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Research, part of a Special Feature on Programme on Ecosystem Change and Society (PECS): Knowledge for Sustainable Stewardship of Social-ecological Systems

Plausible futures of a social-ecological system: Yahara watershed, Wisconsin, USA

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ABSTRACT. Agricultural watersheds are affected by changes in climate, land use, agricultural practices, and human demand for energy, food, and water resources. In this context, we analyzed the agricultural, urbanizing Yahara watershed (size: 1345 km², population: 372,000) to assess its responses to multiple changing drivers. We measured recent trends in land use/cover and water quality of the watershed, spatial patterns of 10 ecosystem services, and spatial patterns and nestedness of governance. We developed scenarios for the future of the Yahara watershed by integrating trends and events from the global scenarios literature, perspectives of stakeholders, and models of biophysical drivers and ecosystem services. Four qualitative scenarios were created to explore plausible trajectories to the year 2070 in the watershed's social-ecological system under different regimes: no action on environmental trends, accelerated technological development, strong intervention by government, and shifting values toward sustainability. Quantitative time-series for 2010–2070 were developed for weather and land use/cover during each scenario as inputs to model changes in ecosystem services. Ultimately, our goal is to understand how changes in the social-ecological system of the Yahara watershed, including management of land and water resources, can build or impair resilience to shifting drivers, including climate.

Key Words: *alternative futures; climate; ecosystem services; eutrophication; governance; lakes; land-use change; phosphorus; scenarios*

INTRODUCTION

Management of regional social-ecological systems requires long-term thinking. Slowly changing properties of ecosystems and social systems have a central role in resilience planning (Folke et al. 2010) but pose challenges because long-term observations are sparse and theory is incomplete. The future dynamics of social-ecological systems are unpredictable (Polasky et al. 2011). Thus, a central challenge is posed by long time frames and considerable uncertainty about future pathways that might be taken by society and nature. Scenarios are plausible stories about how the future of a social-ecological system might unfold from existing patterns, new factors, and alternative human choices (Raskin 2005). Scenario development integrates stakeholder views with research to understand long-term changes and investigate potential futures of social-ecological systems (Raskin 2005, Carpenter et al. 2006*a,* Biggs et al. 2007, March et al. 2012, Priess and Hauck 2014).

Scenarios for social-ecological systems have been applied at a variety of spatial extents, ranging from the entire planet (Millennium Ecosystem Assessment 2005) to regions (Priess and Hauck 2014). When considering regional social-ecological systems, watersheds often emerge as a convenient scale for analysis (Biggs et al. 2010, March et al. 2012). Watersheds are natural and widely accepted units for natural resources management (Montgomery et al. 1995, McGinnis 1999, Koehler and Koontz 2008). Their boundaries and flow paths organize hydrological and biogeochemical processes that underpin ecosystem services such as water supply, flood protection, and food production. Watershed management faces multiple challenges globally: climate is warming, precipitation is more variable, soils are increasingly degraded, water quality is impaired, floods and droughts are increasing, human demand for resources is rising, governance is challenged to address an evolving mosaic of problems, and coming decades seem highly uncertain. In agricultural landscapes, excessive nonpoint pollution leading to freshwater eutrophication has proven to be an exceptionally common and persistent syndrome in the United States (Rissman and Carpenter 2015). Climate change and its interactions with land-use change are affecting water flows and nutrient loads in new and sometimes unexpected ways (Milly et al. 2008). These trends are increasing the uncertainties of watershed management (Harris and Heathwaite 2012).

The Yahara watershed in the Upper Midwest of the United States exemplifies the challenges found in agricultural watersheds throughout the world. Ecosystem services are likely to respond to ongoing changes in climate, land use and land cover, agricultural practices, and growing human demand for energy, water, land, and food. These directional changes and the plausible responses of the watershed's social-ecological system motivate our research questions. What thresholds in social-ecological dynamics should be considered in plans for the watershed's future? Are there opportunities to guide change toward channels that maintain a balance of ecosystem services, meet needs for human well-being, conserve the capacity of ecosystems to provide services into the future, and build resilience for unpredictable changes in climate or other social and environmental drivers?

To address these questions, we used an integrative approach that encompasses scenarios developed with stakeholder participation, quantitative ecosystem models, studies of regional governance,

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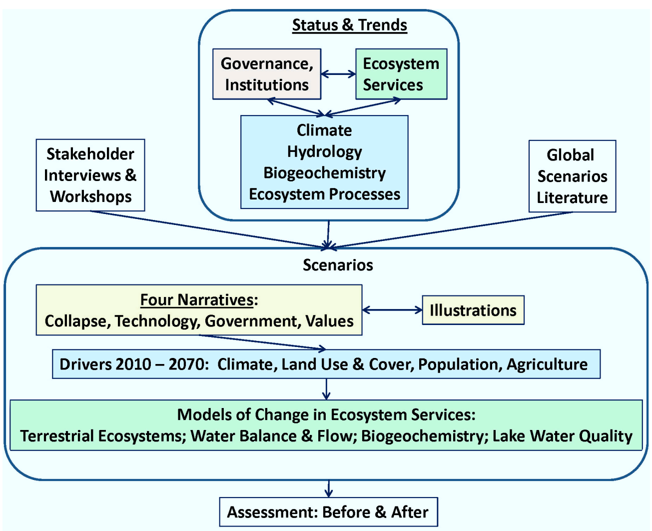
Table 1. Freshwater and other ecosystem services studied.

Ecosystem service category	Ecosystem service	Indicator	Model/method
Freshwater	Freshwater supply	Groundwater recharge	Agro-IBIS/MODFLOW
	Flood regulation	Peak runoff flows and lake levels	THMB†
	Surface water quality	Phosphorus loads and lake total phosphorus	THMB, Agro-IBIS, Yahara Water Quality Model
	Groundwater quality	Nitrate concentration in groundwater	Agro-IBIS, THMB
	Lake recreation	Lake total phosphorus, chlorophyll, cyanobacterial concentrations, and trophic state index	Yahara Water Quality Model
Other	Soil resources	Soil carbon, nitrogen, and phosphorus pools; soil erosion	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 land-cover scenarios
	Food and biofuel production	Corn and soybean yields; *Miscanthus,* switchgrass production	Agro-IBIS/MODFLOW

†Terrestrial Hydrology and Biogeochemistry Model.

and new biophysical field observations (http://wsc.limnology.wisc.edu; Fig. 1). The research focuses on key ecosystem services in the Yahara watershed, for which validated models exist (Table 1).

Fig. 1. Major components of the research process used in this work.



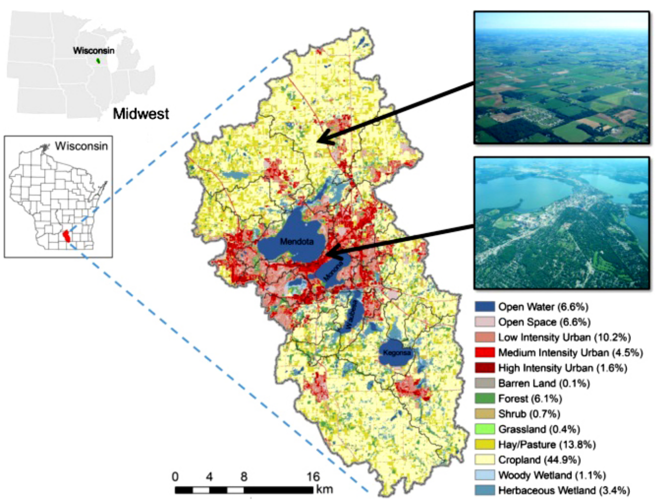
Researchers have taken a variety of approaches to develop watershed scenarios (March et al. 2012, Priess and Hauck 2014, Schneider and Rist 2014). Our approach combined stakeholder engagement with multiple perspectives from natural and social sciences, including the extensive literature on environmental scenarios (Hunt et al. 2012). Scenario narratives were also shaped by the need to couple storylines with biophysical models for subsequent quantitative analysis. In contrast to scenarios designed around specific near-term decisions or environmental impact assessments (Therivel and Paridario 1996), the scenarios for the Yahara watershed consider a 60-year horizon (2010 to 2070). Over these six decades, the Yahara watershed is likely to undergo great changes in climate, land use, and ecosystem services. Sixty years is approximately two human generations, a period that is meaningful to most people.

Various criteria have been used to evaluate the usefulness of regional scenarios (Wiek and Iwaniec 2014). We sought scenarios that would be fruitful for outreach by stimulating discussion among stakeholders, and constructive for modeling by driving development of new tools for watershed simulation. More specifically, the scenarios should be salient, addressing major issues for the watershed; engaging; plausible; and consistent with biophysical knowledge. In addition, the scenarios should offer strongly contrasting outcomes. Strong contrasts help distinguish the scenarios for the readers, sharpen the differences among alternative pathways, and challenge the models to track widely divergent dynamics. We avoided purely bad or purely good outcomes, in the hope that readers would create their own preferred futures by building on the scenarios as a whole. We first describe the Yahara watershed and our process for scenario development. We then describe how scenario components are quantified as biophysical drivers consistent with the scenario storylines.

THE YAHARA WATERSHED

The Yahara watershed of southern Wisconsin, USA (43°6' N, 89° 24' W) drains 1345 km² and contains five major lakes (Mendota, Monona, Wingra, Waubesa, and Kegonsa; Fig. 2). The climate is continental, characterized by warm humid summers and cold winters, with strong seasonal and interannual variability. Temperatures range from monthly averages of −7.3°C in January to 21.8°C in July, with an annual average precipitation of 87.6 cm (1981–2010 climate normals). Influenced by the last glaciation (~14,000 years ago), the terrain of this watershed is generally flat but marked by moraines, drumlins, and shallow depressions that often contain wetlands. Soils are primarily composed of fertile Mollisols and Alfisols, which support high agricultural productivity in the Yahara (Glocker and Patzer 1978).

Fig. 2. Map of the Yahara River watershed (Wisconsin, USA) and the land-use/land-cover pattern (with percent cover) for 2011, derived from National Land Cover Data. Delineations of the Yahara watershed were based on light detection and ranging (LiDAR) elevation, sewer-sheds from the city of Madison, and a field-checked basin map from Dane County, Wisconsin. Two aerial photos in the upper-right corner were taken in summer 2013 and illustrate the typical agricultural landscape (top) and acceleration of urbanization (bottom) in this watershed.



The current Yahara watershed is human-dominated; most land is agricultural, but the region also has densely populated urban (containing the state capital, Madison, Wisconsin) and suburban areas, along with scattered remnants of native vegetation (Fig. 2). The economic base of the region is diverse, including agriculture, some light industry, service industries, emerging technologies, state government, and the state's major research university (Carpenter et al. 2007).

Freshwater is central to the Yahara's cultural identity (Stedman et al. 2007), but freshwater conditions have deteriorated over the past century (Carpenter et al. 2006*b*). Eutrophication of the Yahara lakes has occurred since the mid-1800s, initially as a consequence of sewage effluent and erosion. In the late 1940s, eutrophication worsened, mainly due to excessive nutrient inputs (primarily phosphorus and nitrogen) from increased sewage discharges, fertilizer and manure application, and agricultural and urban runoff (Carpenter et al. 2006*b,* Lathrop 2007). Institutions for managing eutrophication have emerged since the 1950s, and substantial efforts have been expended to curb freshwater eutrophication at state and county levels (Wardropper et al. 2015). Management actions have included wastewater diversion, biomanipulation, soil erosion control, storm water management, nutrient management plans, installation of rain gardens, and wetland restoration (Carpenter et al. 2007, Lathrop 2007). Private groups and conservation organizations have raised public awareness of eutrophication and advocated for sustainable lake management. While many collective policy and practice efforts have been made to control nutrient inputs to freshwater, the long-term legacies of intensive nutrient and manure use persist in the Yahara watershed (Betz et al. 2005, Nowak et al. 2006, Lathrop 2007, Gillon et al. 2015).

The Yahara watershed generates multiple ecosystem services that are used at local and regional scales: providing food, fiber, biofuel, freshwater, carbon sequestration, regulation of water and nutrient flows, and recreational opportunities (Table 1). Freshwater-related ecosystem services are of great concern because eutrophication, flooding, and groundwater pollution accompany urbanization and agricultural intensification (Matson et al. 1997, Brauman et al. 2007, Power 2010). Qiu and Turner (2013) present a comprehensive analysis of 10 ecosystem services for this watershed as a baseline (Fig. 3). Their study described complex spatial patterns of these services, identified their interactions (i.e., synergies and tradeoffs) across the watershed, and uncovered several unrecognized interactions among the ecosystem services. Overall, ecosystem services were not independent of each other, and their distinct spatial heterogeneity and interactions indicated the importance of managing over large areas to sustain multiple ecosystem services (Qiu and Turner 2013).

While multiple ecosystem services are provided in the Yahara, long-term observations suggest that some services have been degraded or may not be sustainable in the future (Gillon et al. 2015). For example, soil organic carbon storage declined by up to 50% following the conversion of native prairie vegetation to agriculture (Kucharik 2007). Groundwater extraction, draining of wetlands, and increased runoff associated with expansion of impervious surfaces have altered hydrology, thereby increasing lake-level variability and flood frequency (Wegener 2001, Lathrop et al. 2005). Nitrate is contaminating groundwater, and phosphorus loads from nonpoint runoff substantially exceed those that occurred prior to agriculture (Carpenter et al. 2006*b*). Overuse of pesticides, fertilizers, and manure, along with increased flashiness of runoff from heavy rainfall events, have amplified concern about freshwater quality because people are sometimes unable to swim or boat in the lakes. Climate change has altered hydrological flows (Motew and Kucharik 2013), lengthened the growing season, increased the occurrence of extreme rainfall events (Kucharik et al. 2010), and altered plant and animal phenology (Bradley et al. 1999). Invasions of nuisance animals and plants also have ongoing effects on ecosystem services in the Yahara watershed (Carpenter et al. 2007). Meanwhile, human population and demands for ecosystem services continue to grow. It is critical to understand how multiple changing drivers and their interactions may reshape future prospects for freshwater resources and other ecosystem services.

PROCESS FOR SCENARIO DEVELOPMENT

The scenarios were developed through an iterative process of adapting archetypal drivers of global change (Hunt et al. 2012) to the perspectives, social processes, and environmental conditions of the Yahara watershed (Liu et al. 2008), within the constraints created by coupling the storylines with biophysical models. The process is diagrammed in Fig. 4, which is adapted from Kok (2009) and Alcamo (2001).

Scenario processes often differ in the composition of the core team, the methods for receiving stakeholder input, and the coordination between the modelers and the story writers. We emphasized three main sources of themes and events in the scenarios: the global scenarios literature, local stakeholder perspectives, and requirements for model simulations (Fig. 4). The global scenarios literature contributes a broad perspective of major drivers of change that are expected or have occurred in other places around the world. We relied on this literature to expand the range of

Fig. 3. Spatial distributions of 10 ecosystem services in the Yahara watershed, Wisconsin, for the baseline year of 2006. The gradation from red to green indicates areas with high to low supply of ecosystem services. The production of individual ecosystem services varied substantially across the landscape and were distinct in their geographic distributions. Reprinted with permission from Qiu and Turner (2013).

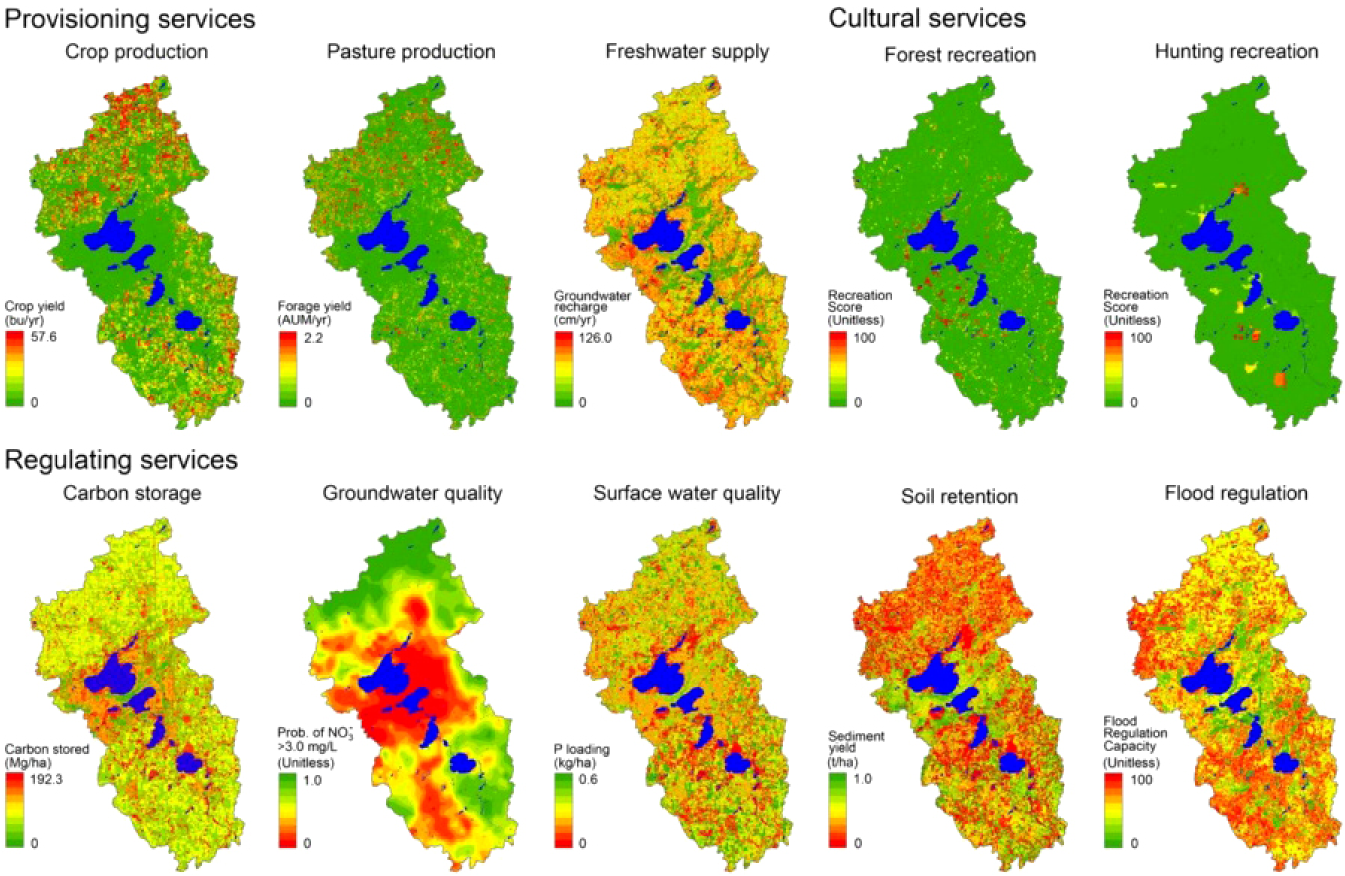
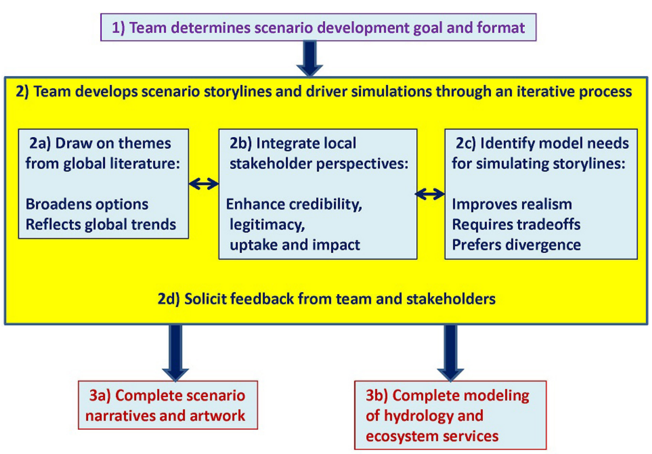


Fig. 4. Steps in the scenario development process. Modified from Kok (2009) and Alcamo (2001).



possibilities for social and environmental change and to contribute ideas that were not already part of the conversation in the watershed. We sought local stakeholder perspectives to improve credibility and relevance of the scenarios, enhance the legitimacy of the scenario development process, and potentially generate novel ideas about the future of the watershed. By involving stakeholders in scenario development, we hoped to augment the scenario outreach by promoting long-term thinking by local stakeholders, building relationships, and enhancing social learning among stakeholders. Stakeholders may have a role in limiting or restricting scenario alternatives based on plausibility given existing conditions and dynamics in the region. Finally, the need to model scenarios in quantitative simulations grounded the scenarios in current knowledge of environmental and social conditions and trends. Biophysical analysis quantifies important trade-offs among ecosystem services such as food production and freshwater quality. Models are improved through the need to consider dramatically different scenarios that imply divergent model outcomes (Kepner et al. 2012). The need to align scenario narratives with model simulations also means that the scenarios need to depict key changes that the team is interested in modeling, including climate change, flood events, drought events, population shifts, and ecosystem services.

We elicited stakeholder perspectives on the future of the Yahara watershed through interviews and workshops during 2011 and 2012. We included primary interest group representatives and government agency staff addressing key ecosystem services. We also sought input from people in the region who were not engaged in watershed governance. A total of 82 watershed residents participated through one or more forums: semi-structured interviews (56 participants), workshops (51), and an online survey (51). Interview audio recordings were transcribed and analyzed using the qualitative software Dedoose (http://www.dedoose.com). Four workshops, each four hours long, generated discussion on drivers and outcomes for scenario narratives. In the workshops, the project team presented information on social and environmental conditions and trends. Small groups discussed diverse futures and brainstormed wildcard surprises. We heard from people with varied professional affiliations and interests, but faced a challenge of nonparticipation from environmental justice nongovernmental organizations and ethnically diverse stakeholders. These groups had less capacity to allocate time to research participation and had been frustrated by time spent on prior academic research.

Questions asked in scenario development were meant to broaden perspectives of both the research team and participating stakeholders, build dialog among diverse stakeholders, and reveal key issues for consideration (Millennium Ecosystem Assessment 2005). In the stakeholder interview process, we asked who or what the interviewee believed would be most influential in determining the region's future social-ecological state. To help define scenarios' social-ecological endpoints, we also solicited perspectives on ideal and worst-case states of the future of the region. Responses revealed diverse priorities and visions for the watershed's future, demonstrating contrasting and sometimes conflicting perspectives (Garb et al. 2008). Definitions of future ideal states varied on the relative importance and roles of agriculture, land use, water quality, and social, economic, and political factors. Understanding participant perspectives on social-ecological change and ideal regional states enabled the development of scenarios that captured issues and values important to regional residents.

The many potential storylines that emerged from the interviews and workshops were condensed to four scenarios for further analysis. This condensation was necessary for practical and heuristic reasons. Only a small number of scenarios can be developed through creative writing, art, and modeling. Also, users of the scenarios can engage effectively with only a few stories for comparison and contrast. Many commonalities among story elements emerged from interviews or workshops. These common features made it possible to cluster the story elements into a few scenarios. The emergence of a few archetypes from complex environmental scenario processes has been noted and discussed by others (Cork et al. 2006, Hunt et al. 2012). In choosing the four themes for the Yahara2070 scenarios, we considered the literature on scenario archetypes, relevance for stakeholders and decision makers, and utility for model development and analysis. The result was the four scenarios described briefly below.

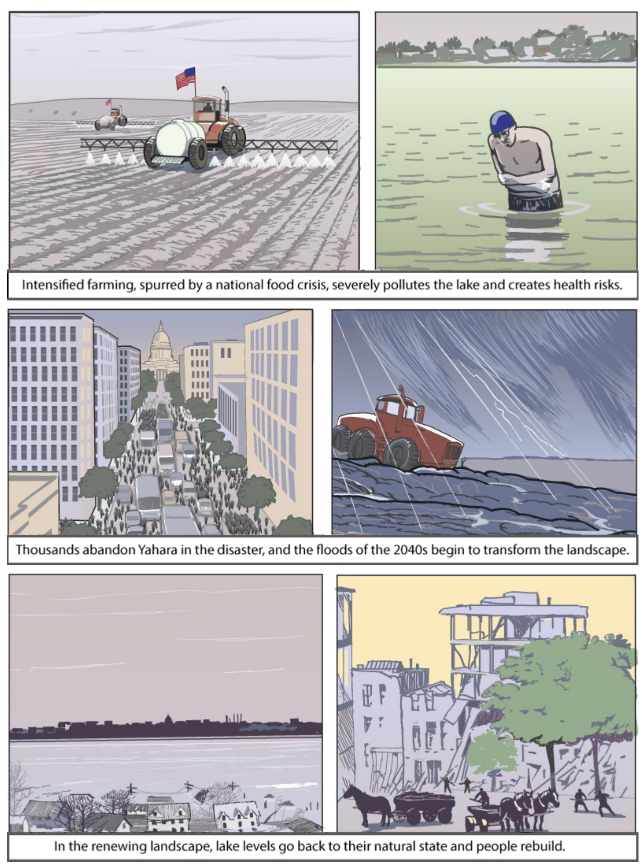
SCENARIO NARRATIVES AND ILLUSTRATIONS

The scenarios diverge from 2010 down different paths based on particular human choices and biophysical events, leading to four very different situations in 2070. Complete storylines and illustrations can be found online (http://Yahara2070.org). Appendix 1 presents a tabular comparison of the four scenarios with respect to change process, ecological outcomes, social outcomes, and opportunities and threats.

Abandonment and renewal

Abandonment and renewal explores what could happen if the people of the Yahara watershed are not prepared for the environmental challenges they face, notably climate change, deteriorating water quality, and emergence of a new toxic species (Fig. 5). An accumulation of climate disasters across the United States leads to a national food crisis by the late 2020s. The crisis puts pressure on the Midwest to increase food production, which exacerbates water quality problems, especially in the Yahara watershed. This eventually leads to an environmental health catastrophe. A new species of cyanobacterium, which emits a toxic fume, emerges in the Yahara's lakes. A series of massive blooms one summer kills tens of thousands of people, and many more abandon the region. In the disaster's wake, the region undergoes an extraordinary transformation. By 2070, few people live in the watershed. Large-scale agriculture is gone. Urban areas are in ruins. People live in dense small towns or on subsistence farms, and survival is the main concern. Equality has increased, but centralized social support systems and governance do not exist. With the landscape now largely feral, prairies, forests, and wetlands are rejuvenating. A diverse collection of native and non-native wildlife and vegetation inhabit the ecosystems. The lakes' waters are recovering, but they still carry scars from their polluted past. The disaster-causing cyanobacterium still lives in the lakes. Climate change has set the global thermostat to approximately 8°F (4.4°C) hotter than the beginning of the century.

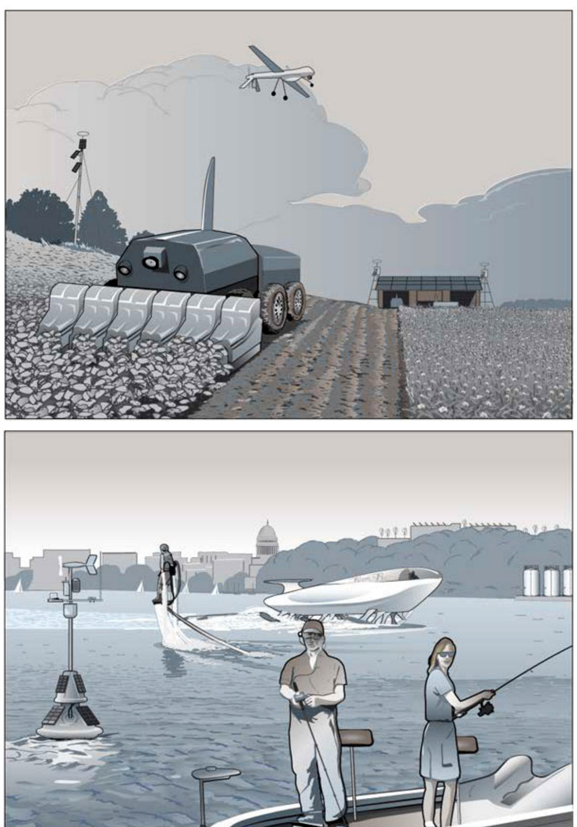
Fig. 5. Timeline of major events during the "Abandonment and renewal" scenario.



Accelerated innovation

Accelerated innovation explores what could happen if the United States prioritizes technological solutions to climate change and other environmental challenges (Fig. 6). A series of global climate-related disasters throughout the 2020s and 2030s incites this shift. The public and private sectors pour money and energy into innovation and technology, specifically in environment, energy, health, and biotechnology. As the seat of a major university, a growing private sector, and local and state government, the Yahara watershed emerges as one of the nation's solution centers. By 2070, technological advances such as cultured meats have greatly decreased demand for agricultural land. The watershed's population increases sharply as entrepreneurs and businesses establish themselves and infrastructure for innovation and technology expands. Dramatic leaps in technological capabilities, especially in agriculture and natural resources management, have improved water quality and assuaged climate change impacts. The physical landscape has become highly engineered as a result. The advanced mechanization and data procurement has also enabled the economic valuation of natural processes, which are now controlled by market mechanisms. However, new technologies sometimes have negative unintended consequences and occasionally trigger disasters. The focus on technology has degraded the intrinsic value of nature, and a subculture of technology skeptics has emerged.

Fig. 6. During the "Accelerated innovation" scenario, agriculture and water quality management are revolutionized by automated farm technology, the rise of do-it-yourself genetic engineering, laboratory-generated artificial meat, and cutting-edge phosphorus removal technologies.



Connected communities

Connected communities explores what could happen if there is a global shift in values toward community and sustainability. By the 2020s, looming environmental and political collapses, caused by climate-related disasters and inadequate political response, incite a worldwide youth movement to shift the course of humanity (Fig. 7). Disenchanted with highly consumptive culture, the younger generations embrace sustainability and organize themselves to make change. When these youth have aged into leadership positions by the 2040s, they incorporate their ideals into policies and collective practices, catalyzing the Great Transition (Raskin et al. 2002). By 2070, the Transition has established a new paradigm in which connectivity, community, and environmental sustainability pervade policy and culture. In the Yahara watershed, people live a community oriented and sustainable lifestyle; many live by a strong sense of connection to nature. Improving and maintaining an enjoyable and healthy quality of life becomes the central focus of economic activity and policy-making. Declining demand for meat and the increase in more sustainable practices have moderated the environmental effects of agriculture. Widespread mitigation measures have moderated climate change impacts. However, the watershed still deals with the legacy effects of pollution: carbon in the global atmosphere and phosphorus in Yahara's soils. While recovery is slow, conditions are gradually getting better, including slowly improving water quality.

Fig. 7 Timeline of major events in the "Connected communities" scenario.

Nested watersheds

Nested watersheds explores what could happen if the United States reforms how it governs freshwater resources in response to increasing water insecurity. Through the 2020s and 2030s, extreme climate change impacts strain the United States' already taxed freshwater supply. Arid western states experience severe water shortages, and the country finds itself in a water crisis. Public outcry escalates. The federal government responds with the Water Security Act of 2040, which creates a new water governance framework called Nested Watersheds (Fig. 8). The Act draws the jurisdiction for water governance around the boundaries of the country's major watersheds. Wisconsin's water governance is split between the Great Lakes Watershed Unit and the Upper Mississippi Watershed Unit; the Yahara Watershed Subunit is part of the latter. Upper Mississippi watersheds must supply clean water to the country's water-scarce regions. While the federal government creates goals, incentives, and regulations to maintain, improve, and distribute freshwater, watershed units and subunits are responsible for developing tailored programs and policies to meet the requirements. By 2070, water conservation has become the norm. Overall, the Yahara Watershed Subunit has created effective policies and practices, and it is usually able to meet its mandated targets. Taxes on meat and dairy consumption and incentives to grow perennial biofuel crops have promoted agricultural practices that reduce erosion and runoff and replenish groundwater. Yahara's municipalities have widely implemented measures to conserve water and prevent urban runoff through regulations and incentives. Water resources are improving, but slowly. However, since society is in a never-ending cycle of incremental adaptation, long-term resilience is uncertain.

Fig. 8. Timeline of major events in the "Nested watersheds" scenario.

DRIVERS FOR MODEL ANALYSES

We developed quantitative trajectories for climate, land use, human population, and agricultural practices that are consistent with the qualitative narratives. We refer to these trajectories as the "drivers" for quantitative model estimates of future ecosystem services. The full set of drivers is presented at http://Yahara2070.org, and the process for generating the drivers is summarized here. Some changes in land cover and climate were explicitly mentioned in the narratives, and others were inferred from the narrative theme. Regular meetings between the narrative developers and modelers were used to maintain consistency between the qualitative and quantitative aspects of the project.

Climate

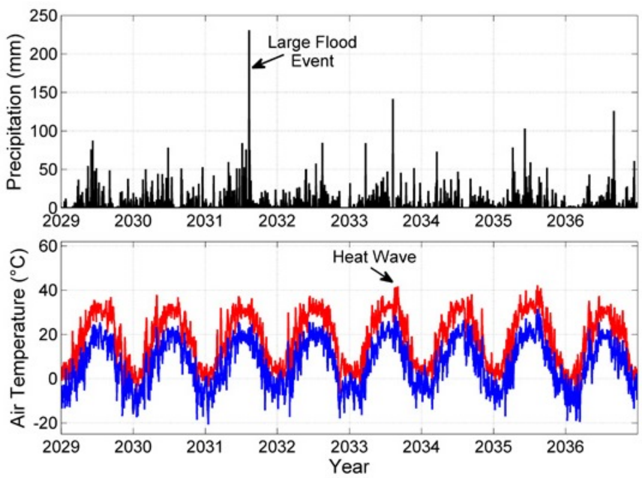
Climate data time-series were developed to re-create climatic events mentioned in the scenario narratives, including extreme temperature and precipitation events, based on future climate models. Scenario climates are based on model output from Notaro et al. (2014), who used a probabilistic approach to downscale statistically output from 13 general circulation models (GCMs), three emissions scenarios (A1B, A2, B2), and two future time periods (2046–2065 and 2081–2100). It created three unique realizations per model, emissions scenario, and time period to create a total of 234 unique 20-year climate time-series. Descriptive statistics were calculated for each time-series, including mean annual precipitation, mean maximum and minimum air temperature, number of extreme hot days and cold nights per year, and number of extreme precipitation events (e.g., > 75 mm/day, > 150 mm/week). These statistics were used to screen for time-series that were appropriate for each scenario. For example, a scenario narrative that mentions frequent drought would be linked with a climate time-series with low precipitation. We then created time-series of daily air temperature (maximum and minimum) and daily precipitation for the scenarios using the stochastic weather generator WeaGETS (Chen et al. 2012).

To replicate climatic events mentioned specifically in the scenario narratives, we used the stochastic weather generator to create synthetic time-series using the appropriate 20-year GCM time-series as input (Fig. 9). For each time-series input, at least 200 years of synthetic data were created to be able to match a 20-year portion of the synthetic time-series with a specific sequence of events mentioned in a scenario narrative. For example, because the "Abandonment and renewal" scenario describes a devastating flood in 2031, a synthetic precipitation time-series with a large precipitation event was chosen to represent that scenario (Fig. 9). The simulated flood provided an opportunity to improve our abilities to model extreme flood conditions and illustrate quantitatively an event in the scenarios.

Land cover

Time sequences of landscape maps were constructed to represent land-use patterns depicted in the scenarios and provide inputs needed to compute ecosystem services (Fig. 10). A rule-based spatial allocation approach was used to generate future landscape maps at 30-m resolution on the basis of transition probabilities for each different land use/cover, with the proportion of each cover type consistent with the driver curves (Appendix 2). Bayesian belief networks (BBN) were constructed to produce the transition probabilities from one land cover to other cover types using designated variables for each 30-m grid cell. The BBN approach is a useful tool for scenario development and landscape mapping (Haines-Young 2011, McCloskey et al. 2011, Bateman et al. 2013). Specific advantages include the ability to incorporate uncertainty and combine quantitative empirical data and qualitative relationships (Haines-Young 2011).

Fig. 9. Example of a portion of the climate driver time-series for the "Abandonment and renewal" scenario showing the matching of events (large flood and heat wave) to the qualitative narrative. Top panel: daily precipitation (black). Bottom panel: daily maximum (red) and minimum (blue) air temperature.

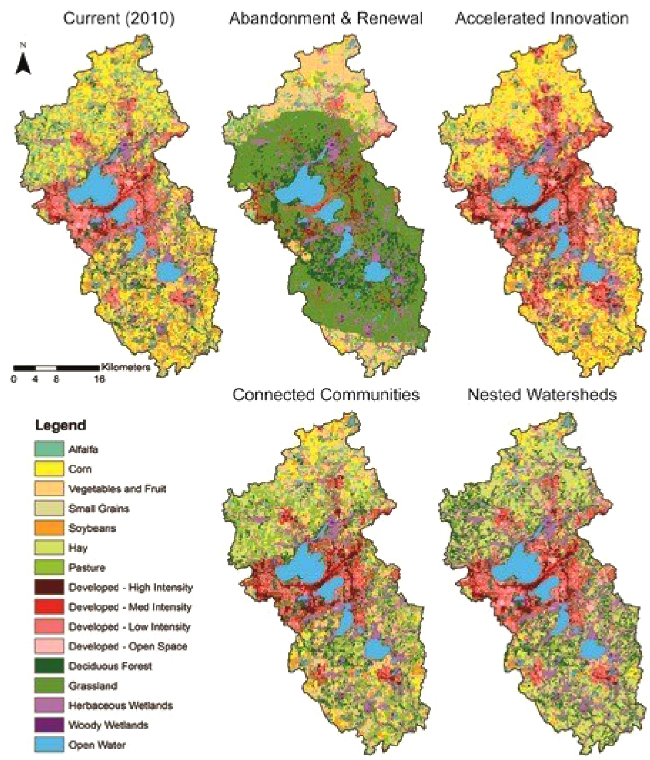


Change in ecosystem services

Regular conversations about narrative development and quantitative drivers were necessary for the scenarios to be internally consistent and plausible. Statements in the narratives about energy sources and use, for example, in transportation, have implications for climate and land-use trajectories during the scenarios. In addition, narrative statements about human diet, especially meat consumption, have implications for agriculture, land management, and land use. Thus, statements in the narratives and assumptions embedded in model drivers related to climate and land use must be harmonized for internal consistency.

To compute time courses of ecosystem services during each scenario, the time-series of climate and landscape maps that correspond to the four scenarios were used as inputs to four linked biophysical models. These models simulate the stocks and flows of water, carbon, energy, and nutrients between groundwater, soils, plants, aquatic ecosystems, and the atmosphere (Table 1): (1) Agro-IBIS, a dynamic model of terrestrial ecosystem processes, biogeochemistry, and water balance (Kucharik 2003, Kucharik and Twine 2007, Soylu et al. 2014); (2) MODFLOW, a model of groundwater flow and its connections to the water cycle, including evapotranspiration, recharge, and discharge to streams, lakes, and wetlands (Harbaugh 2005); (3) THMB (Terrestrial Hydrology and Biogeochemistry Model), an aquatic biogeochemistry and large-scale hydrology model (Coe 2000); and (4) the Yahara Water Quality Model (Carpenter and Lathrop 2014).

Fig. 10. Maps of land cover for 2010 (upper left) and each scenario in 2070. Grassland and other natural land covers replace low-intensity urban land and agricultural land in "Abandonment and renewal". Urbanization increases substantially in "Accelerated innovation" as population increases and the smaller agricultural land base is highly managed and heavily manipulated through technology. Large amounts of land in "Connected communities" are devoted to small-scale agriculture, and the urban footprint shrinks as more restored natural areas and urban farms are created. Row crops are largely replaced with grass-based biofuels, forest, and wetlands in "Nested watersheds" because a strong focus is placed on water quantity and quality protection.



DISCUSSION

The Yahara2070 scenarios address four contrasting pathways of regional change. The hypothetical collapse explored in "Abandonment and renewal" contrasts with the capacities of technology, human values, and governance to forestall collapse, as explored in the other three scenarios. "Accelerated innovation" addresses the consequences of broad societal investments in technological development. The seeds of these investments exist in the Yahara region, and the scenario explores what could happen if these seeds germinate and flourish. "Connected communities" addresses the effects of a generational shift in values toward sustainability (Raskin et al. 2002). Such values are widespread in the Yahara region and beyond (World Values Survey, http://www.worldvaluessurvey.org/wvs.jsp), but thus far have not coalesced into a global transition. The effect of massive governmental reorganization around a national sustainable water framework, based on watershed management literature (Molle 2009), is the subject of “Nested watersheds”. The scenario addresses the hopes and fears of Yahara residents (depending on their views of government) about strong government intervention to address water conflicts (Kuzdas and Wiek 2014).

Scenarios must represent highly diverse alternate futures that are nonetheless provocative, relevant to stakeholder interests, plausible, and consistent with existing biophysical knowledge. These goals are often in conflict. Provocative scenarios may challenge beliefs of some users or seem unlikely based on biophysical data, for example. Such trade-offs have no optimal resolution, and thus far, there are few guidelines for deriving scenarios in this context (Wiek et al. 2013, Wiek and Iwaniec 2014). Our approach (Fig. 4) employed the international scenarios literature, local stakeholder perspectives, and model needs with associated quantitative drivers. The international literature broadens options for the storylines and brings in global patterns of change that affect the Yahara watershed. Local stakeholder perspectives help build the credibility, legitimacy, relevance, and local effects of the scenarios. Modeling deepens the storylines quantitatively and raises questions about energy, food, and water use. Model results sharpen understanding of trade-offs that must be made in management and policy. In addition, the storylines create new challenges for modeling and thereby drive model development.

The three sources of themes and events, i.e., scenarios literature, local stakeholder views, and model needs, contributed to the storylines. All three sources contributed to the societal collapse in the “Abandonment and renewal“ scenario. In the global literature, breakdown scenarios are common (Hunt et al. 2012). The scenario provided an opportunity to discuss recovery of disturbed ecosystems, a priority for some local stakeholders. The weather and flooding events in this scenario prompted modeling to understand extreme events that are known from past centuries but have not occurred in the watershed during modern times. Other events in Yahara2070 were sourced directly from stakeholder interviews and workshops. For instance, interviewees mentioned “motherless meat” as a potential change in the future, and this innovation was incorporated into “Accelerated innovation”. Some aspects of the scenarios drew heavily on the global literature. “Connected communities” derives from research on the Great Transition Initiative (Raskin et al. 2002; http://greattransition.org/)

An important goal of our watershed modeling is to understand the effects of land use on resilience of water resources to changing climate. The outcomes of the four scenarios diverge in ways that allow modelers to test hypotheses about relationships between land use, climate, and freshwater ecosystem services. In “Abandonment and renewal”, the combination of rapid intensification of agriculture and rapid climate change is expected to drive extreme deterioration of water quality, culminating in deadly algal blooms. Following abandonment, the revegetation of the watershed should lead to improvements in water quality. In contrast, extreme climate changes in “Nested watersheds” are expected to have more moderate effects on water quality because of the massive adaptive changes in land use and agricultural practices. In “Accelerated innovation”, where climate change is moderated by global progress in green technology, water quality in the Yahara is hypothesized to improve relative to current levels. In “Connected communities”, in which the Great Transition occurs in response to sharp shocks driven by climate change, we hypothesize that water quality initially worsens, but then gradually improves. The divergent scenario narratives were developed to evaluate these expectations using model results, and thereby evaluate our current understanding of the dynamics of phosphorus cycling and water quality in the watershed.

Successful scenarios must engage the users emotionally as well as intellectually. Our artistic approach to the scenarios, involving creative writing and illustrations, has struck a chord with the public. Lively popular writing and evocative illustrations evoke emotional reactions to the scenarios that stimulate conversations about the future. Creative writing and art are as crucial as traditional research tools such as quantitative surveys or computer models for scenarios that evoke discussion and thereby influence thinking about the future.

Perhaps most important is the need to have dedicated trained personnel managing the engagement with stakeholders. These interactions cannot be accomplished as a side project by those developing the quantitative models and empirical studies. Instead, the empirical researchers, modelers, storyline developers, and stakeholders should be involved in ongoing interactions through a professionally managed outreach process. This process is essential for guiding the communication of scenarios, identifying key issues for analysis, and establishing the credibility of the project and process.

Scenario projects demand a comprehensive view of regional social-ecological change, and therefore have many advantages for integrated assessment (Schneider and Rist 2014). Nonetheless, scenarios pose some challenges as a research tool. The watershed is unreplicated, and there is no reference social-ecological system. Thus, the usual approaches of whole-ecosystem experiments cannot be applied. Despite this shortcoming, scenario projects create multiple opportunities for scientific inference. The scenarios themselves contain deliberate contrasts that will be investigated using model experiments. Using surveys and interviews, we will investigate differences between stakeholders who have vs. have not participated in scenario processes. Beyond Yahara2070, there is need for further comparative analyses of diverse scenario processes and outcomes in the literature. Because scenarios of social-ecological dynamics are likely to be a useful research tool for some time to come, opportunities for comparative studies will expand in the future.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/7433

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Appendix 1. Tables A1.1 – A1.4. Comparisons of the scenarios.

Table A1.1. Overarching Change Agent by Scenario

Abandonment and Renewal	*Accelerated Innovation*	*Connected Communities*	*Nested Watersheds*
Inadequate preparation for environmental challenges, notably climate change and poor water quality	Prioritization of technology to address environmental challenges	Collective values shift toward community and sustainability to address environmental challenges	Government reform geared toward preserving national water supply

Table A1.2. Ecological Outcomes in 2070

Scenario	*Land*	*Water*	*Climate*
Abandonment and Renewal	Rejuvenated and mostly feral ecosystems (forests, wetlands, savannah, grasslands) increase substantially and consist of mix of native and non-native plants and animals; agricultural land and urban land have decreased significantly.	Lakes have a heavy legacy of nutrient runoff to shed, but are recovering in the dearth of humans	Annual average temperatures are around 9°F warmer than in 2010; climate is wetter, but extreme rainfalls have moderated by 2070; drought frequency has increased
Accelerated Innovation	Ecosystems are highly engineered; urbanization has increased but is compact; agricultural land has decreased, but technology maintains productivity; natural areas decrease	Lake water quality has improved due to technological advancements	Annual average temperatures are about 3°F warmer than in 2010; the climate continues to get wetter, but technology has moderated climate change and its impacts overall; drought frequency is similar to historical record
Connected Communities	Agricultural land becomes more diversified, and pasture area increases; urbanization is curbed and compacted; natural areas, especially wetlands, increase; land is managed to improved connections with nature	Water quality improves, but slowly	Annual average temperature is about 6°F warmer than in 2010; climate is wetter but variable overall; drought frequency increases
Nested Watersheds	Agricultural acreage is drastically reduced and replaced mostly by grassland; biofuel production, pastureland, and non-commodity cropland increase; urbanization is more controlled; land management largely centered around water conservation and improvement	Water quality improves but slowly, and setbacks occur sporadically	Annual average temperature is about 7°F warmer than in 2010; climate becomes wetter, but has moderated since mid-century; drought frequency increases

Table A1.3. Social Outcomes in 2070

Scenario	*Lifestyle*	*Economy*	*Governance*
Abandonment and Renewal	Survival and resourcefulness are main concerns; people live in small urban clusters or on subsistence farms; some live somewhat migratory lives, to avoid lakes during dangerous cyanobacteria season	Equity has increased, but material wealth has decreased; bartering system has replaced money.	Centralized government and social support systems are nonexistent; communities are autonomous
Accelerated Innovation	Technology pervades human lifestyles and many interactions with nature	Economy is largely based in tech industry; material wealth increases; ecosystem services are protected with market mechanisms	Government and private sector work in tandem to support innovation; government plays investor role
Connected Communities	Lifestyles are oriented toward building and preserving community, sustainability, and improving quality of life	Economy functions as an ecosystem and is a means to preserve quality of life, not increase GDP; Gross National Happiness becomes index of "wealth"	Public participation in governance increases; social support systems enhanced
Nested Watersheds	Water conservation and climate change adaptation have risen in public salience; many sectors—from farming to construction—have incorporated water management goals into their status quo	Water management becomes important part of economic activity in both private and public sectors	Water governance performed at watershed level; holistic management of water improves; incremental adaptation has become the pattern; government regulation of natural resources has strengthened

Table A1.4. Some opportunities and threats in each scenario

Scenario	*Opportunities*	*Threats*
Abandonment and Renewal	Regeneration of ecosystems and ecosystem services Opportunities for society and culture to start anew Social equality increases	Human survival is difficult Human vulnerability increases General economic and social collapse has occurred
Accelerated Innovation	Region's wealth increases Advancements in human knowledge Ecosystem and societal efficiencies increase Water quality improves Climate change is moderated Strong tech-based economy	Nature loses intrinsic value Risk of unintended consequences and technology failures Negative effects of local population growth Loss of "survival" skills Market risks put ecosystem services at risk Technology can't solve all problems
Connected Communities	Improved quality of life and equality Governance more democratic Increased connection with nature improves ecosystems Water quality improving (but slowly) Stabilized climate Improved social support	Some present-day conveniences are gone (e.g., cheap air travel) Risk of rogue individuals, organizations, and countries Prices increase on foods and goods (to reflect social and environmental costs) Climate has still warmed, even if stabilized
Nested Watersheds	Improved water quality and supply Improved and more holistic water management Improved water-based ecosystems and some ecosystem services (e.g., soil quality) Local economy thrives Improved ability of farmers, businesses, etc. to protect water (i.e., because of incentives and expectations)	Incremental adaptation creates vulnerability Climate change not moderated; impacts ensue Uncertainty around maintaining widespread public support for regulations in the long-term

Appendix 2. Methods for land cover representation and construction of the Bayesian Belief Networks.

Land cover is represented by 16 functional groups with distinct characteristics in the agroecosystem model (Figure 10). The creation of land-cover maps through time for each scenario began with a full inventory of 2010 land cover compiled from multiple sources (CCLID 2005, WDNR 2008, Fry et al. 2011, USDA 2011, RCPECDA 2012, CARPC 2013, USDA 2013). Land-cover changes at a decadal scale up to 2070 were then quantified based on changes described in the qualitative narrative. Decadal watershed population was also quantified for each scenario to guide the appropriate changes in urban land cover.

In constructing the BBNs for land use/cover transitions of each scenario, we selected a set of variables based on current literature, changes stated in scenario narratives, and expert knowledge about this watershed (McCloskey et al. 2011, Swetnam et al. 2011, Celio et al. 2014). Variables were dependent on the particular scenario, time of change, and land use/cover types and included soil crop suitability, soil hydric condition, proximity to stream, proximity to road, distance to current land use/cover, slope, zone of protected areas, etc. Once the transition probabilities were calculated, we used the Netica BBN and ArcGIS software to create the land cover maps (Fig. 10).

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