphics Origin 200 Unix servers; 5 G3 iMacs, 6 G4 Macs (1 AGPG4/450; 5 G4/400); 5 G3 Powerbooks; 4 G4 Titanium Powerbooks, a G4/450 Cube, 3 Beige G3 Macs, 15 iBook wireless computers on a powered, secured cart various laser printers and color inkjet printers; 4 Airport

802.11b wireless Base Stations; and 2 Epson Powerlite Projectors. Most of our research computing needs are being serviced by our Silicon Graphics clusters. However, we have also been experimenting with highly-parallel computing solutions over our network of Apple G3 and G4 Macintosh computers. G4 PowerPC (at 500+ MHz) processors are now capable of sustained gigaflop performance, and will be a highly cost-effective computing solution for our group. IBIS and HYDRA are currently being ported to this system.

In addition, for high-end climate simulations, SAGE has access to the supercomputing facilities of the National Center for Atmospheric Research (NCAR).

Clinical: NA

Animal:

Water Science and Engineering Laboratory (WSEL)

The Center for Limnology manages an aquarium facility in the Water Science and Engineering Laboratory (WSEL). This facility provides flow-through water systems that have automated light, water temperature, and water pressure controls. The facilities configuration can be adapted to suit various research needs, and can house several 5,000+ liter aquaria and dozens of 100-liter aquaria. Water sources include lake water, potable and non-potable city water, and tempered city water. The parameters for the tempered water are controlled by a series of six head tanks located on the ground floor of WSEL, and aquaria in the basement receive their water by gravity feed. Electromechanical controls prevent accidental water flow to aquaria when water temperatures are outside of specified ranges. Nearly all experimentation in the facility involves ectothermic species, such as fishes, amphibians, and crustaceans.

Trout Lake Station

The laboratory at Trout Lake Station has a series of large fiberglass holding tanks, four 75-gallon fiberglass aquaria and assorted small aquaria. Portable generators and pumps allow the use of holding tanks at remote sites.

Computer:

The Laboratory of Limnology runs a Windows NT 10/100 megabit local area network (LAN), with a 10 megabit connection to the campus wide area network (WAN). Two fileservers house a central repository of computer software and end-user data, and provide web services, administrative databases and connections with the Trout Lake Station. One SUN Ultra runs the LTER databases and GIS software. Available for student use are PC and Macintosh desktop and PC laptop computers, printers, slide shooters, slide and document scanners, fixed and portable computer projectors. The Center supports standard office software, graphics software, and a variety of modeling and statistics software, as well as access to major electronic journals. The Trout Lake Station runs a network analogous to that of the Madison laboratory, including a fileserver, T1 Internet connection, general use computers and the peripherals described above. In addition, the station provides wireless ethernet and serial communication.

Between the two facilities, there are nearly 75 computers, with about 1/3 of these being available for student use.

Instruments for data management include Windows NT local area network (LAN) supporting Windows-based microcomputers and a Sun Sparc Ultra2 workstation.

Additional computing capability is available at ERSC and at SAGE (see above).

Office:
The Center for Limnology provides substantial administrative, secretarial, computer, and building and equipment maintenance support that directly benefits the LTER program, in the form of 7.8 FTE funded by Center operational funds. Center personnel (4.8 FTE) manage and coordinate day-to-day operations of the center's research programs and oversee Center administration including all operational funds and research grants. Staff also assist with recruitment and appointment of research staff, maintain and administer accounting records for all operational and grant funds, including purchasing, travel arrangements and reimbursement, and compliance with University and federal requirements. Administrative, secretarial and receptionist services, and general computer hardware, software, and web support to all Center faculty and staff are also provided.

Other PIs are housed in departmental offices throughout campus or at Trout Lake Station. All offices are equipped with desktop computers and ethernet lines.

Other:
The Limnology Library in the Laboratory of Limnology houses a large collection of reprints and tracks reprints from LTER so that a publication list can be obtained. Pertinent LTER government documents are also collected and sorted by the various LTER sites.

MAJOR EQUIPMENT:

Laboratory of Limnology in Madison
Equipment used for LTER water chemistry analyses includes: O/I Model 700 TOC analyzer; Technicon Autoanalyzer II linked to a PC for automated data processing; Dionex DX-500 ion chromatograph equipped with an automated sampler, eluent generator, and gradient pump; Perkin-Elmer Optima 4300 DV Optical Emissions ICP spectrometer; a Beckman DU 640 spectrophotometer; and a Turner Designs TD-700 fluorometer. There are 2 Leica WILD MZ8 dissecting microscopes, 2 Leica WILD M5A dissecting microscopes, and 2 Nikon LABOPHOT compound microscopes.

The Laboratory of Limnology is well equipped for field sampling of the Madison area lakes. Lake Mendota and other lakes of the Madison chain are accessed from powerboats moored in the basement of the Laboratory of Limnology, and from the 31-foot R.V. *Limnos* on Lake Mendota. Other lakes are accessed by trailered boats. We maintain a snowmobile for winter access to the lakes. The Laboratory of Limnology operates a complete array of limnological sampling gear, including an electroshocking boat, nets, and water sampling equipment.

ERSC
Additional major equipment items at ERSC include an ASD FieldSpec hand-held spectroradiometer, several Trimble GPS units, a digital camera, and a videocamera.

Trout Lake Station
Trout Lake Station is well equipped to provide access for researchers to nearly any aquatic site in the region. Major field gear includes: two, four-wheel-drive trucks, eight boat trailers, a ski barge, 15 rowboats, eleven outboard motors, and two canoes. During the peak summer season, several additional vehicles are available for general field use. Scuba gear is also available. Two snowmobiles, ice drills, snowshoes, tents and insulated field boxes are available for winter limnology. We have most standard collecting gear for general limnological work including peristaltic pumps with in-line filtration, meters and probes to measure light (PAR and full spectral characteristics), temperature and oxygen meters including sondes that can be placed in lakes for extended periods, plankton samplers, trawls, fyke nets, gill nets, seines, two electroshocking boats, and a 120 kHZ hydroacoustic data collection system capable of estimating abundance of pelagic fishes.

Our laboratories are equipped with fume hoods, high quality water purification systems, drying ovens, a muffle furnace, dry sterilizers, balances (in a variety of ranges including a Cahn Electrobalance), pH meters, recorders, a Waters High Performance Liquid Chromatograph with a diode array detector, a Kontron Double-Beam Spectrophotometer, an electronic particle counter, a fluorometer, a Lachatt nutrient analysis system, a Beckman models LS 1801 liquid scintillation counter, and an OI Corporation organic carbon analyzer. A set of five, light-and temperature-controlled incubators are available for experimental projects and culture maintenance. Microscopes available at Trout Lake include: a Zeiss Inverted Microscope equipped for epifluorescence, a Nikon Labophot microscope, and 1 Leica and 3 Wild model M5A dissecting scopes. Detailed meteorological data are currently recorded at a nearby land-based station and on a fully-instrumented raft currently operated on Sparkling Lake, 3 km from the station. Chemical precipitation is sampled at an NADP site located at Trout Lake that is serviced by our laboratory.

OTHER RESOURCES:
In addition, Center staff (3.0 FTE) manage and maintain all Center facilities (laboratory and boat facilities, office and common space, and residential units) and equipment in the Laboratory of Limnology and at Trout Lake Station, including constructing and maintaining instruments, sampling gear and other research equipment. Staff also manage the experimental aquarium facilities in the Water Sciences and Engineering Laboratory, oversee construction and remodeling of all facilities, and are responsible for secure storage of all Center sampling equipment, boats, vehicles and limnological

samples. The Center machine, metal and woodworking shop facilities at the Madison Laboratory (1894 sq. ft) and Trout Lake Station (1132 sq. ft) contain many types of equipment available for LTER use, including welders, lathes, table, radial arm and band saws, drill presses, milling machines, and a large variety of hand tools. Staff also oversee all Center vehicle use, including deployment and maintenance of vehicles used for field research in Madison and at Trout Lake Station. Finally, staff provide logistical support for Center for Limnology outreach programs for students and teachers in the Madison and Boulder Junction areas.

Table 1:Electronic Availability of NTL-LTER Core Data.

Type of Data	Directly Accessible by NTL-LTER Researchers	Accessible (A) on the NTL web site
Physical Limnology		
Depth Profiles	ORACLE DATABASE	**A**
Ice Duration	ORACLE DATABASE	**A**
Ice Thickness/Snow Depth	ORACLE DATABASE	**A**
Secchi Disk Depth	ORACLE DATABASE	**A**
Lake Levels*	ORACLE DATABASE	**A**
Chemical Limnology		
Nutrients	ORACLE DATABASE	**A**
Major Ions	ORACLE DATABASE	**A**
Plankton		
Chlorophyll a	ORACLE DATABASE	**A**
Primary Production*	ORACLE DATABASE	**A**
Zooplankton (TLA)	ORACLE DATABASE	**A**
Zooplankton (MLA)	FILE SERVER	in process
Sediment Deposition*	FILE SERVER	**A**
Aquatic Macrophytes		
Macrophyte Biomass	ORACLE DATABASE	**A**
Macrophyte Transect	ORACLE DATABASE	**A**
Pelagic Macroinvertebrates*	FILE SERVER	**A**
Crayfish	ORACLE DATABASE	**A**
Benthic Macroinvertebrates*	FILE SERVER	**A**
Fish		
Fish Abundance	ORACLE DATABASE	**A**
Fish Length Frequency	ORACLE DATABASE	**A**
Groundwater*		
Groundwater Level	ORACLE DATABASE	**A**
Groundwater Chemistry	ORACLE DATABASE	**A**
Sparkling Lake Raft*		
Meteorological Data	ORACLE DATABASE	**A**
Water Temperature	ORACLE DATABASE	**A**
Meteorological*	ORACLE DATABASE	**A**
Historical land use/land cover data	FILE SERVER	in process
Spatial Data		
Hydrography	FILE SERVER	**A**
Elevation/DEM	FILE SERVER	**A**
Soils	FILE SERVER	**A**

* Trout Lake Area lakes only. TLA = Trout Lake Area; MLA = Madison Lake Area

Table 2. NTL-LTER Data and Information Shared (outside of the project).

Requests received via email, mail and phone
during the period 1996 – 2001

For NTL-LTER Data
Investigators at the University of Wisconsin-Madison

Undergraduate	Graduates	Other Researchers
16	17	21

Investigators outside the University of Wisconsin-Madison

University	State/Local Government	Federal	Private	International
63	23	17	17	24

For Information and Data Collection Methods and Data Management
Investigators outside the University of Wisconsin-Madison

University	Other
28	15

Requests via Internet to NTL-LTER World Wide Web home page
compiled from entries in the web server log for January 2000 through December 2001

	Domain						
Information Type	wisc .edu	(other) .edu	.gov, .us	.net, .com	.ca	other countries	other*
General Site Information	410	368	80	531	43	153	1025
Lake Characteristics	161	198	46	501	40	97	651
Major Research Findings	121	144	25	202	19	37	305
Previous Proposals	34	81	18	226	8	20	322
Personnel Directory	206	299	54	213	37	82	537
Publications	137	339	77	586	97	267	995
Data Catalog / Data Sets	657	434	84	479	83	190	1571
Biodiversity Information	26	110	16	185	11	42	223
Education / Outreach	158	89	32	247	9	41	440
Calendar	50	17	1	276		18	180

*The “other” category represents requests from other domains or addresses not easily categorized into domains.

North Temperate Lakes LTER Publications 1996-2001 and in press

Journal Articles

1996

Anderson, W. L., D. M. Robertson and J. J. Magnuson (1996). Evidence of recent warming and El Nino-related variation in ice breakup of Wisconsin lakes. Limnology and Oceanography 41(5): 815-21.

De Stasio, J., Bart T. , D. K. Hill, J. M. Kleinhaus, N. P. Nibbelink and J. J. Magnuson (1996). Potential effects of global climate change on small north-temperate lakes: physics, fish, and plankton. Limnology and Oceanography 41(5): 1136-49.

Hope, D., T. K. Kratz and J. L. Riera (1996). Relationship between P(CO2) and dissolved organic carbon in northern Wisconsin lakes. Journal of Environmental Quality 25(6): 1442-45.

Lathrop, R. C., S. R. Carpenter and L. G. Rudstam. (1996). Water clarity in Lake Mendota since 1900: responses to differing levels of nutrients and herbivory. Canadian Journal of Aquatic Science 53: 2250-61.

Michmerhuizen, C. M., R. G. Striegl and M. E. McDonald (1996). Potential methane emission from north-temperate lakes following ice melt. Limnology and Oceanography 41(5): 985-91.

Sanderson, B. L. and T. M. Frost (1996). Regulation of dinoflagellate populations: relative importance of grazing, resource limitation, and recruitment from sediments. Canadian Journal of Fisheries and Aquatic Sciences 53: 1409-17.

Schneider, D. W. and T. M. Frost (1996). Habitat duration and community structure in temporary ponds. Journal of the North American Benthological Society 15(1): 64-86.

Soranno, P. A., L. Hubler and S. R. Carpenter (1996). Phosphorus loads to surface waters: a simple model to account for spatial pattern of land use. Ecological Applications 6(3): 865-78.

Vavrus, S. J., R. H. Wynne and J. A. Foley (1996). Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. Limnology and Oceanography 41(5): 822-831.

Weaver, M. J. and J. J. Magnuson (1996). Habitat heterogeneity and fish community structure: inferences from north temperate lakes. American Fisheries Society Symposium 16: 335-46.

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(5): 977-84.

Williamson, C. E., R. S. Stemberger, D. P. Morris, T. M. Frost and S. G. Paulsen (1996). Ultraviolet radiation in North American lakes: attenuation estimates from DOC measurements and implications for plankton communities. Limnology and Oceanography 41(5): 1024-34.

Wynne, R. H., J. J. Magnuson, M. K. Clayton, T. M. Lillesand and D. C. Rodman (1996). Determinants of temporal coherence in the satellite-derived 1987-1994 ice breakup dates of lakes on the Laurentian Shield. Limnology and Oceanography 41(5): 832-38.

1997

Fallah, P. M., C. A. Shearer and W. Chen (1997). Ascovaginospora stellipala gen. et sp. nov. from sphagnum bogs. Mycologia 89(5): 812-18.
Fischer, J. M. and T. M. Frost (1997). Indirect effects of lake acidification on Chaoborus population dynamics: the role of food limitation and predation. Canadian Journal of Fisheries and Aquatic Sciences 54: 637-46.
Frost, T. M., L. K. Graham, J. E. Elias, M. J. Haase, D. W. Kretchmer and J. A. Kranzfelder (1997). A yellow-green algal symbiont in the freshwater sponge, Corvomeyenia everetti: convergent evolution of symbiotic associations. Freshwater Biology 38: 395-99.
Hamilton, D. P. and B. T. De Stasio (1997). Modelling phytoplankton-zooplankton interactions in Sparkling Lake, USA. Verh. Internat. Verein. Limnol. 26(2): 487-490.
Hassett, R. P., B. Cardinale, L.B. Stabler and J.J.Elser. (1997). Ecological stoichiometry of N and P in pelagic ecosystems: Comparison of lakes and oceans with emphasis on the zooplankton-phytoplankton interaction. Limnology and Oceanography. 42(4): 648-662.
Kasprzak, P. H. and R. C. Lathrop (1997). Influence of two Daphnia species on summer phytoplankton assemblages from eutrophic lakes. Journal of Plankton Research 19(8): 1025-44.
Kratz, T. K., J. Schindler, D. Hope, J. L. Riera and C. J. Bowser (1997). Average annual carbon dioxide concentrations in eight neighboring lakes in northern Wisconsin, USA. Verh. Internat. Verein. Limnol. 26: 335-38.
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: 209-17.
Magnuson, J. J., T. F. Kratz, T. F. Allen, D. E. Armstrong, B. J. Benson, C. J. Bowser, D. W. Bolgrien, S. R. Carpenter, T. M. Frost, S. T. Gower, T. M. Lillesand, J. A. Pike and M. G. Turner (1997). Regionalization of long-term ecological research (LTER) on north temperate lakes. Verhandlungen Internationale Vereinigung fur Limnologie 26(pt. 2): 522-28.
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 and F. H. Quinn (1997). Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and precambrian shield region. Hydrological Processes 11: 825-71.
Soranno, P. A. (1997). Factors affecting the timing of surface scums and epilimnetic blooms of blue-green algae in a eutrophic lake. Canadian Journal of Fisheries and Aquatic Sciences 54(9): 1965-75.
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(8): 1883-93.
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: 464-73.

Weaver, M. J., J. J. Magnuson and M. K. Clayton (1997). Distribution of littoral fishes in structurally complex macrophytes. Canadian Journal of Fisheries and Aquatic Sciences 54(10): 2277-89.

Wilson, K. and S. R. Carpenter (1997). Making the weedline work for your lake: when life gives you invasive weeds, make habitat. Wisconsin Natural Resources 21(2): 4-8.

1998

Anderson, M. P. and X. Cheng (1998). Sensitivity of groundwater/lake systems in the Upper Mississippi River Basin, Wisconsin, USA, to possible effects of climate change. Hydrology, Water Resources and Ecology in Headwaters, IAHS Publication 248: 3-8.

Arnott, S. E., J. J. Magnuson and N. D. Yan (1998). Crustacean zooplankton species richness: single- and multiple- year estimates. Canadian Journal of Fisheries and Aquatic Sciences 55(7): 1573-82.

Carpenter, S. R., D. Bolgrien, R. C. Lathrop, C. A. Stow, T. Reed and M. A. Wilson (1998). Ecological and economic analysis of lake eutrophication by nonpoint pollution. Australian Journal of Ecology 23: 68-79.

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(3): 559-568.

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. Issues in Ecology Summer 1998(3): 1-12.

Fallah, P. M. and C. A. Shearer (1998). Freshwater ascomycetes: phomatospora spp. from lakes in Wisconsin. Mycologia 90: 323-29.

Fang, X. and H. G. Stefan (1998). Potential climate warming effects on ice covers of small lakes in the contiguous U.S. Cold Regions Science and Technology 27: 119-40.

Frost, T. M., P. K. Montz, M. J. Gonzalez, B. L. Sanderson and S. E. Arnott (1998). Rotifer responses to increased acidity: long-term patterns during the experimental manipulation of Little Rock Lake. Hydrobiologia 387/388: 141-52.

Frost, T. M., P. K. Montz and T. K. Kratz (1998). Zooplankton community responses during recovery from acidification in Little Rock Lake, Wisconsin. Restoration Ecology 6(4): 336-42.

Hrabik, T. R., J. J. Magnuson and A. C. McLain (1998). Predicting the effects of rainbow smelt on native fishes: evidence from long-term research on two lakes. Canadian Journal of Fisheries and Aquatic Sciences 55(6): 1364-71.

Hunt, R. J., M. P. Anderson and V. A. Kelson (1998). Improving a complex finite-difference ground water flow model through the use of an analytic element screening model. Ground Water 36(6): 1011-17.

Keating, E. H. and J. M. Bahr (1998). Reactive transport modeling of redox geochemistry: approaches to chemical disequilibrium and reaction rate estimation at a site in northern Wisconsin. Water Resources Research 34(12): 3573-84.

Keating, E. H. and J. M. Bahr (1998). Using reactive solutes to constrain groundwater flow models at a site in northern Wisconsin. Water Resources Research 34(12): 3561-71.

Lathrop, R. C., S. R. Carpenter, C. A. Stow, P. A. Soranno and J. C. Panuska (1998). Phosphorus loading reductions needed to control blue-green algal blooms in Lake Mendota. Canadian Journal of Fisheries and Aquatic Sciences 55(5): 1169-78.

Magnuson, J. J., W. M. Tonn, A. Banerjee, J. Toivonen, O. Sanchez and M. Rask (1998). Isolation versus extinction in the assembly of fishes in small northern lakes. Ecology 79(8): 2941-56.

Naiman, R. J., J. J. Magnuson and P. L. Firth (1998). Integrating cultural, economic, and environmental requirements for fresh water. Ecological Applications 8(3): 569-70.

Nibbelink, N. P. and S. R. Carpenter (1998). Interlake variation in growth and size structure of bluegill (Lepomis macrochirus): inverse analysis of an individual-based model. Canadian Journal of Fisheries and Aquatic Sciences 55: 387-96.

Olson, M. H., S. R. Carpenter, P. Cunningham, S. Gafny, B. R. Herwig, N. P. Nibbelink, T. Pellett, C. Storlie, A. S. Trebitz and K. A. Wilson (1998). Managing macrophytes to improve fish growth: a multi-lake experiment. Fisheries 23(2): 6-12.

Policansky, D. and J. J. Magnuson (1998). Genetics, metapopulations, and ecosystem management of fisheries. Ecological Applications 8(1): S119-S123.

Riera, J. L., J. J. Magnuson, J. R. Vande Castle and M. D. MacKenzie (1998). Analysis of large-scale spatial heterogeneity in vegetation indices among North American landscapes. Ecosystems 1(3): 268-82.

Schindler, J. E. and D. P. Krabbenhoft (1998). The hyporheic zone as a source of dissolved organic carbon and carbon gases to a temperate forested stream. Biogeochemistry 43: 157-74.

Stow, C. A., S. R. Carpenter, K. E. Webster and T. M. Frost (1998). Long-term environmental monitoring: some perspectives from lakes. Ecological Applications 8(2): 269-76.

Walsh, S. E., S. J. Vavrus, J. A. Foley, V. A. Fisher, R. H. Wynne and J. D. Lenters (1998). Global patterns of lake ice phenology and climate: model simulations and observations. Journal of Geophysical Research 103(D22): 28,825-28,837.

Wynne, R. H., T. M. Lillesand, M. K. Clayton and J. J. Magnuson (1998). Satellite monitoring of lake ice breakup on the Laurentian Shield (1980-1994). Photogrametric Engineering and Remote Sensing 64: 607-617.

1999

Allen, T. F. H., J. A. Tainter and T. W. Hoekstra (1999). Supply-side sustainability. Systems Research and Behavioral Science. 16: 403-27.

Arnott, S. E., N. D. Yan, J. J. Magnuson and T. M. Frost (1999). Interannual variability and species turnover of crustacean zooplankton in Shield lakes. Canadian Journal of Fisheries and Aquatic Sciences 56(1): 162-72.

Bennett, E. M., T. Reed-Andersen, J. N. Houser, J. R. Gabriel and S. R. Carpenter (1999). A phosphorus budget for the Lake Mendota watershed. Ecosystems 2: 69-75.

Carpenter, S. R., W. A. Brock and P. C. Hanson (1999). Ecological and social dynamics in simple models of ecosystem management. Conservation Ecology. 3(2): 4 available on internet www.consecol.org/vol3/iss2/art.

Carpenter, S. R. and R. C. Lathrop (1999). Lake restoration: capabilities and needs. Hydrobiologia 395/396: 19-28.

Carpenter, S. R., D. Ludwig and W. A. Brock (1999). Management of eutrophication for lakes subject to potentially irreversible change. Ecological Applications 9(3): 751-71.

Colby, A. C. C., T. M. Frost and J. M. Fischer (1999). Sponge distribution and lake chemistry in northern Wisconsin lakes: Minna Jewell's survey revisited. Memoirs of the Queensland Museum 44: 93-99.

Descy, J. P., T. M. Frost and J. P. Hurley (1999). Assessment of grazing by the freshwater copepod Diaptomus minutus using carotenoid pigments: a caution. Journal of Plankton Research 21(1): 127-45.

Fassnacht, K. S. and S. T. Gower (1999). Comparison of the litterfall and forest floor organic matter and nitrogen dynamics of upland forest ecosystems in north central Wisconsin. Biogeochemistry 45: 265-84.

Fisher, M. M. and E. W. Triplett (1999). An automated approach for ribosomal intergenic spacer analysis of microbial diversity and its application to freshwater bacterial communities. Applied and Environmental Microbiology. 65: 4630-36.

Frost, T. M., T. K. Kratz and J. J. Magnuson (1999). Focus on field stations : Center for Limnology - Trout Lake Station, University of Wisconsin-Madison. Bulletin of the Ecological Society of America 80(1): 70-3.

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(3, part 2): 784-94.

Gergel, S. E., 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(4): 1377-90.

Gillooly, J. F. and S. I. Dodson (1999). Latitudinal patterns in the size distribution and seasonal dynamics of New World, freshwater cladocera. Limnology and Oceanography 45(1): 22-30.

Hrabik, T. R. and J. Magnuson (1999). Simulated dispersal of exotic rainbow smelt (Osmerus mordax) in a northern Wisconsin lake district and implications for management. Canadian Journal of Fisheries and Aquatic Sciences. 56(Supplement 1): 35-42.

Janssen, M. A. and S. R. Carpenter. (1999). Managing the resilience of lakes: A multi-agent modeling approach. Conservation Ecology :[online] URL: http://www.consecol.org/vol3/iss2/art15 3(2): 15.
Kasprzak, P., R. C. Lathrop and S. R. Carpenter (1999). Influence of different sized Daphnia species on chlorophyll concentration and summer phytoplankton community structure in eutrophic Wisconsin lakes. Journal of Plankton Research 21(11): 2161-74.
Kim, K., M. P. Anderson and C. J. Bowser (1999). Model calibration with multiple targets : a case study. Groundwater 37(3): 345-51.
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(1): 137-46.
Lewis, D. B. and J. J. Magnuson (1999). Intraspecific gastropod shell strength variation among north temperate lakes. Canadian Journal of Fisheries and Aquatic Sciences 56(9): 1687-95.
Lukaszewski, Y., S. E. Arnott and T. M. Frost (1999). Regional versus local processes in determining zooplankton community composition of Little Rock Lake, Wisconsin, USA. Journal of Plankton Research 121(5): 991-1003.
Pierce, F. J. and P. Nowak (1999). Aspects of precision agriculture. Advances in Agronomy 67: 1-84.
Poister, D., D. E. Armstrong and J. P. Hurley (1999). Influences of grazing on temporal patterns of algal pigments in suspended and sedimenting algae in a north temperate lake. Canadian Journal of Fisheries and Aquatic Sciences 56(1): 60-69.
Riera, J. L., J. E. Schindler and T. K. Kratz (1999). Seasonal dynamics of carbon dioxide and methane in two clear-water lakes and two bog lakes in northern Wisconsin, USA. Canadian Journal of Fisheries and Aquatic Sciences 56(2): 265-74.
Sanderson, B. L., T. R. Hrabik, J. J. Magnuson and D. M. Post (1999). Cyclic dynamics of a yellow perch (Perca flavescens) population in an oligotrophic lake: evidence for the role of intraspecific interactions. Canadian Journal of Fisheries and Aquatic Sciences 56(9): 1534-42.
Smith, M. A. and D. J. Hollander (1999). Historical linkage between atmospheric circulation patterns and the oxygen isotopic record of sedimentary carbonates from Lake Mendota, Wisconsin, USA. Geology 27(7): 589-92.
Soranno, P. A., K. E. Webster, J. L. Riera, T. K. Kratz, J. S. Baron, P. A. Bukaveckas, G. W. Kling, D. S. White, N. Caine, R. C. Lathrop and P. R. Leavitt (1999). Spatial variation among lakes within landscapes: ecological organization along lake chains. Ecosystems 2(5): 395-410.
Turner, M. G. and S. R. Carpenter (1999). Tips and traps in interdisciplinary research. Ecosystems 2: 275-76.
Waide, R. B., M. R. Willig, C. F. Steiner, G. Mittelbach, L. Gough, S. I. Dodson, G. P. Juday and R. Parmenter (1999). The relationship between productivity and species richness. Annual Review of Ecology and Systematics 30: 257-300.

Wilson, M. A. and S. R. Carpenter (1999). Economic valuation of freshwater ecosystem services in the United States: 1971-1997. Ecological Applications 9(3): 772-83.

Wolf, S. A. and P. Nowak (1999). Institutional failure in agro-environmental management. Research in Social Problems and Public Policy 7: 293-310.

2000

Baines, S. B., K. E. Webster, T. K. Kratz, S. R. Carpenter and J. J. Magnuson (2000). Synchronous behavior of temperature, calcium and chlorophyll in lakes of northern Wisconsin. Ecology 81(3): 815-25.

Baker, K. S., B. J. Benson, D. L. Henshaw, D. Blodgett, J. H. Porter and S. G. Stafford (2000). Evolution of a multisite network information system: The LTER information management paradigm. Bioscience 50(11): 963-78.

Benson, B. J., J. D. Lenters, J. J. Magnuson, M. Stubbs, T. K. Kratz, P. J. Dillon, R. E. Hecky and R. C. Lathrop (2000). Regional coherence of climatic and lake thermal variables of four lake districts in the Upper Great Lakes Region of North America. Freshwater Biology 43: 517-27.

Carpenter, S. R. and M. Turner (2000). Opening the black boxes: ecosystem science and economic valuation. Ecosystems 3(1): 1-3.

Chipman, J. W., T. M. Lillesand, J. D. Gage and S. Radcliffe (2000). Spaceborne imaging radar in support of forest resource management. Photogrammetric Engineering and Remote Sensing 66(1): 1357-66.

Descy, J.-P., H. Higgins, D. J. Mackey, J. P. Hurley and T. M. Frost (2000). Pigments and phytoplankton composition in LTER lakes (Wisconsin, USA). Verhandlungen. Internationale Vereinigung Limnol. 27: 930-1.

Descy, J.-P., H. W. Higgins, D. J. Mackey and T. M. Frost (2000). Pigment ratios and phytoplankton assessment in northern Wisconsin lakes. Journal of Phycology 36: 274-86.

Dodson, S. I., S. E. Arnott and K. L. Cottingham (2000). The relationship in lake communities between primary productivity and species richness. Ecology 81(10): 2662-79.

Elder, J. F., N.B. Rybicki, V. Carter and V. Weintraub (2000). Sources and yields of dissolved carbon in northern Wisconsin stream catchments with differing amounts of peatland. Wetlands 20(1): 113-125.

Essington, T. E. and S. R. Carpenter (2000). Nutrient cycling in lakes and streams: insights from a comparative analysis. Ecosystems 3(2): 131-43.

Fisher, M. M., J. L. Klug, G. Lauster, M. Newton and E. W. Triplett (2000). Effects of resources and trophic interactions on freshwater bacterioplankton diversity. Microbial Ecology 40: 125-38.

FitzHugh, T. W. and D. S. Mackay (2000). Effects of parameter spatial aggregation on an agricultural nonpoint source pollution model. Journal of Hydrology 236(1-2): 35-53.

Franklin, J. F., D. Lindenmayer, J. A. MacMahon, A. McKee, J. Magnuson, D. A. Perry, R. Waide and D. Foster (2000). Threads of continuity. Conservation Biology in Practice 1(1): 9-16.

Frost, T. M., J. P. Descy, B. T. DeStasio, G. Gerrish, J. Hood, J. P. Hurley and A. L. St. Amand (2000). Evaluations of phytoplankton communities using varied techniques: a multi-media comparison of lakes in Northern Wisconsin USA. Verh. Internat. Verein. Limnol. 27: 1023-30.
Gillooly, J. F. and S. I. Dodson (2000). The relationship of neonate mass and incubation temperature to embryonic development time in a range of animal taxa. Journal of Zoology (London) 251: 369-375.
Gillooly, J. F. and S. I. Dodson (2000). The relationship of egg size and incubation temperature to embryonic development time in univoltine and multivoltine aquatic insects. Freshwater Biology 44: 595-604.
Kim, K., M. P. Anderson and C. J. Bowser (2000). Enhanced dispersion in groundwater caused by temporal changes in recharge rate and lake levels. Advances in Water Resources 23: 625-35.
Klug, J. L., J. M. Fischer, A. R. Ives and B. Dennis (2000). Compensatory dynamics in planktonic community responses to pH perturbations. Ecology 81(2): 387-98.
Kratz, T. K. and T. M. Frost (2000). The ecological organisation of lake districts: general introduction. Freshwater Biology 43: 297-99.
Kuczenski, T. K., D. R. Field, P. R. Voss, V. C. Radeloff and A. E. Hagen (2000). Integrating demographic and Landsat (TM) data at a watershed scale. Journal of the American Water Resources Association 36(1): 215-28.
Lathrop, R. C., S. R. Carpenter and D. M. Robertson (2000). Interacting factors causing exceptional summer water clarity in Lakes Mendota and Monona. Verhandlungen. Internationale Vereinigung für theoretische und angewandte Limnologie. 27: 1776-79.
Lenters, J. D., M. T. Coe and J. A. Foley (2000). Surface water balance of the continental United States, 1963-1995: regional evaluation of a terrestrial biosphere model and the NCEP/NCAR reanalysis. Journal of Geophysical Research 105(D17): 22,393-425.
Lewis, D. B. and J. J. Magnuson (2000). Landscape spatial patterns in freshwater snail assemblages across Northern Highland catchments. Freshwater Biology 43(3): 409-20.
Magnuson, J. J. and T. K. Kratz (2000). Lakes in the landscape: approaches to regional limnology. Verhandlungen Internationale Vereinigung fur Limnologie 27: 1-14.
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(5485): 1743-6.
Naiman, R. J. and M. G. Turner (2000). A future perspective on North America's freshwater ecosystems. Ecological Applications 10(4): 958-70.
Radeloff, V. C., A. E. Hagen, P. R. Voss, D. R. Field and D. J. Mladenoff (2000). Exploring the spatial relationship between census and land-cover data. Society and Natural Resources 13: 599-609.
Reed-Andersen, T., E. M. Bennett, B. S. Jorgensen, G. Lauster, D. B. Lewis, D. Nowacek, J. L. Riera, B. L. Sanderson and R. Stedman (2000). Distribution of

recreational boating across lakes : do landscape variables affect recreational use? Freshwater Biology 43: 439-48.
Reed-Andersen, T., S. R. Carpenter and R. C. Lathrop (2000). Phosphorus flow in a watershed-lake ecosystem. Ecosystems 3(6): 561-73.
Reed-Andersen, T., S. R. Carpenter, D. K. Padilla and R. C. Lathrop (2000). Predicted impact of zebra mussel (Dreissena polymorpha) invasion on water clarity in Lake Mendota. Canadian Journal of Fisheries and Aquatic Sciences 57(8): 1617-26.
Riera, J. L., J. J. Magnuson, T. K. Kratz and K. E. Webster (2000). A geomorphic template for the analysis of lake districts applied to Northern Highland Lake District, Wisconsin, U.S.A. Freshwater Biology 43: 301-18.
Shelley, B. C. L. and J. A. Perry (2000). Evaluation of bacterial recovery efficiency and counting precision from decaying leaf litter in Little Rock Lake, Wisconsin, USA. Journal of Freshwater Biology 15(2): 157-69.
Striegl, R. G., J. E. Schindler, K. P. Wickland, D. C. Hudson and G. C. Knight (2000). Patterns of carbon dioxide and methane saturation in 34 Minnesota and Wisconsin lakes. Verh. Internat. Verein. Limnol. 27: 1424-27.
Watras, C. J., K. A. Morrison, R. J. M. Hudson, T. M. Frost and T. K. Kratz (2000). Decreasing mercury in Northern Wisconsin: Temporal patterns in bulk precipitation and a precipitation-dominated lake. Environmental Science and Technology 34(19): 4051-7.
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.
Weigel, B. M., J. Lyons, L. K. Paine, S. I. Dodson and D. J. Undersander (2000). Using stream macroinvertebrates to compare riparian land use practices on cattle farms in southwestern Wisconsin. Journal of Freshwater Ecology 15(1): 93-106.
Willis, T. V. and J. J. Magnuson (2000). Patterns in fish species composition across the interface between streams and lakes. Canadian Journal of Fisheries and Aquatic Sciences 57(7): 1042-52.

2001
Allen, T. F. H., J. A. Tainter, J. C. Pires and T. W. Hoekstra (2001). Dragnet Ecology, “Just the facts Ma’am”: the privilege of science in a post-modern world. Bioscience 51: 475-485.
Bennett, E. M., S. R. Carpenter and N. F. Caraco (2001). Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience 51(3): 227-34.
Byron, C. J. and K. A. Wilson (2001). Rusty crayfish (Orconectes rusticus) movement within and between habitats in Trout Lake, Vilas County, Wisconsin. Journal of the North American Benthological Society. 20(4): 606-14.
Cardille, J. A., S. J. Ventura and M. G. Turner (2001). Environmental and social factors influencing wildfires in the Upper Midwest, United States. Ecological Applications 11(1): 111-27.

Carpenter, S. R. and L. H. Gunderson (2001). Coping with collapse: ecological and social dynamics in ecosystem management. BioScience 51(6): 451-7.
Carpenter, S.R., B.H. Walker, J.M. Anderies and N. Abel. (2001). From Metaphor to Measurement: Resilience of What to What? Ecosystems 4: 765-781.
Carpenter, S. R. and M. G. Turner (2001). Hares and tortoises: Interactions of fast and slow variables in ecosystems. Ecosystems 3(6): 495-7.
Clark, J. S., S. R. Carpenter, M. Barber, S. Collins, A. Dobson, J. A. Foley, D. M. Lodge, M. Pascual, R. J. Pielke, W. Pizer, C. Pringle, W. V. Reid, K. A. Rose, O. E. Sala, W. H. Schlesinger, D. H. Wall and D. Wear (2001). Ecological forecasts: an emerging imperative. Science 293: 657-60.
Fischer, J. M., T. M. Frost and A. R. Ives. (2001). Compensatory dynamics in zooplankton community responses to acidification: measurement and mechanisms. Ecological Applications 11(4): 1060-1072.
Fischer, J. M., J. L. Klug, A. R. Ives and T. M. Frost (2001). Ecological history affects zooplankton community responses to acidification. Ecology 82(11): 2984-3000.
FitzHugh, T. W. and D. S. Mackay (2001). Impact of subwatershed partitioning on modeled source- and transport-limited sediment yields in an agricultural nonpoint source pollution model. Journal of Soil and Water Conservation 56(2): 137-143.
Greenfield, B. K., T. R. Hrabik, C. J. Harvey and S. R. Carpenter (2001). Predicting mercury levels in yellow perch: use of water chemistry, trophic ecology, and spatial traits. Canadian Journal of Fisheries and Aquatic Sciences 58: 1419-29.
Havlicek, T. D. and S. R. Carpenter (2001). Pelagic species size distributions in lakes: are they discontinuous? Limnology and Oceanography 46(5): 1021-33.
Hrabik, T. R., M. P. Carey and M. S. Webster (2001). Interactions between young-of-the-year exotic rainbow smelt and native yellow perch in a northern temperate lake. Transactions of American Fisheries Society 130: 568-82.
Jackson, R. B., S. R. Carpenter, C. N. Dahm, D. M. McKnight, R. J. Naiman, S. L. Postel and S. W. Running (2001). Water in a changing world. Issues in Ecology 9(Spring): 2-15.
Jorgensen, B. S., M. A. Wilson and T. A. Heberlein (2001). Fairness in the contingent valuation of environmental public goods: attitude toward paying for environmental improvements at two levels of scope. Ecological Economics. 36: 133-48.
Lewis, D. B. (2001). Trade-offs between growth and survival: Responses of freshwater snail to predacious crayfish. Ecology 82(3): 758-65.
Puth, L. M. and K. A. Wilson (2001). Boundaries and corridors as a continuum of ecological flow control: lessons from rivers and streams. Conservation Biology 15(1): 21-30.
Radeloff, V. C., R. B. Hammer, P. R. Voss, A. E. Hagen, D. R. Field and D. J. Mladenoff (2001). Human demographic trends and landscape level forest management in the northwest Wisconsin Pine Barrens. Forest Science 47(2): 229-41.
Riera, J., P. R. Voss, S. R. Carpenter, T. K. Kratz, T. M. Lillesand, J. A. Schnaiberg, M. G. Turner and M. W. Wegener (2001). Nature, society and history in two contrasting landscapes in Wisconsin, USA: interactions between lakes and humans during the Twentieth century. Land Use Policy 18: 41-51.

Scheffer, M., S. R. Carpenter, J. A. Foley, C. Folke and B. Walker (2001). Stochastic events can trigger large state shifts in ecosystems with reduced resilience. Nature 413: 591-96.
Stumborg, B. E., K. A. Baerenklau and R. C. Bishop. (2001). Nonpoint source pollution and present values: a contingent valuation of Lake Mendota. Review of Agricultural Economics, 23(Spring/Summer): 120-132.
Urban, N. R. and A. E. Monte (2001). Sulfur burial in and loss from the sediments of Little Rock Lake, Wisconsin. Canadian Journal of Fisheries and Aquatic Sciences 58: 1347-55.
Winter, T. C. (2001). The concept of hydrologic landscapes. Journal of the American Water Resources Association 37(2): 335-49.

In Press

Anderson, M. P. and K. P. Chung (In Press). Zones of high hydraulic conductivity for representing lakes in groundwater flow models. Water Resources Research.
Benson, B. J., J. J. Magnuson, R. L. Jacob and S. L. Fuenger (In Press). Response of lake ice breakup in the Northern Hemisphere to the 1976 interdecadal shift in the North Pacific. Verhandlungen Internationale Vereinigung fur Limnologie 27.
Carpenter, S.R (In Press). Ecological futures: building an ecology of the long now. Ecology
Dodson, S. I. (In Press). Effects of environmental heterogeneity in aquatic ecology. Verh. Internat. Verein. Limnol. 27.
Donner, S.D., M.T. Coe, J.D. Lenters, T.E. Twine, and J.A. Foley. (In Press).Modeling the impact of hydrological changes on Nitrite transport in the Mississippi River Basin from 1955-1994. Global Biogeochemical Cycles
Hamilton, D. P., C. M. Spillman, K. L. Prescott, T. K. Kratz and J. J. Magnuson (In press). Effects of atmospheric nutrient inputs and climate change on trophic status of Crystal Lake, Wisconsin. Verh. Internat. Verein. Limnol.
Jackson, R. B., C.N. Dahm, S.L. Postal, S.R. Carpenter, D.M. McKnoght, R.J. Naiman and S. W. Running (In Press). Water in a changing world. Ecological Applications.
Jorgensen, B. S. and R. C. Stedman (In Press). Measuring sense of place : lakeshore property owner's attitude toward their properties. Journal of Environmental Psychology. In Press.
Kratz, T. K., D. W. Bolgrien, S. Giblin and J. O'Leary (In Press). Human Influences on the Spatial Distribution of Coarse Woody Debris in Lakes in Northern Wisconsin, USA. Verh. Internat. Verein. Limnol.
Kratz, T. K., B. P. Hayden, B. J. Benson and W. Y. B. Chang (In Press). Patterns in the interannual variability of lake freeze and thaw dates. Verh. Internat. Verein. Limnol. 27.
Lathrop, R. C., B. M. Johnson, T. B. Johnson, M. T. Vogelsang, S. R. Carpenter, T. R. Hrabik, J. F. Kitchell, J. J. Magnuson, L. G. Rudstam and R. S. Stewart (In Press). Stocking piscivores to improve fishing and water clarity: a synthesis of the Lake Mendota biomanipulation project. Freshwater Biology.

Lenters, J. (In Press). .Long-term trends in the seasonal cycle of Great Lakes water levels. Journal of Great Lakes Research.

Magnuson, J. J. (In Press). Three generations of limnology at the University of Wisconsin. Verh. Internat. Verein. Limnol. 28.

Magnuson, J. J., R. H. Wynne, B. J. Benson and D. Robertson (In Press). Lake and river ice as a powerful indicator of past and present climates. Verh. Internat. Verein. Limnol. In Press.

Mittlebach, G. G., C. R. Steiner, K. L. Gross, H. L. Reynolds, S. M. Scheiner, R. B. Waide, M. R. Willig and S. I. Dodson (In Press). What is the relationship between species richness and productivity? Ecology.

O'Keefe, T. C. and S. I. Dodson (In Press). Long-term population dynamics of zooplankton in northern temperate lakes. Verh. Internat. Verein. Limnol. 27.

Robertson, D. M., R. H. Wynne and W. Y. B. Chang (In Press). Variability in ice cover across the Northern Hemisphere during the 1900's associate with El Nino events. Verh. Internat. Verein. Limnol.

Rusak, J. A., N. D. Yan, K. M. Somers, K. L. Cottingham, F. Micheli, S. R. Carpenter, T. M. Frost, M. J. Paterson, and D. J. McQueen. (In Press). Temporal, spatial, and taxonomic patterns of crustacean zooplankton variability in unmanipulated north-temperate lakes. Limnology and Oceanography.

Schell, J., C. J. Santos-Flores, B. M. Hunker, S. Klowhn, A. Michelson, R. A. Lillie and S. I. Dodson (In Press). Zooplankton of small lakes and wetland ponds in Wisconsin, USA. Hydrobiologia.

Stedman, R.C. Toward a social psychology of place. (In Press). Environment and Behavior.

Turner, M. G., S. L. Collins, A. L. Lugo, J. J. Magnuson, T. J. Rupp and F. J. Swanson (In Press). Disturbance dynamics and ecological response: the contribution of long-term ecological research. BioScience.

Wynne, R. H. and T. G. Gregoire (In Press). Statistical modelling of lake ice phenology: issues and implications. Verh. Internat. Verein. Limnol. 27.

Books

National Research Council (1996). Freshwater ecosystems: revitalizing educations programs in limnology. Washington, D.C., National Academy Press.

Bates, J. (2001). River Life: the natural and cultural history of a northern river. Mercer, WI, Manitowish River Press.

Turner, M. G., R. H. Gardner and R. V. O'Neill (2001). Landscape ecology in theory and practice: pattern and process. New York, Springer-Verlag,.

Book Chapters
1996

Arnell, N., B. Baytes, H. Land, J. J. Magnuson, P. I. Mullholland, S. Fischer, C. Lui, D. McKnight, O. Starosolov and M. Taylor (1996). Hydrology and Freshwater Ecology. Climate Change 1995 - Impacts, Adaptations and Mitigations of climate change: Scientific and Technical Analysis. Contributions of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change Working Group II. R.T. Watson, M.C. Zinyowera, and R.H. Moss.Cambridge University Press:325-363.

Carpenter, S., T. Frost, L. Persson, M. Power and D. Soto (1996). Freshwater ecosystems: linkages of complexity and processes. Functional roles of biodiversity: a global perspective. H. A. Mooney, J. H. Cushman, E. Medina, O. E. Sala and E.D. Schulze, John Wiley & Sons Ltd.: 299-25.

Frost, T. M. and E. R. Blood (1996). The role of major research centers in the study of inland aquatic ecosystems. Freshwater ecosystems: revitalizing educational programs in limnology. Washington, D.C., National Academy Press: 279-88.

Kiefer, R. W. and T. M. Lillesand (1996). Remote sensing. Engineering Handbook: Chap 151 pp.1614-1620.

Lillesand, T. M. (1996). A protocol for satellite-based land cover classification in the upper midwest. Gap Analysis: A Landscape Approach in Biodiversity Planning. J. M. Scott, T. H. Tear and F. W. Davis, American Society of Photogrammetry and RemoteSensing: 103-118.

Naiman, R. J., P. A. Bisson, R. G. Lee and M. G. Turner (1996). Approaches to management at the watershed scale. Watershed Managment. J. F. Franklin. New York, Springer-Verlag.

1997

Magnuson, J. J. (1997). Freshwater Ecosystems, Hydrology, & Water Resources. in Hassol, S.J. and Katzenberger. J. [eds]. Elements of Change 1996, Aspen Global Change Institute, Aspen CO.: 172-176.

Magnuson, J. J. and B. T. De Stasio (1997). Thermal niche of fishes and global warming. Global warming: implications for freshwater and marine fish. W. C.M. and D. G. McDonald. Cambridge, U.K., Cambridge University Press. Society for Experimental Biology Seminar Series 61: 377-408.

Monger, B. C., J. M. Fischer, B. A. Grantham, V. Medland, B. Cai and K. Higgins (1997). Frequency response of a simple food-chain model with time-delayed recruitment: implications for abiotic-biotic coupling. Structured-population models. S. Tuljapurkar and H. Caswell, Chapman Hall: 433-50.

1998

Benson, B. J. (1998). The World Wide Web as a tool for ecological research programs. Data and information management in the ecological sciences: a resource guide. W. K. Michener, J. H. Porter and S. G. Stafford. Albuquerque, New Mexico, Long-Term Ecological Research Network Office, University of New Mexico: 59-63.

Benson, B. J. and M. Stubbs (1998). Information access and database integrity at the North Temperate Lakes Long-Term Ecological Research Project. Data and information management in the ecological sciences: a resource guide. W. K. Michener, J. H. Porter and S. G. Stafford. Albuquerque, New Mexico, Long-Term Ecological Research Network Office, University of New Mexico: 95-97.

Briggs, J. M., B. J. Benson, M. Hartman and R. Ingersoll (1998). Data entry. Data and information management in the ecological sciences: a resource guide. W. K. Michener, J. H. Porter and S. G. Stafford. Albuquerque, New Mexico, Long-Term Ecological Research Network Office, University of New Mexico: 29-31.

Carpenter, S. R. (1998). Ecosystem ecology: integrated physical, chemical and biological processes. Ecology. S. I. Dodson. London, Oxford University Press: 123-62.

Carpenter, S. R. (1998). The need for large-scale experiments to assess and predict the response of ecosystems to perturbation. Successes, Limitations, and Frontiers in Ecosystem Science. M. L. Pace and P. M. Groffman. New York, Springer-Verlag: 287-312.

Henshaw, D. L., M. Stubbs, B. J. Benson, K. Baker, D. Blodgett and J. Porter (1998). Climate information access across research sites. Data and information management in the ecological sciences: a resource guide. W. K. Michener, J. H. Porter and S. G. Stafford. Albuquerque, New Mexico, Long-Term Ecological Research Network Office, University of New Mexico: 123-27.

Kratz, T. K., B. Bojanovsky, V. Drabkova and S. V. (1998). International networks of lake sites: report of working group 4. Management of lakes and reservoirs during global climate change. D. G. George, J. G. Jones, C. S. Puncochar, C. S. Reynolds and D. W. Sutcliffe, Kluwer Academic: 307-32.

Kratz, T. K., P. A. Soranno, S. B. Baines, B. J. Benson, J. J. Magnuson, T. M. Frost and R. C. Lathrop (1998). Interannual synchronous dynamics in north temperate lakes in Wisconsin, USA. Management of lakes and reservoirs during global climate change. D. G. George, J. G. Jones, C. S. Puncochar, C. S. Reynolds and D. W. Sutcliffe, Kluwer Academic Publishers: 273-87.

Nowak, P. and P. Korsching (1998). The human dimension of soil and water conservation: a historical and methodological perspective. Advances in Soil and Water Conservation. F. J. Pierce and W. W. Frye. Chelesa, MI, Ann Arbor Press: 159-84.

Nowak, P., F. Madison and R. Shepard (1998). Farmers and manure management: a critical analysis. Animal Waste Utilization: Effective Use of Manure as a Soil Resource. J. Hatfield and B. Stewart. Chelesa, MI, Ann Arbor Press: 1-32.

Turner, M. G., S. R. Carpenter, E. J. Gustafson, R. J. Naiman and S. M. Pearson (1998). Land use. Status and Trends of the Nation's Biological Resources. M. J. e. a. Mac. Reston, VA, U.S. Department of the Interior, U.S. Geological Survey. 1: 37-61.

Walker, J. F. and D. P. Krabbenhoft (1998). Groundwater and surface-water interactions in riparian and lake-dominated systems. Isotope Tracers in Lake-dominated Systems. J. J. McDonnell and C. Kendall. Amsterdam, Netherlands, Elsevier: 467-88.

1999

McCallister, R. and P. Nowak (1999). Whole-soil knowledge and management: a foundation of soil quality. Soil Quality and Soil Erosion. R. Lal. Boca Raton, FL, CRC Press: 173-93.

2000

Bolgrien, D. W. and T. K. Kratz (2000). Lake shore riparian areas. Riparian management in the Continental Eastern United States. E. S. Verry, J. W. Hornbeck and C. A. Dolloff. Washington, D.C., Lewis Publishers: 207-217.

Frost, T. M. and J. M. Fischer (2000). Assessing the effects of acidification on aquatic ecosystems. Methods in Ecosystem Science. O. Sala, R. Jackson, H. Mooney and R. Howarth. New York, Springer: 330-40.

Veroff, D. and P. R. Voss (2000). Population Issues and the Great Lakes Region. In The Future of the Great Lakes: Perspectives on North America's Most Vital Region, Harbor House Publishers, Inc. and the Great Lakes Commission.

Voss, P. R. (2000). Rural areas. Encyclopedia of the U.S. Census. M. J. Anderson. Washington, D.C., C. Q. Press: 320-22.

2001

Allen, T. F. H. (2001). The nature of the scale issue in experimentation. Chapter 3. Scaling relations in experimental ecology. R. H. Gardner, W. M. Kemp, V. S. Kennedy and J. E. Petersen. New York, Columbia Press: 89-111.

Allen, T. F. H. (2001). Applying the principles of ecological emergence to building design and construction. Construction ecology Metabolism: nature as a model for the built environment. C. Kibert, J. Sendzmir and B. Guy. London.

Carpenter, S. R. (2001). Alternate states of ecosystems: evidence and some implications. Ecology: achievement and challenge. M. C. Press, N. J. Huntly and S. Levin. Oxford, Blackwell Science: 357-83.

Frost, T. M., R. E. Ulanowicz, S. C. Blumenshine, T. F. H. Allen, F. Taub and J. H. Rodgers Jr. (2001). Scaling issues in experimental ecology: freshwater ecosystems. Scaling relations in experimental ecology. R. H. Gardner, W. M. Kemp, V. S. Kennedy and J. E. Petersen. New York, Columbia University Press: 253-79.

Magnuson, J. J. (2001). Lakes and Rivers. Encyclopedia of Global Environmental Change. T. Munn, John Wiley & Sons Limited.

In Press

Carpenter, S., R. Lathrop, P. Nowak, D. Armstrong, E. Bennett, K. Brasier, B. Kahn and T. Reed-Anderson (In Press). The ongoing experiment : the restoration of Lake Mendota. Lakes in the Landscape. J. J. Magnuson and T. K. Kratz, Oxford University Press.

Frost, T. M. (In Press). Freshwater sponges. Paleoenvironmental Research. H. J. B. J.P. Smol, & W.M. Last,, Kluwer Academic Publishers. 2 Biological Techniques.

Frost, T. M., H. M. Reiswig and A. Ricciardi (In Press). Porifera. Ecology and Classification of North American Freshwater Invertebrates (Second Edition). J. H. T. a. A. P. Covich. New York, New York, USA, Academic Press. .

Habiba, G., S. Brown, W. Easterling, B. Jallow, J. Antle, M. Apps, R. Beamish, T. Chapin, W. Cramer, J. Frangi, J. Laine, L. Erda, J. Magnuson, I. Noble, J. Price, T. Prowse, T. Root, E. Schultz, O. Sirotenko, B. Sohngen and J. Soussana. (In

Press). Ecosystems and their goods and services. Climate change 2001: Impacts , Adaptation, and Vulnerablility. Contribution of Working group II to the third Assessment Report of the Intergovernmental Panel on Climate Change. J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White. Oxford, Oxford University Press.

Jorgensen, B. S., D. Nowacek, R. Stedman, K. Brasier and D. Long (In Press). People in a forested lake district. Lakes in the Landscape. J. Magnuson and T. Kratz, Oxford University Press.

Turner, M. G., T. R. Crow, D. R. J. Liu, C. F. Rabeni, P. A. Soranno, W. W. Taylor, K. A. Vogt and J. A. Wiens (In Press). Bridging the gap between landscape ecology and natural resource management. Integrating landscape ecology into natural resource management. J. Liu and W. Taylor, Cambridge University Press.

Dissertations and Theses

1996

Bobo, M. R. (1996). Incorporation of categorical ancillary data into multispectral image classifications using a modified Bayesian decision rule, M.S. University of Wisconsin-Madison: 171.

Fischer, C. S. (1996). Use of multi-temporal remote sensing data to detect forest canopy change on the Nicolet National Forest. M.S. Forest Ecology and Management, University of Wisconsin-Madison.

Gergel, S. E. (1996). Scale-dependent landscape effects on north temperate lakes and rivers. M.S. Zoology/Limnology and Oceanography. University of Wisconsin-Madison: 46.

Jennings, N. P. (1996). An investigation of data integration and texture analysis using ERS and Landsat TM data for land cover assessment, M.S. University of Wisconsin-Madison:viii-169.

Lewis, D. B. (1996). The roles of lake calcium concentration and crayfish abundance in mediating crayfish predation on snails. M.S. Oceanography and Limnology, University of Wisconsin-Madison:iii-68.

1997

Fischer, J. M. (1997). Zooplankton community responses to acidification: the role of rapid evolution and compensatory dynamics. Ph.D. Zoology, University of Wisconsin-Madison: 114.

Puth, L. M. (1997). Finding a powerful definition of ecological corridors: lessons from the spread of an exotic crayfish in northern Wisconsin. M.S. Conservation Biology and Sustainable Development, University of Wisconsin-Madison: 52.

1998

Arnott, S. E. (1998). Species turnover and richness of aquatic communities in north temperate lakes. Ph.D. Zoology. Madison, University of Wisconsin-Madison: 176.

Champion, G. (1998). Transient and steady-state flow models of a ground-water and lake system: Trout Lake Basin, northern Wisconsin. M.S. Geology, University of Wisconsin-Madison: 109.

Lathrop, R. C. (1998). Water clarity responses to phosphorus and daphnia in Lake Mendota. Ph.D. Oceanography and Limnology, University of Wisconsin-Madison: 140.

Sanderson, B. L. (1998). Factors regulating water clarity in northern Wisconsin lakes. Ph.D. Zoology, University of Wisconsin-Madison: 170.

Webster, K. E. (1998). Responses of lakes to drought: geomorphic and landscape controls. Ph.D. Oceanography and Limnology, University of Wisconsin-Madison: i; 180.

1999

Bennett, E. M. (1999). Human impacts on erodable phosphorus and eutrophication. Land Resources, M.S. University of Wisconsin-Madison: 56.

Fallah-Moghaddam, P. (1999). Ascomycetes from north temperate lakes in Wisconsin. Ph.D. Plant Biology, University of Ilinois at Urbana-Champaign: 190.

Foreman, W. J. (1999). Carp-mediated phosphorus cycling in a shallow eutrophic lake: Lake Wingra, Wisconsin, U.S.A. M.S. Oceanography and Limnology, University of Wisconsin-Madison: 113.

Hrabik, T. R. (1999). Factors influencing fish distribution and condition within lakes and across landscapes. Ph.D. Oceanography and Limnology. Madison, University of Wisconsin-Madison: 234.

Reed-Andersen, T. (1999). Flows of phosphorus on an agricultural landscape: implications for eutrophication and restoration of Lake Mendota. Ph.D. Zoology, University of Wisconsin-Madison: 180.

Willis, T. V. (1999). Patterns in species composition across the interface between streams and lakes. M.S. Oceanography and Limnology, University of Wisconsin-Madison: 40.

2000

Greenfield, B. K. (2000). Predicting mercury levels in fish: use of water chemistry, trophic ecology, and spatial traits. M.S. Zoology/Oceanography and Limnology, University of Wisconsin-Madison: ii-53.

Lauster, G. H. (2000). Nutrient Limitation of Aquatic Bacteria, and the Importance of Bacteria and Algae to Colloid Dynamics in Lake Michigan. Ph.D. Oceanography and Limnology. University of Wisconsin-Madison: i-169.

Lewis, D. B. (2000). Niche-based and biogeographic constraints on benthic communities. Ph.D. Limnology and Marine Science. Madison, University of Wisconsin:205.

Schnaiberg, J. A. 2000. Breaking waves: an analysis of lakeshore development in Vilas County, Wisconsin, USA. M.S. Land Resources, University of Wisconsin-Madison.

Stedman, R. C. (2000). Up north: A social psychology of place. Ph.D. Sociology/Rural Sociology. University of Wisconsin-Madison: 283pp.

Wilson, M. A. (2000). Rethinking Scope Sensitivity and Contingent Valuation Surveys: Strong Environmental Attitudes and Contingent Economic Values. Ph.D. University of Wisconsin-Madison.

2001
Dripps, W. (2001). Temporal and spatial variability of natural groundwater recharge. M.S. Water Resoures, University of Wisconsin-Madison.
Wegener,M. (2001). Long-term land use/cover change patterns in the Madison Lakes Area and their impacts on runoff volume to Lake Mendota. M.S. University of Wisconsin-Madison.

2002
Bennett, E.M. (2002). Patterns in soil phorphorus: variability and concentrations in an urbanizing argricultural watershed. Ph.D. Limnology and Marine Sciences, University of Wisconsin-Madison: 150.
Wilson, K.A. (2002). Impacts of the invasive rusty crayfish (*Orconectes rusticus*) in northern Wisconsin lakes. Ph.D. Zoology, University of Wisconsin-Madison.

Other Publications
1996
Benson, B. J. (1996). The North Temperate Lakes LTER research information management system. Eco-Informa '96: Global Networks for Environmental Information, Lake Buena Vista, Florida, Environmental Research Institute of Michigan.
Cardille, J. A., D. W. Bolgrien, R. H. Wynne and J. W. Chipman (1996). Variation in landscape metrics derived from multiple independent classifications. Eco-Informa '96, Lake Buena Vista, Florida.
Stafford, S. G., J. W. Brunt and B. J. Benson (1996). Training environmental information managers of the future. Eco-Informa '96, Lake Buena Vista, Florida.
Stubbs, M. and B. J. Benson (1996). Query access to relational databases via the world wide web. Eco-Informa '96, Lake Buena Vista, Florida.

1998
Hunt, R. J., V. A. Kelson and M. P. Anderson (1998). Linking an analytic element code to MODFLOW - implementation and benefits. MODFLOW 98: Proceedings of the 3rd International Conference of the International Groundwater Modeling Center, Golden, Colorado, Colorado School of Mines.

1999
Lathrop, R. C. and T. K. Kratz (1999). Long term ecological research on Wisconsin lakes affected by human activities. Proceedings of the ILTER Regional Workshop : Long Term Ecological Research : Examples, Methods, Perspectives for Central Europe.: 67-71.

2000
Chipman, J. W., T. M. Lillesand and F. L. Scarpace (2000). Assessing the bias in interferometric radar measurements of elevation acquired over a forested region.

Proceedings of the American Society for Photogrammetry and Remote Sensing (ASPRS), Washington, DC.

Hoekstra, T. W., T. F. H. Allen, J. Kay and J. A. Tainter (2000). Appendix H: Criteria and indicators for ecological and social system sustainability with system management objectives. North American test of criteria and indicators of sustainable forestry. Inventory and Monitoring Institute Report No.3, Washington DC., USDA Forest Service.

McCormick, R. J., T. A. Brandner and T. F. H. Allen (2000). Toward a Theory of Meso-scale Wildfire Modeling - A Complex Systems Approach Using Artificial Neural Networks. The Joint Fire Science Conference and Workshop, "Crossing the Millennium Integrating Spatial Technologies and Ecological Principals for a New Age in Fire Management., Moscow, Idaho, University of Idaho and the International Association of Wildland Fire. .

Walker, J. F. and T. D. Bullen (2000). Trout Lake, Wisconsin: A Water, Energy, and Diogeochemical Budgets Program Site: U.S. Geological Survey Fact Sheet: 161-99.

2001

Allen, T. F., H. T. Havlicek and J. Norman (2001). Wind tunnel experiments to measure vegetation temperature to indicate complexity and functionality. Proceedings of the Second Biennial International Workshop on Advances in Energy Studies, Porto Venere, Italy.

Allen, T. F. H., J. A. Tainter and T. W. Hoekstra. (2001). Complexity, energy transformations and post-normal science. Proceedings of the Second Biennial International Workshop on Advances in Energy Studies, Porto Venere, Italy.

Allen, T. F. H. (2001). Hierarchy theory in Ecology. Encyclopedia of Environmetrics, Wiley.

Bauer, M., L. , S.M. Olmanson, M. Kloiber, P. Schultze, P. Brezonik, J. Chipman, J. Riera and T. Lillesand. (2001). Assessment of Lake Water Clarity in the Upper Great Lakes Region. Proceedings, Annual Meeting of the American Society for Photogrammetry and Remote Sensing (ASPRS), St. Louis, MO.

Lillesand, T. M., J. Riera, J. Chipman, J. Gage, M. Janson, J. Panuska and K. Webster. (2001). Integrating Multi-Resolution Satellite Imagery Into A Satellite Lake Observatory. Annual Meeting of the American Society for Photogrammetry and Remote Sensing (ASPRS), St. Louis, MO.

Lillesand, T., J.Chipman, J. Schmaltz and J. Leale (In Press). A Multi-sensor Approach to Monitoring the Transparency of Wisconsin's Lakes. Workshop on Remote Sensing and Resource Management in Nearshore and Inland Waters, Wolfville, Nova Scotia.

Publications resulting from Workshops organized and lead by NTL Scientists

The following list includes articles produced as a result of two workshops, one on Ice Phenology and the other on the Ecological Organization of Lake Districts, organized by NTL-LTER researchers and held at the University of Wisconsin Trout Lake Station. The publications listed here do not use NTL-LTER data. Publications from these workshops that use NTL data are listed in NTL publication list above.

Ice Phenology Workshop

Adrian, R. and N. Walz. (In Press). How far do winter conditions propagate in time? Effects of the ice phenology on the plankton succession in a shallow lake. Verh. Internat. Verein. Limnol. 27

Arai T. (In Press). Long term ice record of Lake Suwa in Japan and its hydroclimatological significance. Verh. Internat. Verein. Limnol. 27

Assel, R.A. and L.R. Herche. (In Press). Coherence of long-term lake ice records. Verh. Internat. Verein. Limnol. 27

Elo, A.R.. and S. Vavrus. (In Press). Ice modelling calculations, comparison of models PROBE and LIMNOS. Verh. Internat. Verein. Limnol. 27

Granin, N.G., D.H. Jewson, A.A. Zhdanov, L.A. Levin, A.T. Averin, R.Y. Gnatovsky, L.A. Gorbunova, V.V. Tcekhanovsky, and N.P. Minko. (In Press). Physical processes and mixing of algal cells under the ice of Lake Baikal. Verh. Internat. Verein. Limnol. 27

Gronskaya, T. (In Press). Ice thickness in relation to climate forcing in Russia. Verh. Internat. Verein. Limnol. 27

Kuusisto, E. and A.R. Elo.(In Press). Lake ice variables as climate indicators in Finland. Verh. Internat. Verein. Limnol. 27

Likens, G.E. (In Press). A long-term record of ice cover for Mirror Lake, New Hampshire: effects of global warming? Verh. Internat. Verein. Limnol. 27

Livingstone, D.M. (In Press). Large-scale climatic forcing detected in historical observations of lake ice break-up. Verh. Internat. Verein. Limnol. 27

Stewart, K.SM. (In Press). Annual variability of ice thickness on two lakes in western New York State. Verh. Internat. Verein. Limnol. 27

Vuglinsky, V. (In Press). Extremely early and late dates of lake freezing and breakup in the northern hemisphere. Verh. Internat. Verein. Limnol. 27

Ecological Organization of Lake Districts Workshop

Baron, J.S. and N. Caine. (2000). The temporal coherence of two alpine lake basins of the Colorado Front Range, U.S.A. Freshwater Biology 43(3): 643-476.

Bukaveckas, P.A., M. Robbins-Forbes: (2000). Role of dissolved organic carbon in the attenuation of photosynthetically active and ultraviolet radiation in Adirondack lakes. Freshwater Biology 43(3): 339-354.

Dixit, A.R., R.I Hall, P.R. Leavitt, R. Quinlan and J. P. Smol. (2000). Effects of sequential depositional basins on lake response to urban and agricultural pollution: a palaeoecological analysis of the Qu'Appelle Valley, Saskatchewan, Canada. Freshwater Biology 43(3): 319-338.

George, D.G., J.F. Talling, and E. Riggs. (2000). Factors influencing the temporal coherence of five lakes in the English Lake District. Freshwater Biology 43(3): 449-462.
Gronskaya,T.P. (2000). Lake districts of northwestern Russia: identification of sub regions based on analyses of hydrologic data. Freshwater Biology 43(3): 385-390.
Kling,G.W., G.W. Kipphut, M.M. Miller, and W.J. O'Brien. (2000). Integration of lakes and streams in a landscape perspective: the importance of material processing on spatial and temporal coherence. Freshwater Biology 43(3): 477-498.
Kopacek, J., E. Stuchlik, V. Straskrabova, and P. psenakova. (2000). Factors governing nutrient status of mountains lakes in the Tatra Mountains. Freshwater Biology 43(3): 385-390.
Lyons, B.W., A. Fountain, P. Doran, J.C. Priscu, K. Neumann, and K.A. Welch. (2000). The importance of landscape position and legacy: the evolution of the lakes in Taylor Valley, Antarctia. Freshwater Biology 43(3): 355-368.
Paszkowski, C.A. and W.M. Tonn. (2000). Community concordance between the fish and aquatic birds in northern Alberta lakes: the relative importance of environmental and biotic factors. Freshwater Biology 43(3): 421-438.
Saunders, P.A., W.H. Shaw and P.A. Bukaveckas. (2000). Differences in nutrient limitation and grazer suppression of phytoplankton in seepage and drainage lakes of Adirondack region, NY, U.S.A. Freshwater Biology 43(3): 391-408.