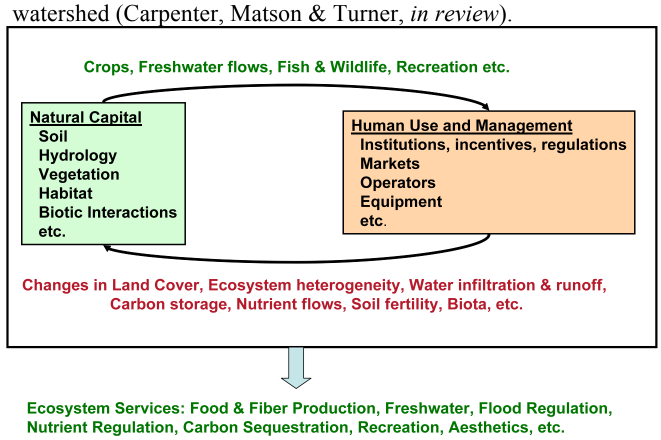
INTRODUCTION

The sustainability transition – ensuring human wellbeing while maintaining the life-support systems of the planet – is among society's great challenges (NRC 1999, Kates et al. 2001, Matson 2009). Recent reports prioritize the agenda of an interdisciplinary research enterprise for sustainability (International Council of Science 2009, Levin and Clark 2010). The vast intellectual landscape of sustainability science is connected by networks of social, economic, physical and ecological interactions that involve water quality and quantity (Millennium Ecosystem Assessment 2005a, International Assessment of Agricultural Knowledge, Science and Techology 2009, World Water Assessment Programme 2009). Human needs for freshwater are growing as changes in climate, landscapes, the built environment and institutions alter water flows and quality in sometimes unpredictable ways. These changes affect ecosystem services related to freshwater, such as flows of freshwater for domestic, agricultural, industrial, recreational and other uses; regulation of floods; water quality; and aspects of human health (Carpenter and Biggs 2009). Such patterns are global, *but water use decisions and impacts are often most apparent in regional watershed studies of human-environment systems*. To strengthen conceptual frameworks and improve predictive capacity, interdisciplinary analyses should integrate biophysical and social-economic aspects of regional water systems. This need evokes the overarching question of our proposal:

How will ecosystem services related to freshwater vary and how can they be sustained in regional watersheds as climate, land use and land cover, land management, the built environment and human demands change?

Figure. 1 Natural capital and ecosystem services of an agricultural watershed (Carpenter, Matson & Turner, *in review*).



Landscapes of the Upper Midwest, USA include some of the world's richest croplands, vibrant cities, valuable remnants of forests, grasslands and wetlands, and extensive freshwater ecosystems. These landscapes generate multiple ecosystem services, providing cultivated and wild food, fiber, biofuel, freshwater, carbon storage, recreation for a growing human population, and regulation of water and nutrient flows (**Fig. 1**). Changing land use has already altered ecosystem services in Midwest US watersheds. Increasing fertilizer use and mismanagement of manure has led to excess flows of nitrogen (N) and phosphorus (P) to surface and groundwater systems, causing serious degradation of aquatic ecosystems and risk to human health (Carpenter et al. 1998, Goolsby et al. 1999, Donner and Kucharik 2008). Use of buffer strips, wetlands, manure management technology, and land set-aside programs can decrease erosion and nutrient inputs to rivers and lakes (Gilliam 1994, Gold et al. 2001). Conversion of native prairies to agricultural row crops since the mid 1800s has led to 50% loss of soil carbon (C) (Kucharik et al. 2001). Soil C storage is associated with soil fertility and water holding capacity and is a proxy for climate regulation of the planet, and much attention is now focused on increasing C sequestration through soil conservation practices (Post and Kwon 2000, Kucharik 2007). Future land use change to support bioenergy feedstocks could alter rates of evapotranspiration (ET) and surface runoff, potentially changing the large-scale water balance in agricultural watersheds. Population increases can lead to significant drawdown of aquifers, and urbanization can intensify "heat island" footprints, reduce groundwater recharge, increase surface runoff and flooding, and potentially eliminate baseflow in the worst case scenarios; however, engineering solutions to stormwater management offer a tool to ameliorate some of these consequences (Steuer and Hunt, 2001). Adaptation to climate change could emerge from strategic human-environment interactions that cause landscapes and the water system to become more resilient to climate change.

As the environment of the Upper Midwest changes, scientists and decision makers are increasingly confronted by freshwater problems such as flood regulation, eutrophication, and pollution of drinking water supplies. Climate change could further alter water flows, and interest in managing agroecosystems for C sequestration could alter regional hydrology. At the same time, human populations and demands for agricultural production are expected to grow. While extensive changes may be inevitable, there are tremendous opportunities for guiding change toward channels that maintain *a balance of ecosystem services, meet needs for human wellbeing, conserve the capacity of Midwestern environments to provide services into the future, and build resiliency for unpredictable changes in climate or other environmental drivers*. But what pathways are possible, what are the benefits and tradeoffs, and in what ways might human systems react to the options? These issues lead us to three specific research questions:

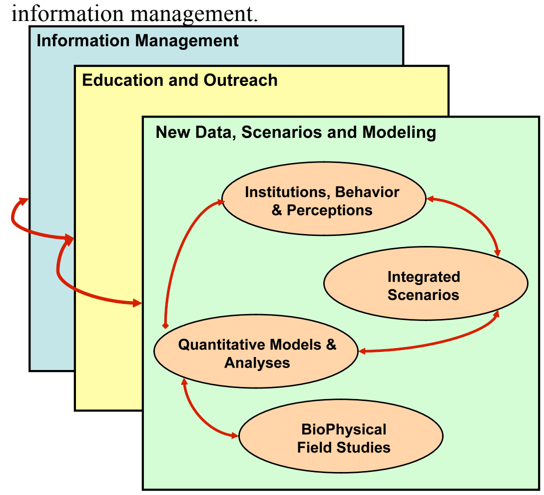
1) **How do different patterns of land use, land cover, land management, and water resource engineering practices affect the resilience and sensitivity of freshwater ecosystem services under a changing climate?**

2) **How can regional governance systems for water and land use be made more resilient and adaptive to meet diverse human needs?**

3) **In what ways are regional human-environment systems resilient and in what ways are they vulnerable to potential changes in climate and freshwaters?**

To address these questions we propose an interdisciplinary program of research on the Yahara Watershed, a well-studied, diverse landscape in the Upper Midwest. The watershed is located in southern Wisconsin and is home to the capital city of Madison and the University of Wisconsin.

Figure 2. This project coordinates studies of institutions, quantitative models, biophysical field studies and integrated scenarios across three levels: new research, education and outreach, and information management.



APPROACH

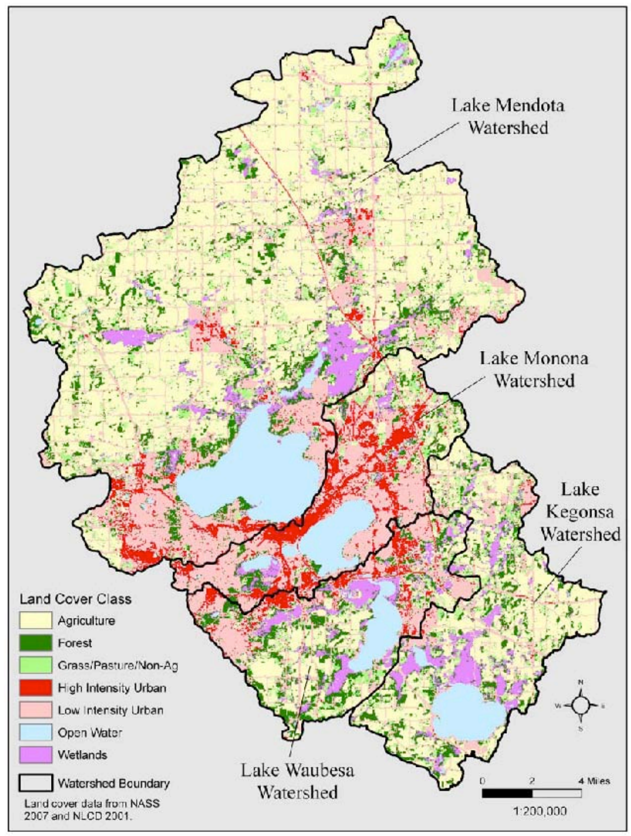
Understanding change in complex watershed systems subject to large and uncertain trends in climate and other large-scale drivers requires the integration of vast amounts of information, including perceptions, beliefs and priorities that affect decisions of individuals and organizations. The problem is not a shortage of information. Rather, the challenge is to organize the information in ways that illuminate alternative pathways and their logical consequences. We will develop, investigate and evaluate an approach for assessing future pathways of watershed development on decadal time scales using a watershed that is an exemplar of water-related issues in the Upper Midwest. Our approach integrates scenarios, quantitative models, and new empirical studies of institutions and the biophysical system, across three layers of the project: research, outreach and education, and information management (**Fig. 2**). In this section, we describe our study system and explain the four research elements: (1) Quantitative Modeling; (2) Biophysical Field Studies; (3) Regional Governance; and (4) Integrated Scenarios.

Study Region

The **Yahara** watershed of southern Wisconsin (contains **Madison, WI**, USA: 43˚6'N, 89˚24'W) drains 996 km^2 and contains five major lakes (**Fig. 3**) that have been significantly impacted already by changes in seasonal climate over the past 60 years (Kucharik et al., 2010), agricultural land use, and a growing urban environment. Changing land-use, management, urbanization, and policy are placing competing demands on the water system, and may affect the resilience of built and natural environments under a changing climate. Many players typically aroused by competing water management goals are already present in the watershed, including farmers, urban and suburban residents, developers, realtors, recreationists, policy-makers, neighborhood associations, environmental NGOs, and business associations. Water and land use governance in the watershed is complex and multilayered. Although most resource sectors are managed independently, efforts to link land use with water quality impacts have prompted the establishment of regional authorities. This watershed also exemplifies three features that often stymie implementation of environmental reform: (1) a complex ecological system where cause-and-effect relationships are not easily understood, (2) benefits and costs of different land management scenarios accrue largely in the future, and (3) a situation where actors degrading the water system are different from the users who suffer the costs.

Drivers of recent change. The Yahara Watershed is largely agricultural (principally corn, soy and dairy) but includes a densely populated urban area and some remnant native vegetation (**Fig. 3**). The mix of urban areas, croplands, forests, pastures, wetlands and prairie make for a complex environment to interact with water. Stresses on ecosystem services of the Yahara watershed typify many agricultural landscapes (Turner et al. 1998). Organic C storage in watershed soils has declined by ~50% (Kucharik et al. 2003, Kucharik 2007). Groundwater extraction, loss of wetlands, reduced infiltration, and increased runoff from impervious surfaces have altered the hydrology and increased flood frequency (Soranno 1996, Wegener 2001). Nitrate is contaminating groundwater, and P loads from nonpoint runoff substantially exceed those that occurred prior to agriculture (Carpenter et al. 2006, Lathrop 2007). Today, a high incidence of use of pesticides, fertilizers and manure have contributed to water quality issues in area lakes, as well as increased "flashiness" of runoff from heavy rainfall events. Climate change is already occurring; since 1950, the growing season has lengthened, the number of extremely cold days has declined, and rainfall on frozen soil conditions and the frequency of intense rainfall events have both increased (Kucharik et al., 2010). Plant phenology has also changed, with emergence and flowering occurring earlier for many species (Bradley et al., 1999). Remote sensing studies (Zhang et al., 2004) have also confirmed an early season green-up by 3-6 days in the Madison area, attributed to an Urban Heat Island (UHI). The dynamics of ET, infiltration, and runoff may be significantly different within the urban setting vs. agricultural regions due to temperature differences in addition to direct effects of the built environment (i.e. increased impervious area and engineered drainage systems). Residential water use in summer may also increase as UHI footprints expand (Guhathakurta and Gober, 2007). These drivers interact to challenge the sustainability of freshwater resources and other ecosystem services throughout the region.

Figure 3. Current land cover in the Yahara Watershed. Madison is the centrally located high intensity urban area (red/ pink).



To address our first research question "**How do different patterns of land use, land cover, land management, and water resource engineering practices affect the resilience and sensitivity of freshwater ecosystem services under a changing climate?**", we will use a comprehensive program of model experiments and biophysical measurements to evaluate changes in five freshwater ecosystem services and five related ecosystem services.

<u>Quantitative Models and Analyses</u>

We will evaluate the consequences of future scenarios on five freshwater ecosystem services that are fundamental to the sustainability transition in the Yahara Basin (**Table 1**). As an added benefit, our modeling approaches also allow impacts on other ecosystem services to be addressed (**Table 1**). Because even correlated ecosystem services, such as those associated with water, may interact with the amounts and quality of other services, evaluating tradeoffs is inherent in studies of resource sustainability. We will use a range of plausible scenarios of alternate land uses, agroecosystem management and water resource engineering practices and changing climates to evaluate the capacity of landscape management to maintain flows of ecosystem services despite potentially adverse changes in climate. Our work will contribute to understanding the limits within which delivery of ecosystem services can be sustained, the potential tradeoffs that result from maximizing some services, and landscape hotspots where ecosystems are especially vulnerable to undesirable change. In contrast to the short (months to years) time frame of current management projects in the Yahara watershed, this project will address potential changes to 2050. This time frame is commensurate with scenario planning methods as well as emerging forecasting tools for climate, hydrology and ecosystems.

Table 1. Freshwater and other ecosystem services to be quantified in this study.

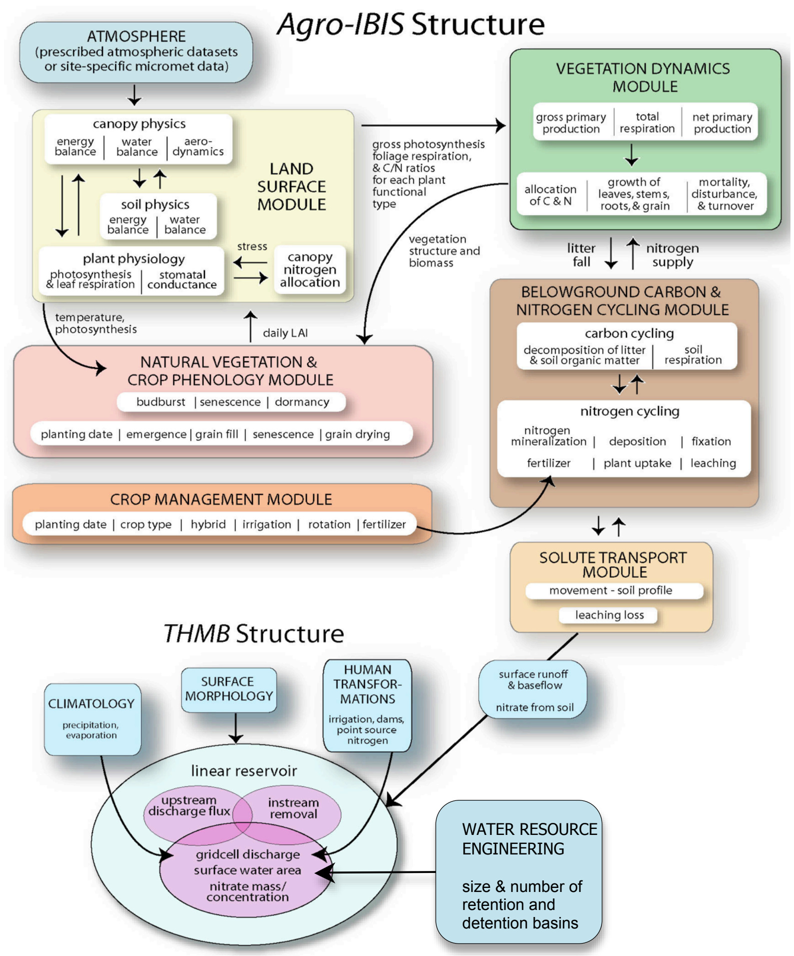
Ecosystem Service Category	Ecosystem Services	Indicator	Method
Freshwater	Freshwater supply	Groundwater recharge	Agro-IBIS
	Flood regulation	Peak runoff flows and lake levels	THMB
	Surface water quality	Phosphorus loads and lake total phosphorus	THMB, Agro-IBIS, Lake Water Quality Model
	Groundwater quality	Nitrate concentration in groundwater	Agro-IBIS, THMB
	Lake recreation	Lake total phosphorus, chlorophyll, cyanobacterial concentrations and trophic state index (Carlson 1977)	Yahara Water Quality Model
Other	Climate regulation - carbon	Soil organic carbon pool	Agro-IBIS
	Climate regulation - albedo	Albedo / surface energy budget	Agro-IBIS
	Terrestrial aesthetics and recreation	Extent and location of agricultural lands and natural areas	Land use and cover scenarios
	Food and biofuel production	Corn and soybean yields; Miscanthus, Switchgrass	Agro-IBIS

Next, we summarize the modeling tools that we will use, improvements to expand capabilities, and model validation. The three models are: (1) Agro-IBIS – a dynamic model of terrestrial ecosystem processes, biogeochemistry and water balance (Kucharik 2003); (2) THMB, an aquatic biogeochemistry and large-scale hydrology model (Coe 2000); and (3) a Lake Water Quality Model (Carpenter and Lathrop 2008).

Agro-IBIS: A Comprehensive Model of Land Surface and Ecosystem Processes (Fig. 4). Agro-IBIS simulates Midwest US natural vegetation (forests, grasslands) and corn, soybean, and wheat agroecosystems, including terrestrial C and N cycling (Kucharik et al. 2000, Kucharik and Brye 2003, Kucharik and Twine 2007, Donner and Kucharik 2008). Agro-IBIS accounts for agricultural management (fertilizer application, planting and harvest date) and the effects of environmental stressors on crop development and water balance and uses a 1 hr timestep. At a continuum of horizontal grid resolutions from 5 m to 250 km, Agro-IBIS simulates optimal planting date, crop yields, water balance, and nitrate leaching, crop yield and nitrate leaching response to varied N-fertilizer applications, and yield response to climate change. Agro-IBIS has been previously validated at the field scale (Kucharik and Brye 2003), including several AmeriFlux sites for coupled C and water cycling (Kucharik et al. 2006, Kucharik and Twine 2007), and the Mississippi basin-wide scale (Kucharik 2003, Donner and Kucharik, 2003, Twine and Kucharik 2008) for yields, NO_3 leaching, soil moisture, ET, phenology, and net primary production.

THMB: A Terrestrial Hydrology and Biogeochemistry Model (**Fig. 4**). To follow the surface runoff and sub-surface flows (and associated flows of leached N) simulated by Agro-IBIS into stream networks, we use the land surface hydrologic routing model THMB (Terrestrial Hydrology Model with Biogeochemistry). THMB is a continental-scale model that simulates the flow of water and nutrients from land surfaces to the ocean through a network of dynamic rivers, floodplains, and lakes (Coe 1998, 2000). As in previous work, the river flow paths will be developed from high-resolution topographic data sets of the basin and topographic maps. The derived hydrological network and floodplain morphology are linked at 30-m resolution to simulate the stage and discharge of rivers, the stage and geographic extent of flooded area and lakes, and the flux and concentration of nutrients in the river and floodplain all using a 1-hr timestep. The nitrate mass and concentration in the river and on the floodplain is calculated at each

Figure 4. Schematic of the Agro-IBIS and THMB ecosystem models.



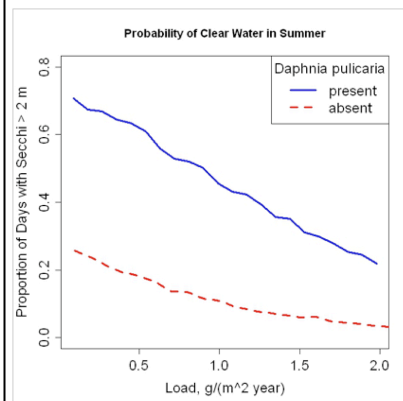
time step as a function of non-point sources (nitrate leaching from the soils simulated by Agro-IBIS), point source inputs, upstream fluxes, downstream transport and nitrate removal processes. THMB has been extensively tested and applied towards understanding hydrology and biogeochemical cycling across the Mississippi Basin (Coe 1998, Lenters et al. 2000, Donner et al. 2002, Donner and Kucharik 2003, 2008; Donner et al. 2004). Agro-IBIS and THMB together allow us to mechanistically simulate the hydrology and biogeochemistry of the entire basin simultaneously from source to sink including: (1) rainfall and N application on farm fields; (2) plant growth and uptake of water and nutrients; (3) crop growth and harvest; (4) surface and subsurface runoff of water and N; (5) soil moisture; and (6) transport of water and N in rivers and floodplain. Agro-IBIS and THMB will be run on a 250m grid across the watershed, will be parameterized with soil textural information as a function of soil depth (to 2.5 m) from the SSURGO digitized county soil surveys (~30m x 30m) and will use a 30-m digital elevation model (DEM) in the WTM8391 coordinate system for the Yahara watershed, available from the North Temperate Lakes (NTL) LTER project.

Model Innovations: In addition to the uses of Agro-IBIS and THMB in model experiments and scenarios described below, we will create three new modules: (1) We will link surface-water processes (THMB) and soil processes (Agro-IBIS) with a groundwater module to link subsurface components of the hydroscape and allow for spatially-distributed simulation of hydrologic responses of the watershed. This will enable us to simulate the consequences that increasing the amount of municipal pumping or changing its distribution will have on ecosystem services provided by the watershed. (2) We will expand the agricultural production model to include key perennial bioenergy cropping systems (switchgrass and *Miscanthus*) that are likely to expand in the Yahara watershed. (3) We will incorporate P transport to surface waters using Agro-IBIS and THMB. These innovations are useful contributions to ecosystem modeling and will enhance our ability to address the scientific questions of this proposal.

Lake Water Quality Modeling. Water and phosphorus flows from the Agro-IBIS/THMB models will be input to a Yahara Water Quality Model (YWQM) to project changes in water quality resulting from P management actions (Fig. 5). The YWQM includes inputs, outputs and recycling of P and is calibrated using annual P budgets (1975-present) and water quality data maintained by NTL LTER (http://lter.limnology.wisc.edu; Carpenter and Lathrop 2008, Lathrop 2007). The model will predict probability distributions during summer stratification of four water quality variates: chlorophyll, cyanobacteria ("blue-green algae"), total phosphorus and Secchi disk transparency for the four major lakes of the chain – Mendota, Monona, Waubesa and Kegonsa. The approach is similar to earlier models based on shorter time series for Lake Mendota (Lathrop et al. 1998, Stow et al. 1997). We will expand the time frame to encompass data from 1975 to 2012 and projections to 2050, and the scope to the large lakes of the Yahara chain.

Model validation. We will validate the application of the integrated modeling across the Yahara watershed using a comprehensive observational database. *(i) Soil moisture profiles, ET, stomatal conductance and the urban environment.* We will use soil moisture measurements, measurements of stomatal conductance, and meteorological observations (see following section on Biophysical Measurements) to quantify ET responses for each vegetation type that is simulated by Agro-IBIS to changes in air temperature, vapor pressure deficit, solar radiation, and soil moisture. *(ii) River discharge, nitrate leaching (Fig. 6), and nitrate export.* Multiple years of river discharge (1975 through Aug 2000), total N, NO_3, and NH_4 data available from the National Water Information System (http://waterdata. usgs.gov/nwis) for stations on the Yahara River and other tributaries will be used to calibrate the THMB model. *(iii) P export.* Agro-IBIS/THMB simulations of sediment and P loadings to surface waters will be validated using observed loadings available for stations on the Yahara River and other tributaries from the National Water Information System ((http://waterdata.usgs.gov/nwis). Lakewide loadings will be validated using syntheses of annual and seasonal loadings (Lathrop et al. 1998, Carpenter and Lathrop 2008, Lathrop 2007). *(iv) Crop yields, C balance and productivity of bioenergy cropping systems.* A field project at the Arlington Agricultural Research Station (located in the northern portion of the watershed) is assessing C sequestration potential associated with bioenergy cropping systems using measurements of leaf area index, soil temperature and moisture, soil respiration, and photosynthesis. These field observations will be used to parameterize and validate Agro-IBIS for poplar, corn, switchgrass, and *Miscanthus* bioenergy crops. *(v) Yahara Water Quality Model*. We will validate the YWQM for other major lakes of the Yahara chain (Monona, Waubesa, Kegonsa) by repeating the procedure used for Lake Mendota. Annual P loadings will be based on monitored loadings from the respective upstream lake plus modeled loadings for direct drainage areas. Predicted distributions of annual P mass are validated using time series of annual P budgets (Carpenter and Lathrop 2008). Predicted distributions of cyanobacteria, Secchi disk transparency, and TSI are computed from the annual P mass distributions, and validated using the long-term data base maintained by the North Temperate Lakes LTER program (Lathrop 2007, http://lter.limnology.wisc.edu).

Figure 5. Probability of clear water in summer versus annual phosphorus load. Clear water is defined as Secchi disk transparency greater than 2 m (Carlson 1977). Results are shown for Lake Mendota in the current food web configuration with *Daphnia pulicaria* present and a hypothetical future condition with *D. pulicaria* eliminated by changes in management practice or species invasion (Kitchell 1992).



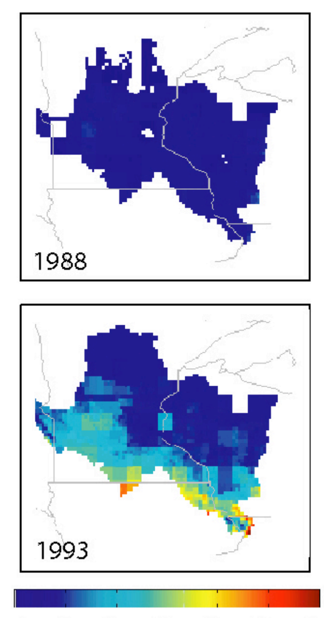


Fig. 6. Agro-IBIS simulated nitrate leaching (kg/ha) at 5' resolution for a drought year (1988) and high spring precipitation year (1993).

Examples of Model Experiments

We will implement a factorial experiment of model runs (**Table 2**) to examine the impacts on water resources for plausible scenarios using the likely drivers of change in the Yahara Watershed during the next 40 yrs. These scenarios will vary in the kinds and amounts of land use/land cover (LULC) in the watershed (i.e., landscape composition), their geographic locations and spatial arrangements (i.e., configuration), agricultural land management options, water resource engineering practices and changing climate and atmospheric CO_2. This approach will bracket the extremes, identify potential tipping points, and lead to a range of alternative landscapes that produce both desirable and undesirable outcomes that will be used in discussions during the development of Integrated Scenarios. First, we will explore future land use scenarios under current climate, atmospheric CO_2, and management of N, P, and crop residue (tillage). Next, simulations, perturbations to N-fertilizer usage, P management, and tillage will be superimposed on future land use scenarios. Then, simulations will consider the effect of water resource engineering practices that are employed to control lake levels and treat stormwater (detention and retention basins). Last, future climate change will be an additional driver of change, as well as increasing atmospheric CO_2. Our factorial design will allow us to identify what land use practices are most influential on water resources given plausible changes in climate and climate variability.

Table 2. Sample experimental design of model simulations for quantitative scenarios of change.

Simulated effect(s)	Land-use scenarios	Management scenarios	Climate + CO_2
Land-use change	(i) 2030 Dane County Plan, (ii) Urbanization, (iii) Corn ethanol, (iv) Cellulosic Bioenergy	Contemporary management (~2005)	Current climate
Land management	Current (~2005) land use	N-fertilizer, P management, and crop residue changes	Current climate
Water Resource Engineering (WRE)	Current (~2005) land use and management	Enhanced stormwater management facilities	Current climate
Climate change/CO_2	Current (~2005) land use	Contemporary management (~2005)	Year ~2030, ~2050
Land-use change + management	(i) 2030 Dane County Plan, (ii) Urbanization, (iii) Corn ethanol, (iv) Cellulosic Bioenergy	N-fertilizer, P management, and crop residue changes	Current climate
Land management + climate/CO_2	Current (~2005) land use	N-fertilizer, P management, and crop residue changes	Year ~2030, ~2050
Land-use change + climate/CO_2	(i) 2030 Dane County Plan, (ii) Urbanization, (iii) Corn ethanol, (iv) Cellulosic Bioenergy	Contemporary management (~2005)	Year ~2030, ~2050
Water Resource Engineering + climate/CO_2	Current (~2005) land use	Enhanced stormwater facilities; Contemporary agricultural management	Year ~2030, ~2050
Land-use change + management + climate/CO_2	(i) 2030 Dane County Plan, (ii) Urbanization, (iii) Corn ethanol, (iv) Cellulosic Bioenergy	N-fertilizer, P management, and crop residue changes	Year ~2030, ~2050

Land use/land cover change. (i) We will first simulate current land-use patterns and the 2030 land-use plan developed in the 2007 Dane County Comprehensive Plan (http://www.daneplan.org/) (termed 2030 Dane County Plan). This plan incorporates a projected influx of 153,000 residents and 75,000 housing units in the county from 2000-2030, the majority occurring within the Yahara Watershed. The plan reflects a 40% increase in urban development. In model simulations, we will vary the rates of agricultural land conversion and the types and locations of land uses within the watershed to simulate: (ii) Rapid urbanization – increased conversion rate (compared to the 2030 Dane County Plan) of farmlands to developed lands; (iii) Corn ethanol – large increases in corn grown for biofuels; (iv) Cellulosic biofuels – large increases in land planted in perennials, such as switchgrass and *Miscanthus*. We will conduct a factorial simulation experiment in which we vary the amount of each land cover (e.g., in 10% increments) and its arrangement (ranging from randomly distributed to strategically-designed patterns).

Agricultural management. We will examine the consequences for water resources when agricultural management scenarios are "crossed" with land-use changes under current climate and future climate change (**Table 2**). The management drivers are: (i) N fertilizer. We will examine how widespread 10, 20, and 30% reductions and increases in optimal fertilizer use on corn and soybean will impact crop yield, nitrate leaching, and river nitrate export. We will examine relationships between crop yield, N-leaching and N-export to varied N-fertilizer usage. (ii) P management. We will develop scenarios for future P management and compute their effects on lake water quality. Scenarios will include (1) business-as-usual, based on projection of current trends in the watershed; (2) manure management in which applications of manure to land are decreased by diverting manure flows to CH_4 digesters; (3) decreases in application of P fertilizer; (4) decrease in confined feeding and increase in pasture grazing for dairy cattle; and (5) increased erosion control through implementing upland and riparian vegetated buffers. Scenarios 1-4 will be based on existing P budgets for the watershed (Bennett et al. 1999), an updated watershed P budget currently under development by the PIs of this proposal, Dane County's data for manure digester planning, and data from ongoing water-quality assessments in the watershed. Erosion control scenarios will be based on the Wisconsin Buffer Initiative (Diebel et al. 2008). (iii) Tillage. We will examine the sensitivity of local energy balance, ET, runoff, and soil biogeochemistry comparing (a) widespread no-tillage management (complete cover of soil by crop residue), (b) conservation tillage (15-30% of soil covered with residue), (c) widespread conventional tillage management (no residue left on soil surface).

Water resource engineering. We will modify the hydrologic routing in THMB simulations to examine the flow attenuation effects of water resource engineering practices that are employed to (1) control lake levels and (2) to treat stormwater. Specifically, we will increase/decrease the size and number of detention and retention basins to better understand the sensitivity of the entire water system to intentional management practices used to manage stormwater and alter the design of the lake outflow structures that control lake levels. These scenarios will be subsequently "crossed" with the other drivers of change.

Climate change and variability datasets. PI Kucharik developed a historical dataset of gridded daily climate data from 1950-2006 across Wisconsin (Serbin and Kucharik 2009; Kucharik et al., 2010). The dataset includes daily solar radiation, wind speed, relative humidity, precipitation, and minimum and maximum temperature, which are the key variables needed to drive our modeling tools. Kucharik has worked with the UW-Madison Center for Climatic Research to downscale and de-bias Global Circulation Model (GCM) projections of 21st century climate for models contributing data to the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset[1]. The IPCC future climate scenarios from a subset of 14 GCMs will be used to represent the range in future climatic conditions that can be expected in WI during the mid-21st century (2046-2065) time period. Each of these climate scenarios will include multiple realizations (~3 emissions scenarios) from ~14 GCMs from the IPCC 4th assessment that have already been downscaled and debiased across WI at 8 km resolution as part of the Wisconsin Initiative on Climate Change Impacts (www.wicci.wisc.edu). Therefore, a daily dataset of *historical and future* projections of total precipitation, maximum and minimum temperature, solar radiation, humidity, and wind speed for the time period 1950-2099 at an 8-km spatial resolution across Wisconsin is available to use in the proposed project for scenarios of climate change. These 8 km data will be interpolated to higher spatial resolution (250 m) to drive our simulation models across the watershed. Atmospheric CO_2 levels will vary according to three emission scenarios from the IPCC 4th assessment (2007) that coincide with the corresponding GCM model output.

Supporting Biophysical Measurements

There is a wide gap in our scientific knowledge regarding the magnitude and directional changes in water balance considering climate change and widely varying land use across diverse watersheds. In general, the differential sensitivity and response of each land cover type is unknown, but clearly is critical in formulating hypothesis about the future sustainability of our water resources. In this section, we highlight our plan to collect new observations that will (1) increase our understanding of how water cycling differs as a function of land use/land cover, and will (2) help validate our models and lend confidence to our future projections. Because we are applying our models at relatively fine spatial (250m) and temporal (hourly) resolution across a diversely managed watershed, we have a crucial need to ground our models more firmly in field data. Our new set of proposed biophysical measurements are carefully chosen, strategic measurements that complement, but do not duplicate, existing studies by NTL-LTER and mission agencies, and have high benefit-to-cost ratios for this research.

Agro-IBIS relies on highly established, yet largely unparameterized, formulations to derive ET from energy balance and stomatal conductance models (Kucharik et al., 2000). Recent work has extended the model use to urban areas to account for a more realistic mix of land uses found in Midwest agricultural watersheds. However, additional field measurements are needed to validate these models and increase confidence in decadal projections driven by alternative climate, land use/management, and land cover. We will measure soil moisture, stomatal conductance, and meteorological variables to quantify ET responses for each major land cover type to changes in albedo, air temperature (Jarvis, 1980), vapor pressure deficit (Mackay et al. 2003; Tang et al., 2006; Jarvis, 1980; Pataki et al., 2000), solar radiation, and soil moisture (Jones, 1992; Lhomme et al., 1998; Lhomme, 2001; Daly et al., 2004; Mackay 2003). These field data will be used to further parameterize and validate our models of energy balance and ET, soil water movement, rootwater uptake, groundwater recharge, and overland flow generation as represented in the Agro-IBIS / THMB dynamic modeling system.

Observations of Soil Moisture, Stomatal Conductance, and ET. We will establish monitoring plots, each with three replicates, in the primary vegetation types encountered in the watershed including hickory/oak forest, grassland (land in the Conservation Reserve Program), wetland, and turf (residential

[1] These are the same models that contributed to the IPCC 4th Assessment Report.

development of high and low density). We will collect hourly data on soil water potential using tensiometers (Soil Moisture Equipment Corp, Santa Barbara CA) and soil moisture (Decagon, Pulman, WA) at 5 discrete depths within the root zone. Periodic measurements of stomatal conductance will be collected during the growing season using a porometer (Decagon, Pulman, WA). At each new study site we will also install a Campbell Scientific ET107 Weather Station (Campbell Sci., Logan UT) that will measure a full suite of hourly average meteorological variables (e.g., wind speed/direction, total solar radiation, relative humidity, temperature, snowfall, rainfall) as well as estimates of potential ET. In the watershed, corn, switchgrass, prairie, and poplar vegetation treatment plots with 5 replicates for each are already studied by Kucharik at the Arlington Agricultural Research Station as part of the Dept. of Energy funded Great Lakes Bioenergy Research Center (GLBRC). These plots are already monitored for CO_2 exchange, canopy leaf area index (LAI), phenological development, soil moisture, and meteorological conditions. Other soil temperature and moisture data (to a depth of 1.2m) are also collected in the Yahara watershed at the UW Arboretum (prairie/oak savanna landscape, since 2002) and Cherokee Marsh (wetland; since 2008) and will complement our new measurements.

Observations of air temperature and humidity along a land use/land cover gradient. A more detailed analysis of temperature patterns across the region is needed to better understand the links between environmental conditions, land cover characteristics, and hydrology. To quantify the magnitude and detailed spatial patterns of Madison's UHI, we will install 125 dual temperature/relative humidity-recording instruments across the city and surrounding countryside in transects from high intensity urban development to agricultural regions of the watershed. Each instrumented location will consist of a two-channel data logger (HoboPro® v2 by Onset Computer Corporation) installed with a radiation shield that will measure and record temperatures and relative humidity on a 30-minute basis (Hinkel et al., 2003; Basara et al., 2008; Hart and Sailor, 2009). A need for quantifying the Madison heat island footprint is further substantiated by two urban LTER sites in Baltimore and Phoenix (Brazel et al., 2000).

Our modeling efforts and biophysical measurements will support work on our second research question **"How can regional governance systems for water and land use be made more resilient and adaptive to meet diverse human needs?"** Our approach will evaluate governance of water and land use, study the spatial and temporal fit between governance and ecosystem services, interview diverse decision makers to compare their evaluations of policy effectiveness and legitimacy, and link these evaluations with the quantitative data and integrated scenarios.

Regional Governance

Water quality and supply, urbanization, bioenergy and food production, agricultural practices, and climate are influenced by actors and institutions across spatial and temporal scales (Young 2002, Sabatier et al. 2005). Adaptive and resilient governance has been recognized as critical for maintaining ecosystem services in stressed and changing systems (Dietz et al. 2003). This investigation aims to unpack the dynamic and reflexive relationships between land use and water governance, individual and collective decision-making, and ecosystem change.

The current era is characterized by dual forces toward globalization and devolution of authority to local governments and nongovernmental organizations, with important implications for the resilience of social-ecological systems (Kettl 2000, Young 2006). Resilience is expected to increase with polycentric, multilayered, flexible, and accountable institutions with a capacity for learning, in social and policy networks, and where ecological knowledge is high (Langridge et al. 2006). However fixed rules structured at one scale are likely to fail in the face of social, economic, or environmental change (Dietz et al. 2003, Folke et al. 2005). Fragmented and scale-mismatched governance structures for specialized resource sectors may create barriers and unintended consequences that impede adaptive behavior, increase conflict, and reduce resilience (Young 2002, Scholz and Stiftel 2005).

Evaluating regional governance systems, policy instruments, and climate adaptations requires an analysis of their effectiveness (do they achieve desired outcomes?), efficiency (at a minimum cost?), equity (with fair distribution of impacts?), and legitimacy (are they acceptable to those affected?) (Adger et al. 2005). To evaluate regional governance of water and land use, we propose to: (1) map the spatial and temporal scale of water and land use authorities and policy instruments, and their potential for adaptation, onto the dynamics of water and land resources; (2) conduct a discourse analysis of policy documents and local media to examine the politics of scale and the framing of water and land use systems and their governance; (3) interview diverse decision-makers (i.e. policy-makers, interest group leaders, residents, farmers, developers) to compare their evaluations of policy instruments under current conditions and future scenarios; and (4) link these evaluations with the results of quantitative models to identify system leverage points for improving water quality and the reliability of water quantity. All research components will be developed and piloted with input from the Scenarios Advisory Group described below under "Integrated Scenarios."

1. Scale of institutional and resource dynamics. Overlapping local, county, state, national, and international authorities for climate, urbanization, bioenergy and food production, agricultural practices, and surface and groundwater quality and supply will be mapped both through rich descriptive historical narratives and through a Geographic Information System (Mitchell 2005). Specific policy instruments such as regulations, land and water rights purchases, stream buffers, and education and outreach programming will be mapped throughout the watershed by year to examine how they are distributed across an urbanization gradient. Each instrument's flexibility and potential for adaptation will be compared. The matches and mismatches between the spatial and temporal scale and flexibility of authorities and instruments and the scale and variability of water and land resources will be examined. For example, some parcel-based tools designed to prevent urbanization and improve agricultural practices impose permanent requirements that may create their own barriers to adaptation (Rissman 2010). We will examine the effect of unevenly overlapping authorities and instruments on system resilience and adaptive capacity.

2. Discourse analysis of water and land use governance. To understand meanings and framings of water, land use, and climate resources and governance systems, we will conduct a discourse analysis of watershed plans and policies, public comments and meeting minutes, regional print and television media, and online resources (Krippendorff 2004). Discourse refers to "shared ways of apprehending the world" and involves the creation of narratives that shape and are shaped by social-ecological structures (Dryzek 1997). This analysis will examine scenario variables such as climate, urbanization, bioenergy and N / P management in relation to water quality and quantity. The politics of scale is of particular interest in the framing of regional resource and governance systems (Macleod and Goodwin 1999). The discourse analysis will identify dominant and alternative narratives and refine expectations for diverse perspectives on the effectiveness, efficiency, equity, and legitimacy of governance and policy instruments.

3. Semi-structured interviews on water and land use governance. We propose to investigate the opportunities and barriers to individual and collective transitioning to landscape mosaics that increase resilience and reduce vulnerability. Through semi-structured interviews with a broad set of decision-makers, from individual farmers and residents to interest group leaders and policy-makers, we will examine resource use and perceptions of the water and land use governance system; opportunities, barriers and information needs for transitioning to alternative practices; and a multicriteria evaluation of policy instruments. We will focus on two scenario variables, agricultural practices and urbanization, and their relations with climate and water. We hypothesize uneven characterization of land use and water governance as effective, efficient, equitable, and legitimate depending on participants' profession and resource use, location in the watershed, concept of entitlements and responsibilities, education and socioeconomic status, and knowledge of the effects of land use on water outcomes.

Census, agricultural census, and environmental data will be used to develop a stratified sampling scheme for semi-structured interviews and identify socioeconomic indicators of adaptive capacity and vulnerability. Policy-makers and interest groups will be identified through an existing social network analysis of the watershed (Breshak in preparation). Interviews (estimated n=200) will be tape-recorded and transcribed. Likert-item responses and open-ended questions will assess each participant's knowledge and attitudes about water quality, land use, and climate change, and their feelings of responsibility and entitlement for water and land use. Each respondent will be asked to evaluate a subset of current or potential policy instruments and authorities, including local and regional regulatory, incentive-based, and market-based instruments for reducing the water quality impacts of agricultural practices and urbanization. Likert responses will be analyzed through multiple ordinal regression while open-ended questions will be analyzed in a grounded-theory hierarchical classification approach using NVivo software (Fernandez-Gimenez 2007).

4. Link evaluations with the results of quantitative models. Finally, participants in semi-structured interviews and in the Scenarios Advisory Group will be asked to respond to multiple scenarios of land use mosaics and associated water outcomes developed by the Scenario Core Team, ranging from high degradation to high sustainability. We will elicit participants' opinions about whether each scenario is credible and desirable given the scenario's inherent tradeoffs, probe perceptions of the resilience and adaptive capacity of governance systems, and identify additional criteria for evaluation. Together with our biogeochemical models, these social data will reveal how thresholds for acceptance and evaluation of policy and regional authority align with ecological thresholds for system resilience. We will assess tradeoffs and synergies among effectiveness, efficiency, equity, and legitimacy to identify pathways to more resilient cross-scale governance that improves water quality and quantity for diverse needs. Engaging diverse decision-makers in this research will build social capital and create shared understanding of diverse participant needs and constraints.

To address our third scientific question **"In what ways are regional human-environment systems resilient and in what ways are they vulnerable to potential changes in climate and freshwaters?**" we will develop integrated scenarios to synthesize decision-maker perspectives, alternative approaches to resource governance, plausible trends in demographic and economic drivers, and model projections under alternate climate regimes to understand future conditions of the watershed and its ecosystem services.

Integrated Scenarios

The condition of the Yahara watershed in 2050 and beyond depends on paths taken by social and biophysical drivers over several decades. Current trends could lead to divergent outcomes, given alternative plausible assumptions about economic, political, social and technological changes, and the ways in which institutions, values and ecosystems respond to historically novel changes in climate. Integrated Scenarios have emerged as a useful tool for organizing information about alternative outcomes and evaluating the effects of uncertain drivers on ecosystem conditions (Alcamo 2001, Carpenter et al. 2006, Carpenter 2008, Millennium Ecosystem Assessment 2005, Peterson et al. 2003, Raskin 2005, Swart et al. 2004). An Integrated Scenario combines plausible, internally-consistent assumptions about drivers of social-ecological change with model-based assessments of the likely consequences of the changes in drivers. Comparisons among a suite of contrasting Integrated Scenarios are used to understand the factors and feedbacks that lead to diverse trajectories of social-ecological change. Integrated Scenarios also focus discussions among researchers and decision-makers as well as other outreach and education activities.

Integrated Scenarios are different from the usual meaning of "scenario" in ecosystem modeling, where the term refers to a set of model experiments to test a particular idea. An Integrated Scenario is an internally-consistent body of assumptions, narratives, drivers and model simulations organized to assess a potential trajectory of a complex social-ecological system, as a part of a suite of contrasting scenarios (Alcamo 2001, Swart et al. 2004, Raskin 2005).

We will develop a suite of Integrated Scenarios to synthesize observed data (both social and biophysical, from our project as well as other research on the Yahara watershed), projections of our models, and stakeholder perspectives to understand potential future trajectories of the Yahara watershed. The Integrated Scenarios will evolve throughout the project in order to adapt to new findings and perspectives as they emerge. Synthesis using Integrated Scenarios will enable us to address several of the key challenges of sustainability science (Kates et al. 2001, Swart et al. 2004, Carpenter et al. 2009, Clark et al. in review) (Table 3).

Table 3. Research Challenges of Sustainability Science to be addressed using Integrated Scenarios in this project (Kates et al. 2001, Swart et al. 2004).

Research Challenge	Key Aspects	Contribution of Integrative Scenarios
Span spatial scales	Local, regional and global processes interact	Identify cross-scale feedbacks and their potential consequences.
Span response times	Societal decisions about long-term change must be made in the short term.	Link long-term goals to short-term decisions.
Recognize wide range of outlooks	Values and preferences for the future differ among people.	Account for perspectives that are recognized through outreach activities, surveys etc.
Reflect critical thresholds, surprise	Unprecedented changes cannot be calibrated in models, and nonlinear thresholds are hard to measure	Creative "what if" scenarios suggest novel analyses and model simulations.

and uncertainties		
Account for human volition	Human behaviors have strong effects yet are hard to forecast	Normatively distinct viewpoints of desired or undesired futures can be cast as scenarios for analysis and model simulation.
Combine qualitative and quantitative thinking	Values, culture and institutions have as much impact on sustainability as do quantifiable aspects of social, economic and biophysical change	Narrative scenarios can be combined with quantitative model simulations.
Engage stakeholders	Stakeholders have deep local knowledge of the system. Engaging them widens the knowledge base, helps address normative aspects of sustainability, and increases learning by all participants	Scenarios provide a framework for synthesis and communication among researchers and stakeholders.

Integrated Scenarios will be designed and synthesized by a Scenario Core Team (SCT) (Alcamo 2001). The SCT will consist of representatives drawn from the PIs, local government agencies, NGOs, businesses and civil society. Members must be collaborative, creative, imaginative and willing to commit time to the scenarios process; their composition must be diverse; and the team must be nimble and proteractive. We expect that the SCT will include about 10 people who meet monthly during the project. In addition, we will form a much larger, broadly-constituted Scenarios Advisory Group (SAG) that will meet annually with the SCT to review progress, findings and new directions. In addition, SCT members and project staff will regularly present scenario findings in public presentations throughout the watershed which provide opportunities to communicate with the public at large. Integrated Scenarios are a key element of our outreach plan (see Broader Impacts).

Integrated Scenarios will be linked to models developed in this project in an iterative way that builds on experience during the Millennium Ecosystem Assessment (Carpenter et al. 2006). Initial model runs will use sensitivity analyses to explore the range of potential outcomes and the likely consequences of each Integrated Scenario. On the basis of these results, feedback from the SAG and feedback from outreach activities, the SCT will revise the Integrated Scenarios to ensure that they explore a range of outcomes useful to decision makers. The Integrated Scenarios will provide a coherent, internally-consistent suite of narratives, data and model results that together explain different trajectories that the watershed may follow until 2050. Thus they will be a nexus for synthesis of project results, a mechanism to guide and focus model simulations, and a venue for engagement with the public, businesses, civil society and agencies. Specific products will include a dynamic website that explains the scenarios as they evolve and organizes feedback through various media, educational materials, public meetings, and the annual meetings of PIs, SCT and SAG.

BROADER IMPACTS: OUTREACH AND EDUCATION

Freshwater resources are central to the cultural identity and future of the Yahara Watershed. Our outreach and education program will build on the widely acknowledged importance of water to the long-term vitality of the region and will be supported by the foundation of our research. We propose an innovative set of outreach and education activities designed to reach diverse stakeholders, including residents of the Yahara Watershed and citizens of Wisconsin; undergraduate and graduate students at UW-Madison and Edgewood College; and policy makers at local, state, national and international levels.

Engaging the local public. We will develop an interpretive **"Water Walk"** along the shore of Lake Mendota on the UW-Madison campus (along the well used Lakeshore Path), and a virtual **online "Water Walk"** in collaboration with the UW-Madison Lakeshore Nature Preserve (see letter of support). This strategy follows on a similar project in which Kucharik developed a "Carbon Walk" at the Merrimac Preserve in central WI along walking trails visited frequently by K-12 school groups. Interpretive signs along the Water Walk will consist of ~10 stations where the science issues confronting the watershed will be explained through pictures and text. A handout and map of the walk will be available online. In parallel, **video podcasts** will also be developed for internet downloads to correspond to the trail signs; videos will also be posted to **YouTube** and similar public websites.

For formal educational activities geared specifically for K-12 students, we will partner with the existing programs operating through the North Temperate Lakes Long-term Ecological Research Site (NTL-LTER) and the Center for Biology Education (CBE) at UW-Madison. NTL-LTER has a long history of effective educational outreach programs, and the findings and activities of the proposed work will feed directly into these activities. Research and methods have been developed and tested for K-12 students, middle and high school science teachers, and for undergraduate introductory biology and ecology courses.

Our Integrated Scenarios involve both research and outreach. Activities include **workshops and forums** designed to discuss water issues in the Yahara Watershed and solicit input from a wide range of stakeholders, as well as a Scenarios Advisory Group comprised of diverse stakeholders. We will also work closely with the developing **Yahara Lakes Legacy Partnership**, which includes a number of grass-roots groups such as Clean Wisconsin, Gathering Waters, and Yahara Clean, and is building linkages to the business community, agricultural sector, and other non profits and NGOs.

Reaching out to the state. We will work with the staff of **Wisconsin Public Television** (WPT; see letter of support) to produce approximately five segments for the feature show, **In Wisconsin** (http://wpt2.org/npa/ IW819.CFM) focused on sustainability of water resources in the Yahara Lakes Watershed. In Wisconsin airs statewide twice per week and covers a wide range of issues of interest to Wisconsinites and has covered a number of topics related to Environment/Wildlife. WPT is currently developing a pilot project focused on environmental sciences. This program is called "Quest," and it is modeled after an NSF-funded program at KQED in San Francisco. We will also seek additional media-based outlets for science outreach, including short segments such as Office Hours on the Big10 Network.

Undergraduate students. We will provide numerous opportunities for undergraduate students to gain research experience by participating in our field studies, and we will also provide **mentored research opportunities** for students in Introductory Biology. UW-Madison's two-semester 10-credit Introductory Biology course (151-152) is widely recognized for engaging students in research at the beginning of their college career. As freshman or sophomores, students may choose mentored research as part of the second semester. Students are paired with a professor and often a graduate student or postdoc to develop a study, conduct the research and present the results orally and in a poster session. About half of the 1000 students who take Introductory Biology annually choose mentored research, and these students are 3x more likely to remain involved in research throughout their undergraduate studies than students who do not participate. The inherent interest among students in water resources, the quality of the Madison lakes, and climate change provide excellent opportunities for rewarding mentored projects. In addition, through our undergraduate teaching activities, we reach hundreds of students each year.

Graduate students. Training graduate students will be a central goal of this study, and the proposed research will contribute to training **5-7 doctoral students**. However, we will reach a greater number of students by offering a **new graduate course** at UW-Madison focused on ecosystem modeling and scenario development related to the sustainability of water resources in the context of climate and land-use change. The course will be led by the PIs and offered twice during this grant cycle, during years two and four, as we have done successfully in the past. In 2001, Turner and Carpenter each coordinated one semester of a year-long graduate seminar, "Modeling Interactions between Terrestrial and Aquatic Ecosystems." The seminars enrolled > 30 students and led to two published papers from class modeling projects (Hanson et al. 2004, Roth et al. 2007). In 2009, Carpenter and Turner coordinated a 2-credit "Ecosystem Services" seminar that focused explicitly on the Yahara Lakes watershed. Other faculty participated, including Kucharik and Jim Lorman (collaborator from Edgewood College), and 21 students from a variety of degree programs were enrolled. At an early stage of the project, we will teach an interdisciplinary practicum on Integrative Scenarios. The seminar will build on an existing course, 'Scenario Thinking' (Biggs et al. 2009, http://limnology.wisc.edu/ courses/zoo955/spring2007/). The course will engage students from diverse disciplines across campus in the process of building scenarios for the future of the Yahara basin. Rissman also facilitates the group **People, Institutions, and Ecosystems** (PIE), a biweekly training experience for graduate students interested in **social sciences** in the Department of Forest and Wildlife Ecology. This group would provide intellectual support to graduate students undertaking social science research as part of this proposal.

Graduate students involved in the proposed research will participate in the **DELTA certificate program** on Research, Teaching, and Learning (see http://www.delta.wisc.edu/). DELTA is part of the Center of the Integration of Research, Teaching, and Learning (CIRTL), which is also funded by NSF and of which UW-Madison is a founding member. Through the DELTA program, graduate students are trained and recognized in three key areas (teaching as research, learning community, and learning through diversity) to strengthen their professional preparation.

Through our collaboration with Jim Lorman at nearby Edgewood College, we will contribute to Edgewood's **Sustainability Leadership Graduate Certificate Program**, a new 1-yr program beginning in August 2010 (http://www.edgewood.edu/academics/graduate/sustainability/**)**. Edgewood College is a liberal arts college located in Madison on the shore of Lake Wingra. The new certificate program emphasizes three aspects of sustainability: environmental quality, social justice, and economic vitality. Students will address real-world issues and build a network of relationships with program colleagues, mentors, community leaders, and faculty experts in sustainability. Thus, the proposed research aligns very well with the certificate program. The Edgewood students will also participate in our summer field research experiences as part of the program.

Informing policy discussions. Throughout this project, we will continue to provide scientific information concerning the sustainability of water resources in the face of changing climate and land use to a variety of audiences. The PIs have an excellent record of engaging in policy discussions at all levels and responding positively to requests for information from the media and other interested parties, and we will actively continue these modes of outreach. We do not draw a sharp line between the Integrated Scenarios and the Outreach and Education components of our project. The Integrated Scenarios must be guided by the interests of decision makers (including individual farmers or homeowners, businesses, diverse NGOs, and various agencies). Thus presentations and discussions of the Integrated Scenarios are part of the engagement with decision makers. Our proposed work on the sustainability of water resources in the face of changing climate and land use will provide valuable information of interest to people of all ages, including students, public agencies, private organizations, business leaders and government officials. We are excited by all our opportunities to share our discoveries to help shape the future of water resources.

SIGNIFICANCE

Our research directly addresses the growing need for new interdisciplinary modes of research and new approaches for environmental education and public engagement (AC-ERE 2009). Although complex human-watershed systems are undergoing massive changes, there are great opportunities to guide change in ways that maintain diverse ecosystem services, increase human wellbeing and increase resilience to unexpected shifts in climate or other drivers. Our research focuses on the outcomes of contrasting pathways, the benefits and tradeoffs, human reactions to various options, and modes of governance that build resilience of human-watershed systems. The interdisciplinary team includes PIs with expertise in terrestrial and aquatic ecology, engineering, social science, simulation modeling and regional studies, and the research framework we develop will be readily transferable to other groups and places. The knowledge gained about future freshwater resources and other ecosystem services in the Yahara Watershed—particularly understanding the alternative pathways to sustainability and tradeoffs among different ecosystems services—is relevant for the Midwest and other regions experiencing similar changes in climate and land use.

Our overarching question, "**How will ecosystem services related to freshwater vary and how can they be sustained in regional watersheds as climate, land use and land cover, the built environment and human demands change**" will be addressed through a coordinated program of integrated scenarios, model experiments to assess effects of changing drivers on broad set of ecosystem services, evaluations of the governance system and leverage points, outreach and public engagement, and information management. In complex social-ecological systems where cause-and-effect relationships are difficult to discern, a multi-faceted approach that effectively links empirical studies and models with active participation by decision makers is especially powerful. The proposed work will advance sustainability science, identify the short- and long-term benefits and costs that accrue from different land management scenarios, and directly engage the public. By identifying institutional barriers to societal adaptation to change in key interacting drivers as well as solutions, our research may lead to real-world improvements in ecosystem services related to freshwater.

Meeting the sustainability challenge requires science to understand how human behavior affects the environment and how human behavior changes in response to perceptions of environmental change, combined with new models for education and engagement with the public. By addressing the three specific research questions posed in this study, we will identify potential development pathways and engineering solutions that maintain freshwater and other ecosystem services and meet needs for human wellbeing. Our comprehensive program employs a systems approach that combines landscape, agroecosystem, hydrologic and water quality models to evaluate changes in key freshwater ecosystem services (flood regulation, groundwater recharge, surface water quality, groundwater quality, and lake recreation) and other ecosystem services in the face of climate change. Improved understanding of the institutions and decision-makers that influence water and land use can promote sustainable use and governance of ecosystem services in the context of changing climate, urbanization, and agricultural practices. We will study the spatial and temporal fit between governance and ecosystem services, conduct a discourse analysis of the politics of scale for land-water systems, interview diverse decision makers to compare their evaluations of policy effectiveness, efficiency, fairness, and legitimacy, and link these evaluations with quantitative models and integrated scenarios to identify leverage points for managing the watershed's portfolio of ecosystem services. The future condition of the Yahara watershed could follow different pathways consistent with plausible, but contrasting, assumptions about changing governance, land-use policy, economic forces affecting agriculture and development, technology, and the responses of decision makers to changes in climate. We will develop integrated scenarios to evaluate resilience of the human-environment system and prospects for transition to different pathways. Integrated scenarios engage interdisciplinary researches with the public in new ways that transform the traditional practices of research, education and outreach, and are applicable to a wide range of sustainability challenges in addition to the freshwater issues addressed here.

Public outreach, communication with decision makers, education and training of future leaders in the natural and social sciences are fully integrated with the research we propose. Our approach will greatly enhance environmental awareness and literacy in the public through a robust outreach and education plan and by involving the public, stakeholders, and policy decision-makers from day one in our work plan. The place-based, integrated biophysical and social-ecological research we propose will produce the kind of systems-level understanding of regional water systems needed to reach the sustainability transition.

RESULTS OF PRIOR SUPPORT

(NTL-LTER; DEB-0217533) Title: LTER: Comparative Study of a Suite of Lakes in Wisconsin. The North Temperate Lakes Long-Term Ecological Research program (2008-14 = $6,720,000; PIs include Carpenter, Gries, Kucharik, Loheide, Turner) has been operating since 1981 and builds upon data for the Yahara lakes initiated by E.A. Birge in the 1880s, including near-continuous water quality data since 1900 (Carpenter et al. 2006). NTL-LTER provides data and an intellectual network of interdisciplinary scientists that will serve this project. The proposed research will be integrated with the information management system of NTL-LTER. *Intellectual merit*: A central goal of the NTL-LTER program is to develop an understanding of long-term regional change in two lake districts in Wisconsin (Magnuson et al. 2006, Carpenter et al. 2007). NTL-LTER has produced about 280 research articles and book chapters during the period 2002-2007. A full publication list, summary of research findings, and description of research sites is found at http://lter.limnology.wisc.edu. *Broader impact*: NTL-LTER has an extensive outreach program, including schoolyard LTER, interactions with local, regional, and national media, and presentations at a variety of public venues. Approximately 35 graduate student theses were attributable in whole or part to NTL during the period 2002-2008.

(CBET-0729838) Title: Collaborative Research: Mountain Meadow Restoration with a Changing Climate PI: Loheide (U of Wisc), Lundquist (U of Wash) **Grant Amount:** $425,000 ($212,500 UW) **Duration:** 09/01/07-08/31/10. This collaborative research combines field and modeling approaches for understanding the linkages between climate, snowmelt, runoff, groundwater flow, and vegetation patterning in Tuolumne Meadows, Yosemite National Park, CA. We have established an observatory network of instrumented groundwater monitoring wells, stream gages, temperature sensors, and soil moisture sensors. We are investigating how meadow restoration strategies and projected climatic scenarios will alter groundwater-dependent, meadow ecosystems by modeling watershed runoff, meadow groundwater flow, unsaturated flow in the root zone and snowmelt-induced, surface water/groundwater interactions. **Key Publications: (1)** Loheide SP, EG Booth, Effects of changing channel morphology on vegetation, groundwater, and soil moisture regimes in groundwater dependent ecosystems, *Geomorph.* in press **(2)** Loheide, SP, JD Lundquist, 2009. Snowmelt-induced diel fluxes through the hyporheic zone, *Water Resour. Res*. **(3)** Li Q, K Ito, ZS Wu, CS Lowry, SP Loheide, 2009. COMSOL Multiphysics: A Novel Approach to Groundwater Modeling. *Ground Water*.