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From qualitative to quantitative environmental scenarios: Translating storylines into biophysical modeling inputs at the watershed scale

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ABSTRACT

Scenarios are increasingly used for envisioning future social-ecological changes and consequences for human well-being. One approach integrates qualitative storylines and biophysical models to explore potential futures quantitatively and maximize public engagement. However, this integration process is challenging and sometimes oversimplified. Using the Yahara Watershed (Wisconsin, USA) as a case study, we present a transparent and reproducible roadmap to develop spatiotemporally explicit biophysical inputs [climate, land use/cover (LULC), and nutrients] that are consistent with scenario narratives and can be linked to a process-based biophysical modeling suite to simulate long-term dynamics of a watershed and a range of ecosystem services. Our transferrable approach produces daily weather inputs by combining climate model projections and a stochastic weather generator, annual narrative-based watershed-scale LULC distributed spatially using transition rules, and annual manure and fertilizer (nitrogen and phosphorus) inputs based on current farm and livestock data that are consistent with each scenario narrative.

1. Introduction

Anthropogenic environmental changes are challenging the sustainability and resilience of social-ecological systems. These changes are expected to accelerate in the next decades and may pose unprecedented challenges for the delivery of ecosystem services that are essential for human wellbeing (Chapin et al., 2010; Foley et al., 2005; Nelson et al., 2013). It is therefore necessary to anticipate potential future trajectories of environmental changes and understand how these changes may reshape the future prospects of ecosystem services. Such understanding is remarkably challenging and requires long-term thinking (Alcamo et al., 2005; Carpenter et al., 2015). Predictive models have been used to project future conditions of social-ecological systems. However, the future is inherently uncertain and highly unpredictable due to complex feedbacks, the possibility of regime shifts in social-ecological systems, the lack of historical analogs, and other factors (Folke et al., 2004; Maier et al., 2016).

Scenario analysis is a tool for envisioning the range of futures that might unfold from the complex dynamics of social-ecological systems (Mahmoud et al., 2009; Raskin, 2005). Scenarios have been increasingly used at local to global scales for fostering long-term thinking and exploring the dynamics and sustainability of social-ecological systems (O'Neill et al., in press; Oteros-Rozas et al., 2015; Thompson et al., 2012). Scenarios often comprise a set of plausible contrasting stories about the future, and can be integrated with biophysical models to explore the range of potential outcomes

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and the likely consequences for vital ecosystem services (Bennett et al., 2003; Peterson et al., 2003; Polasky et al., 2011).

Scenarios of multiple ecosystem services that combine qualitative components with quantitative models have been mostly developed at the global to national scales (e.g., Carpenter et al., 2005; Schroter et al., 2005) with relatively fewer at the regional to watershed scale (Bryan et al., 2011; Lebel et al., 2005). Methods for spatial downscaling of integrated scenarios exist (van Vuuren et al., 2010) but can suffer from issues with validity and credibility by not incorporating the role of local agents of change and neglecting important local processes (Özkaynak and Rodríguez-Labajos, 2010). In addition, some have argued that the creation of locally based, bottom-up, and diverse scenarios can be particularly effective at engaging citizens and decision-makers, while also highlighting vulnerabilities and opportunities for building resilience (Kok et al., 2016). Thus, connecting such regional scenarios with quantitative modeling assessments of multiple ecosystem services may be a valuable strategy but methods for the linkage are few (e.g., Bolte et al., 2007) and not yet well-developed.

A wide array of scenario studies have quantified the impacts on one or a few ecosystem services in response to alternative paths of quantitative drivers such as climate (Bangash et al., 2013; Koca et al., 2006), land use/land cover (Lawler et al., 2014; Metzger et al., 2006), or both (Byrd et al., 2015; Fan et al., 2016). A review of 52 water-related scenarios found that most only considered one key driver of change, with climate change being the most common (March et al., 2012). Similarly, a review of biodiversity scenarios found future land use/management changes largely ignored (Titeux et al., 2016). While these quantitative scenarios can play an important role in exploring key sustainability drivers and ecosystem service impacts, they are often limited by not connecting to narratives about changes to social drivers such as land management practices, changing market demand, or shifts in human diets and preferences. This limitation is especially consequential because the impact of social, political, and economic changes may exceed that of biophysical changes such as climate (Alexander et al., 2015; Kriegler et al., 2012).

In parallel, a largely different set of scenario studies have explored alternative social-ecological futures using rich storylines that integrate complex economic, political, and social dynamics (e.g., Hanspach et al., 2014; Palomo et al., 2011). Some have argued that creating such rich and descriptive narratives may be as important as quantitative models in transdisciplinary scenarios research, since narratives improve the scenarios' accessibility, credibility and relevance (Burnam-Fink, 2015). In addition, these enriched scenarios tend to be strongly interactive with diverse stakeholders, which can facilitate social learning and potentially generate novel ideas to achieve sustainable futures (Butler et al., 2014). While these qualitative scenarios are often quite comprehensive in terms of drivers, they tend to involve little or no quantitative modeling projections.

We present an approach for bridging rich social, political, and economic storylines developed with significant stakeholder input to a suite of spatially-explicit biophysical models for quantifying multiple ecosystem services. While this type of integration has been performed at national to global scales (e.g., Calvin et al., 2016; Carpenter et al., 2005) and is consistent with the “Story and Simulation” approach (Alcamo, 2008), the authors know of no such integration performed at the regional or watershed scale where local processes such as urbanization and agricultural management interact with global drivers such as human diet and climate change. Incorporating and understanding fine-scale spatio-temporal dynamics of a watershed and consequences for a suite of ecosystem services under a wide range of futures is an emerging research frontier and would provide critical information for decision-makers and managers (Renard et al., 2015), even though progress still lags behind regarding how to use and implement such understanding in real-world decisions.

One challenge of using rich narratives is how to convert them into quantitative estimates of drivers that can be used as inputs for biophysical models. This process is a weak link in integrated scenario development (Alcamo, 2008) and can be complex, particularly if the scenario incorporates many interacting drivers of change. If the criteria and rules are not described explicitly, this process is sometimes perceived as arbitrary and difficult to replicate. In addition, rich narratives can often be reduced to simple and one-dimensional representations during the translation to model inputs (Titeux et al., 2016).

Several methods exist for translating qualitative statements from scenario narratives into quantitative values suitable for model input, including fuzzy set theory and pairwise comparison (Mallampalli et al., 2016). However, when considering a large suite of driver variables these methods become quite onerous. An alternative to using them is to rely on the scenario team's “best judgment” in making the qualitative to quantitative translation. This tends not to be reproducible, but it can be transparent and allows for the flexibility and specificity necessary to create quantitative inputs that vary in space and time.

In this study, we address these knowledge gaps by demonstrating a scenario translation process that strikes a balance between using the scenario team's best judgement in a transparent manner and formal quantitative approaches. We start with four previously-developed scenario storylines that are provocative, contrasting but plausible, and include multiple drivers of environmental changes (e.g., climate, human demands, diets and other social factors) along with extreme conditions (Carpenter et al., 2015). The ultimate goal of the scenarios is to simulate the provision of a suite of terrestrial and freshwater ecosystem services from 2014 to 2070 using spatially explicit mechanistic models. While other studies have presented examples of translating storylines into biophysical modeling inputs, we present an innovative translation method that produces quantitative estimates of climate, land use/land cover, and nutrient input drivers that are spatially explicit and temporally dynamic, and can be readily integrated with process-based biophysical models.

2. Study area

The Yahara River watershed in south-central Wisconsin, USA, is a 1344 km^2 urbanizing agricultural watershed dominated by dairy agriculture in the northern third, the Madison metropolitan area in the middle third, and corn-soybean commodity agriculture in the southern third. Current and anticipated future challenges in the watershed include striking a balance between farmland preservation and urban population growth, increasing milk production to meet rising domestic and global demands for dairy products while improving water quality, and managing flood risk with increasing impervious surface area and increasing frequency of heavy rainfall events (Gillon et al., 2015; Lathrop et al., 2005). How these (and unanticipated) challenges will evolve and impact ecosystems and residents of the watershed in the future is highly uncertain.

3. Scenario narratives

Scenario narratives that describe four contrasting, yet plausible futures of the Yahara River watershed to 2070 were developed between 2011 and 2014 (Carpenter et al., 2015). The scenarios were intended to explore the potential futures of water resources and ecosystem services as land use/land cover, climate, and human needs change. These qualitative scenarios included artistic images and were meant to engage the public using the power of storytelling. The scenarios were also designed and intended to fully integrate with quantitative biophysical models to further enrich the scenarios.

Design criteria for the scenario narratives sought stories that were provocative, holistic, participatory, and iterative between the researcher team and key stakeholders. Provocative stories were sought to enhance outreach and stimulate discussion among diverse stakeholders. Scenarios that are holistic were also desired to ensure compatibility among the broad range of complex social and environmental factors that drive long-term change. Making the scenarios participatory through the solicitation of ideas from local community members was another important criteria that was intended to lead to scenarios perceived as credible, relevant, and plausible by the community.

The iterative aspect of the scenario development process was also critical as the narratives cycled back and forth between the lead writer, the biophysical modeling team, and a smaller group interacting with qualitative and quantitative aspects. The modeling team extracted cues and themes from the narratives to make decisions on the three key driver categories: climate, land use/land cover, and nutrient (nitrogen and phosphorus) inputs (Fig. 1). If the modeling team found that insufficient details were present in a narrative to make a reasonable decision regarding a driver category, then modelers consulted with the narrative team to develop the missing information. In some cases the narratives changed as a result of these discussions (Carpenter et al., 2015).

The scenarios were also designed to be distinctly different to help readers differentiate them, highlight the consequences of alternative pathways, explore a wide range of possible dynamics, and challenge the models to simulate divergent and novel environmental conditions. Finally, extreme climate events were intentionally included in the scenarios because of their ability to impact ecosystems and humans in potentially non-linear ways and the increased probability of their occurrence in the future under climate change.

We present a short summary of each scenario narrative below with an emphasis on characteristics most relevant to biophysical modeling. The complete storylines are available at Yahara2070.org.

3.1. *Abandonment & Renewal (AR)*

This scenario's driving theme is societal inaction leading to disasters. Urban growth continues unabated and agricultural production and intensity increase to boost the U.S. food supply in light of a national food crisis driven by climate change. This is followed by a series of devastating events that include a very large flood in 2031, an oppressive heat wave in 2033, and the emergence of an airborne cyanobacterial toxin in 2035 that subsequently reduces the population by ~90% through death and migration. Farmland is largely abandoned, and most urban areas deteriorate from lack of maintenance. By the mid-2040s, a new society starts to emerge in the watershed that is almost completely self-sufficient in terms of food and energy. Agricultural areas are diverse to sustain local diets and include vegetables & fruits, small grains, hay, corn, and pasture for livestock. However, the climate is vastly different with mean annual temperatures around 4.5 °C warmer than 2010.

3.2. *Accelerated Innovation (AI)*

The main driver of this scenario is extensive technological development. Following continued global environmental degradation and several high-profile disasters outside the watershed, society fully embraces technology as the primary tool in addressing issues related to climate change and dwindling resources. The Madison metropolitan area becomes a hub for the booming high-tech and green-tech sectors and population increases along with employment. Existing urban areas become more densely populated to accommodate this growth, but new “smart” developments appear on the fringe. Precision agriculture is the norm, and individual farmers have the power to tinker with DNA to increase productivity and nutrient-use efficiency. A new market emerges for cultured meat (Tuomisto and de Mattos, 2011) and vegan cheese developed and produced in the watershed to circumvent problems with excessive manure disposal. However, some techno-skeptics are still present and drive a market for locally-produced “natural” meat, dairy, and produce. While heavy rainfall events continue to challenge stormwater infrastructure, climate has not warmed as much as most early-century models predicted.

3.3. *Connected Communities (CC)*

A large change in social values toward less resource consumption and more community-building is central to this scenario. Widespread social unrest and pivotal environmental disasters in the 2020s and 2030s inspire a global youth movement that emphasizes low resource consumption, happiness, and community. Population increases slightly but the urban footprint shrinks due to increased population density and the conversion of substantial amounts of turfgrass to restored prairie and urban farms. Diets in the region and most developed countries have shifted away from meat and dairy after increasing recognition of their environmental impacts (e.g., Eshel et al., 2014). Thus, the agricultural landscape consists of a diverse mix of pasture, vegetables and fruits, small grains, and more moderate amounts of corn, soybeans, and alfalfa. The climate is warmer than most early-century models predicted,

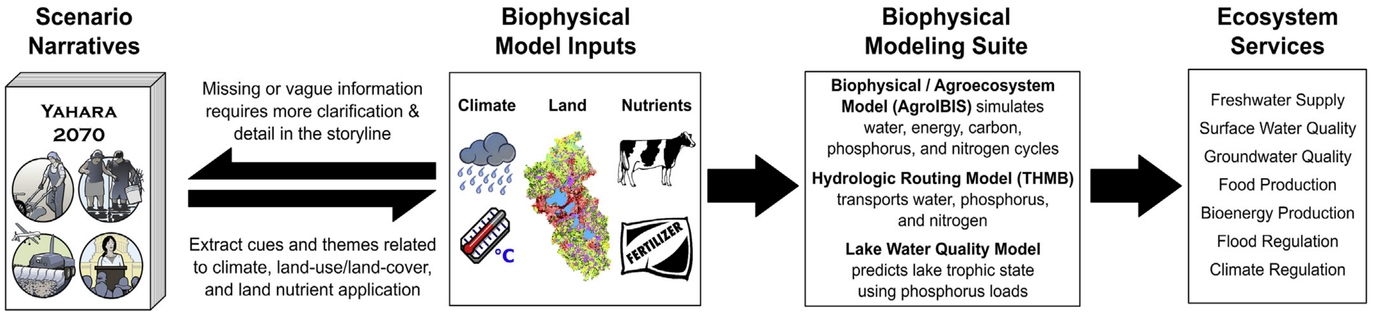


Fig. 1. Diagram showing the development of the integrated qualitative-quantitative scenarios of the Yahara River watershed starting with narratives that iteratively connect to biophysical model inputs. The inputs are then used to drive a biophysical modeling suite that can output a suite of ecosystem services. This paper explains the method for translating scenario narratives to biophysical model inputs (first two boxes).

and heavy rainfall events continue to increase in frequency. One such multi-day event occurs in 2069.

3.4. Nested Watersheds (NW)

A major reorganization and expansion of federal water policy is the theme of this scenario. Severe climate disasters in the United States in the 2020s and 2030s – including a prolonged drought in the desert Southwest and major blooms of cyanobacteria – push citizens for a complete overhaul of the nation's water and food policies. Jurisdiction for the governance of land and water is redrawn to match natural watershed boundaries. Tax disincentives for agricultural land uses such as livestock and corn, as well as subsidies for grass-based biofuel crops and small-scale vegetable and fruit producers completely transform the rural landscape. Policies and regulatory rules encourage the production of human-edible crops to minimize energy use, greenhouse-gas emissions, and land devoted to agriculture (e.g., McAlpine et al., 2009). Farmers are also encouraged to farm water like a crop – i.e., to manage their land in a way that supports clean and sufficient water. Environmental monitoring is pervasive to evaluate compliance with rules and regulations. By 2070, mean annual temperatures are much warmer than early-century climate model predictions. Precipitation has decreased substantially in the latter decades with severe droughts occurring in 2060 and 2065, but severe rainfall events, like in 2070, still test the stormwater system.

4. Methods

4.1. Biophysical modeling suite

In this study we describe methods for translating qualitative scenario narratives into quantitative drivers that can be input to a biophysical modeling suite for projecting future watershed outcomes. The products are spatially explicit and temporally continuous (daily) inputs of climate, land use/cover, and land nutrient applications (phosphorus and nitrogen from fertilizer and manure).

The biophysical modeling suite specific to our case study consists of three integrated models: 1) Agro-IBIS land surface model (Soylu et al., 2014); 2) THMB hydrologic routing model (Coe et al., 2008) and 3) Yahara Lakes water quality model (Carpenter and Lathrop, 2014). Agro-IBIS simulates flow and storage of water, energy, nutrients (phosphorus and nitrogen), and carbon in terrestrial ecosystems under different land-cover types including natural grassland, common cropping systems such as corn and soybeans, and urban areas with mixed impervious and pervious cover. The previous model has been calibrated and validated extensively throughout the Upper Midwest USA (Kucharik and Brye, 2003; Motew and Kucharik, 2013). Fluxes of water and nutrients from the land surface and subsurface are input to THMB and routed downstream through the channel network with potential losses by evaporation and sediment deposition. Grid cell dimensions for Agro-IBIS and THMB are 220 m × 220 m. Phosphorus loads from THMB are then input to the Yahara Lakes water quality model to estimate the lake's nutrient and eutrophication status as well as water clarity indices (Carpenter and Lathrop, 2014).

Below we present the approach for quantifying each key driver.

4.2. Model inputs: climate

Climate scenarios were generated by combining downscaled climate model projections (daily precipitation and air temperature) and a stochastic weather generator to balance the benefits of well-validated climate simulations with the flexibility provided by a weather generator to match specific climate events in the scenario storylines (Fig. 2). This approach differs from solely using downscaled climate projections (Mote et al., 2011), which have limitations in terms of reproducing a broad range of potential climate changes, most notably the extreme events (Brown et al., 2012; Stainforth et al., 2007). These two aspects are critically important in the Yahara 2070 scenario storylines as they often focus on impacts related to extreme events. Next, a regression model using urban land cover extent is used to account for future urban heat island impacts by altering air temperature values. Finally, regression models based on historical weather data were used to generate daily solar radiation, relative humidity, and wind speed values. The implementation of this method for the Yahara 2070 scenarios is described below.

We obtained climate model projections from Notaro et al. (2014) who used a probabilistic-based approach for downscaling 12 general circulation models (GCMs) with 3 emission scenarios (A2, A1B, and B1) from the Coupled Model Intercomparison Project Phase Three (CMIP3) for two future time periods (2046–2065 and 2081–2100). The probabilistic downscaling approach spatially interpolates the daily-varying parameters of probability density functions (PDF) representing the distribution of daily P_r and daily T_{max} and T_{min} at each $0.1° \times 0.1°$ grid cell. Three randomly generated realizations were created for each PDF and only 9 GCMs were available for the later period. All combined this provided 234 unique 20-year climate time-series for a single grid cell representing the location of the Madison airport (43.14°N, 89.34°W).

We did not attempt to match an emissions scenario from the IPCC Special Report on Emissions Scenarios (SRES) with one of our scenario storylines. Instead, we included all SRES emissions scenarios as well as all available GCMs to maximize the size of the climate scenario space upon which we drew. Descriptive statistics for air temperature and precipitation were calculated for each of the 234 20-year time-series including annual means, extreme precipitation events (number of days with $P_r > 75$ mm and >150 mm per decade), extreme heat events (number of days with $T_{max} > 32$ °C and >38 °C per decade), and extreme cold events (number of days with $T_{min} < -18$ °C per decade). These statistics were used as screening indicators to help match time series with the appropriate climate components and themes of each scenario narrative. For example, a scenario narrative that describes an increasing frequency of drought would be matched with a time-series with relatively low values of annual precipitation. However, the same hypothetical narrative might mention increasing frequency of heavy rain events and thus the current pool of appropriate climate time series would be reduced to reflect this.

Once the qualifying time series were selected for each of the three 20-year divisions per scenario, they were input into a stochastic weather generator to create 500 years of synthetic climate data that preserved the original statistical properties. We chose the weather generator WeaGETS (Chen et al., 2012) because of its wide application in climate change studies and its ability to reproduce extreme precipitation events. The occurrence of a precipitation event was simulated using a 2^{nd}-order Markov model and the daily precipitation amount was estimated using a two component mixed-exponential probability distribution. Unique model parameters were estimated for 14-day periods over the year. T_{max} and T_{min} were determined by fitting a 1st order linear autoregressive model with wet and dry days handled separately.

The reason for generating such a long synthetic climate time-series (500 years) was to provide a large sample from which to draw specific events and sequences – in 20-year increments (2011–2030, 2031–2050, 2051–2070) – that the narratives required. For example, a scenario narrative could describe a large precipitation event followed by a heat wave. This specific sequence of events could be reproduced by the weather generator within the

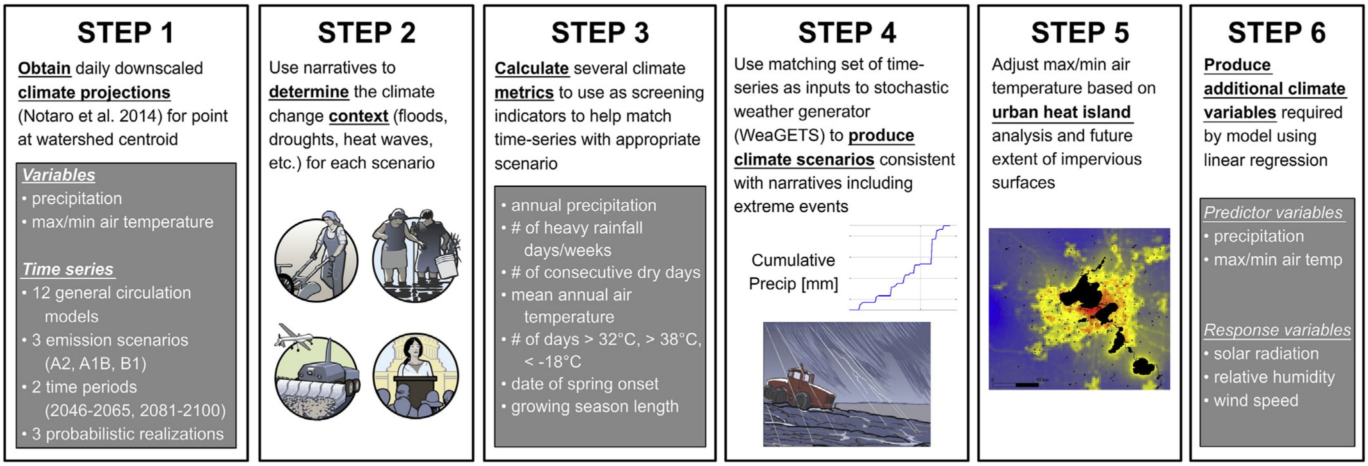


Fig. 2. Steps involved in developing the daily climate inputs (e.g. precipitation, air temperature) for each scenario (art credit in Step 4: John Miller).

500-year sample and inserted in the correct place within the 2014–2070 time window. A 20-year increment length was chosen to allow for a gradually changing climate time series (e.g., warming from 2014 to 2070). The statistics that were used as screening indicators were then determined for each set of climate scenarios (Appendix A).

Future air temperature was also modified spatially to account for the urban heat island, the extent of which is dependent on future urban land cover. The Madison metropolitan area currently experiences a persistent urban heat island (UHI) effect, which peaks in intensity during the summer growing season when urban-rural temperature differences average up to 4 °C at night and 1.5 °C during the day (Schatz and Kucharik, 2014). Land cover change from 2010 to 2070 will alter patterns of urban development and associated UHI effects, changing temperatures across the Yahara watershed. To incorporate these effects into our scenarios, we developed empirical models of the UHI using data from an extensive network of temperature sensors across the region. The details of this method are available in Appendix B.

Finally, the land surface module of our biophysical modeling suite (AgroIBIS) also requires daily inputs of solar radiation, relative humidity, and wind speed. These variables were created based on the generated daily maximum and minimum air temperatures and precipitation using linear regression models with a stochastic element representing model residuals. More details are available in Appendix C. Relevant climate metrics (number of heavy rainfall events per decade, growing season length) for each scenario are included in Appendix D.

4.3. Model inputs: land use/cover

The first step to determining land use/cover (LULC) changes for use with a biophysical model is to determine the number of categories that are biophysically-distinct. The categories depend on the complexity and specificity of the biophysical model that one uses for a quantitative scenario assessment. Next, a map of current LULC for each category is created. The narratives are then used to determine the various contexts for LULC changes (e.g., urban growth, diet changes impacting crop types). These contexts are then used to determine the future changes in area for each LULC category and scenario at the watershed-level. At this step the LULC driver curves can be negotiated between research team members and stakeholders to best reflect the group's interpretation of each narrative. To facilitate a reasonable level of changes during the negotiation process, only decadal changes are determined. After the final LULC driver curves are obtained, a set of transition probability rules are used to spatially distribute the LULC changes described by the driver curves. This method differs from traditional land use change models that determine a landscape from a base condition using model inputs and parameters (Agarwal et al., 2002) but we believe that it allows for more flexible interpretation and stronger contrast among scenarios. Finally, annual crop rotations are implemented using a semi-random algorithm.

For the Yahara 2070 assessment, LULC was first categorized into 17 biophysically distinct groups (Fig. 3) and maps of current (2010–2013) conditions were created based on several data sources. The most recent county land-use data were obtained for Dane (2010), Columbia (2005), and Rock (2012) counties (CARPC, 2013; CCLID, 2005; RCPECDA, 2012). Data from the 2010–2013 Cropland Data Layers (CDL) (USDA, 2014) and 2006 and 2011 National Land Cover Datasets (NLCD) (Fry et al., 2011; Homer et al., 2015) were obtained to further distinguish LULC types. Data were also obtained from the Wisconsin Department of Natural Resources Wetland Inventory (WDNR, 2008) and the hydric soils layer from the USDA-SSURGO database (USDA, 2013) to further refine the wetland category. Integrating these different datasets provided a reliable estimate of current (2010–2013) conditions that could then be used as a starting point for the four scenarios.

To estimate future LULC changes under each scenario (yearly from 2014 to 2070), we first developed decadal changes for each category at the watershed-scale. The ‘open water’ and ‘barren’ categories (7.4% and 0.1% of watershed, respectively) were assumed to stay constant in each scenario leaving 14 categories to estimate per decade per scenario. Changes in land cover were based on scenario storylines regarding land policy, food and agricultural policy, changes in human diet, water policy, and energy policy. In addition, values for watershed population were determined based on the narrative to inform urban growth. If a component necessary for providing context for land-cover change was missing in a draft of the storyline, then the modeling team would inform the narrative writer. This iterative process between the writer and modeling team led to a more complete picture of the scenario storyline (Fig. 1).

Currently, LULC in the Yahara watershed is strongly controlled by an increasing national and international demand for dairy products, specifically cheese (reflected as corn, alfalfa, and soybean in the northern part of the watershed), and livestock feed and ethanol (corn and soybean in the southern part of the watershed). This strong influence of the energy and food sectors on the current landscape prompted us to create a coherent energy and diet context

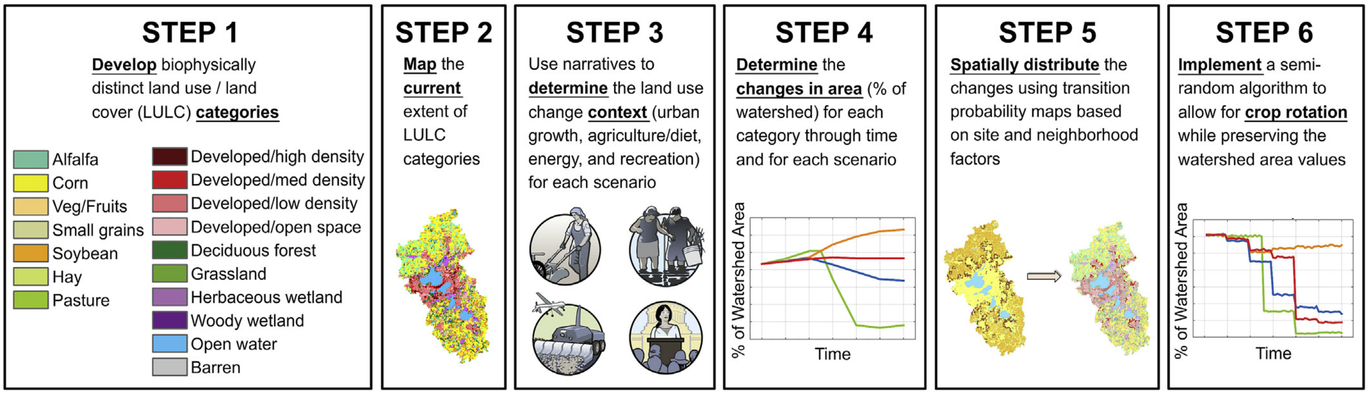


Fig. 3. Steps involved in the development of the land-use/land-cover model inputs for each scenario.

for each scenario (Table 1). For instance, a reduction in global demand for dairy products would allow for more changes in rural LULC.

With the watershed-scale LULC values set as limits, an immediate next task was to manifest these changes spatially across the landscape (Fig. 3). A rule-based spatial allocation approach (Bateman et al., 2013; Haines-Young, 2011) was used to construct time-sequences of future landscape maps at 30-m resolution and at 10-year time steps from 2010 to 2070, in accordance with the narratives of each scenario. The approach sets distinct rules for each scenario to determine the probability of change from one land cover to another while considering geographic and biophysical characteristics of each cell. Taking the Abandonment and Renewal (AR) scenario for example, during the collapse period (2030–2050), there is a higher probability that agricultural and developed lands near lakes would be abandoned and replaced by natural vegetation such as grassland, forest and wetland. As the society rebuilds, a new agricultural locus emerges during late 2050s and 2060s in fertile

Table 1
Summary of various contexts relevant to the scenario-narrative-to-model-input translation process.

Scenario name	Climate	Energy context	Diet context	Agricultural land	Urban land	Natural land
Abandonment & Renewal	Exceptionally warmer (5.5 °C) by 2070, exceptional heat wave and flood events in 2030s, much drier in 2060s	Conventional energy sources are no longer supplied following collapse; some solar but mostly solid bioenergy (wood)	Connections to food markets outside the region are largely severed following collapse; diets are simple with sparse meat and dairy	Crop production intensifies before collapse; cropland is mostly abandoned afterwards and is dominated by small grains and vegetables	Urban areas slowly deteriorate after abandonment with grassland replacing turfgrass; new communities create minimal hardscapes	Initial agricultural productivity boost reduces natural land area; large increase in grassland and forest following collapse
Accelerated Innovation	Moderately warmer (2 °C) by 2070, more frequent heavy rainfall events	Rapid technological advances increase use of solar energy and small-scale nuclear reactors; fossil fuels are phased out	Food becomes more highly processed but much more efficient at delivering calories from farm to table through innovations like cultured meat and dairy	Cropland area is reduced by urban growth but genetic modification and intensive management of crops increases productivity	Increased population leads to new development as well as increased density in existing urban centers	Natural land area declines with urban growth but remaining areas are highly engineered to deliver several ecosystem services
Connected Communities	Substantially warmer (3.5 °C) by 2070, more frequent droughts and heavy rainfall events (largest flood event in 2069)	Changing lifestyles and increasing energy prices dramatically reduce energy consumption; remaining energy supply is from solar, wind, and geothermal	Less consumptive lifestyles lead to substantially reduced demand for meat and dairy and more locally-sourced vegetables, fruits, and small grains	Corn, soy, and alfalfa are largely replaced by vegetables, fruits, small grains, and pasture	Population stabilizes but urban area declines; density increases in existing urban centers	Natural areas increase as prairies and wetlands are restored and replace some former agricultural and urban land
Nested Watersheds	Substantially warmer (4 °C) by 2070, extreme events increase in frequency with severe droughts in 2060 and 2065 and flood in 2070	Big government investment in grass-based biofuels increases their use; however, natural gas and oil are still dominant	Emphasis on water quality spurs strict regulation on livestock operations, higher prices and reduced demand for meat and dairy	Agricultural land declines following wetland and prairie restoration projects; Grass-based biofuel crops largely replace corn and soy	Population increases but urban area stabilizes; density increases in existing urban centers	Natural areas increase as forest and wetlands are restored to help comply with strict downstream water quality regulations

soils adjacent to remnant human communities. Similarly, under the Nested Watershed (NW) scenario, the higher probability of transfers out of agriculture occurred in hydric soils (transitioned to wetlands mostly), marginal lands (i.e., low fertility or steeper slopes) and cells near streams or lakes (transitioned to riparian buffers). Specification of rules was primarily based on scenario narratives, expert knowledge and current literature (Celio et al., 2014; Swetnam et al., 2011).

Bayesian belief networks (BBN) were used to implement the rules determining the transition probabilities for each 30-m grid cells. We did not choose an existing land change model for three reasons: (1) land use change models predict the amount of changes in the future based on social and economic factors, whereas in our case the amount of changes was already determined from the narrative; (2) nonlinear changes in LULC are challenging to represent in these models; (3) some drivers or assumptions for land-use changes such as diet shifts or energy/water policies are difficult to be explicitly modeled. Specifically, the characteristics of each 30-m cell were input into the BBN and the rules appropriate to each scenario were applied to generate the probability of changing from one LULC type to another. The BBN approach is a useful tool for scenario development and landscape mapping (Bateman et al., 2013; Haines-Young, 2011). Specific advantages of this approach include the ability to incorporate uncertainty, handle nonlinear changes in LULC (i.e., AR scenario), and combine quantitative empirical data and qualitative relationships (Haines-Young, 2011). Conceptually, the spatial allocation procedures were similar for each scenario, and implemented by decade. Given the total number of LULC categories (N=17) and number of grid cells (i.e., ~1.5 million), the transition matrix for LULC types was very large and thus we used a two-step semi-automatic process, starting with broad categories (i.e., agriculture, urban, and natural covers), and then further dividing the broad categories into secondary LULC classes (e.g., urban is further divided into high-, medium-, low-density urban and open spaces). Once the transition probabilities were calculated, grid cells with the highest probabilities up to the amount of needed changes were converted. For instance, the NW scenario dictated a 1.6% increase in urban areas, and grid cells up to 1.6% with the highest probabilities of transition to urban areas will be finally converted to urban. This process was repeated for all LULC types. We used the program Netica (Norsys Software, Vancouver, Canada) to construct and implement the BBN, and used the "process cases" tool to generate the outputs. These outputs were subsequently translated into digital maps using a geographic information system (ArcGIS 10.0). Please refer to Table E.1 in Appendix E for detailed rules used to define land cover transition matrices and Fig. E.1 for an illustrative example of a created BBN.

The next step was to resample the original 30-m resolution of LULC to the resolution of the model grid cells (220-m). Resampling was done by taking the most common category within the 220-m filtering window. This caused slight discrepancies between the original specified area values and the areas implemented in the model, which can be seen in the LULC driver curves for each category and each scenario (Appendix F).

To specify LULC types across the watershed in the years between the 10-year intervals, we assumed that each 10-year value applied to the next 9 years (e.g., 2030 values would apply to 2031–2039). However, for the grid cells with a crop LULC type (corn, alfalfa, soy, or hay) we implemented a semi-random component to represent crop rotations. The rotation algorithm treats each cell independently and uses a random number to determine which crop type will be assigned while preserving the relative proportions of crop types at the watershed scale. Re-scaling and implementing crop rotation resulted in a slight difference (<2%) between the original watershed-scale LULC area values and the ones input to the model, but reflected a more realistic production system (Appendix F).

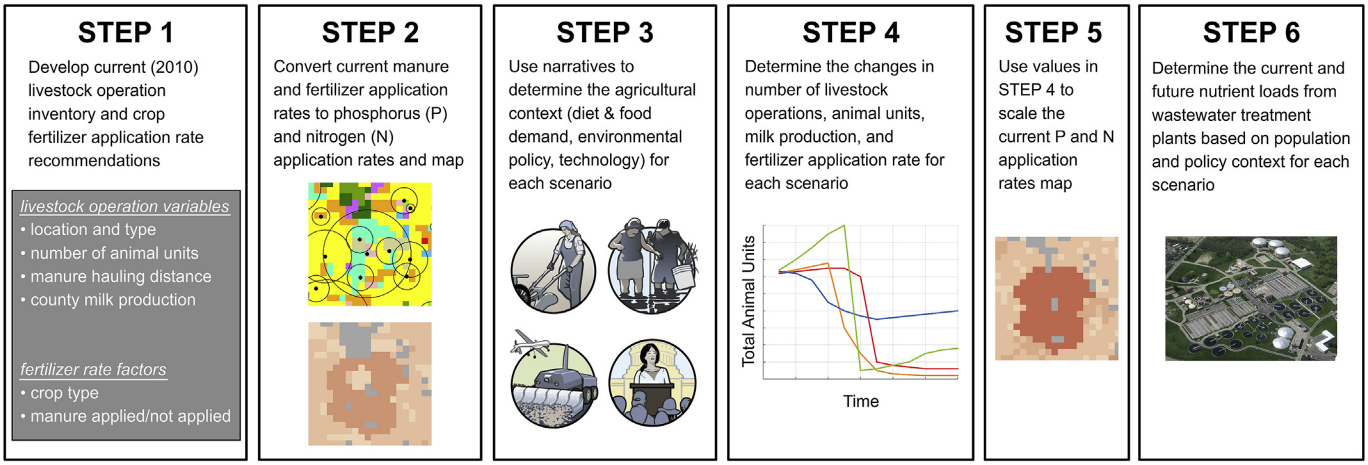
4.4. Model inputs – land nutrient applications

The first step for developing the land nutrient application scenarios (manure and fertilizer phosphorus, manure and fertilizer nitrogen) is to create an existing inventory of livestock operations in the region of interest including livestock type, number of animals, and maximum manure hauling distance. In the United States, farm-level data is not typically available to the public unless it is a permitted Concentrated Animal Feeding Operation. However, estimates by county agricultural/conservation staff can be made and data collection efforts exist for watersheds such as the Chesapeake Bay (Hively et al., 2013). Manure application rates are then determined for each farm based on standard manure conversion methods (e.g., USDA, 2008). Next, current fertilizer application rates are estimated based on local university extension recommendations. Actual application rates can differ widely from recommendations (e.g., Powell et al., 2007) but as with livestock operations farm-level data is largely unavailable.

The agricultural context for each scenario narrative is then determined with specific attention to human diet and food demand, policy, and technology. These contexts then inform the determination of driver curves for the number of livestock operations, animal units, milk production, and fertilizer application rate (relative to current rates). Next, these driver curves are used to scale the current nutrient application maps. More details for how this method (Fig. 4) was implemented for the Yahara 2070 scenarios assessment is discussed below.

The current livestock inventory in the Yahara Watershed (Fig. 5) was performed using unpublished livestock operation data from the Dane County Land & Water Resources Department (DCLWRD), Concentrated Animal Feeding Operation (CAFO) data from the Wisconsin Department of Natural Resources (WDNR, 2015), and milk producer locations from the Wisconsin Department of Agriculture, Trade, and Consumer Protection (WDATCP, 2015). Inventory included location of livestock housing facility, livestock type (beef, dairy, swine, horses, sheep), estimated number of animal units, and estimated maximum manure hauling distance. Annual production of "as excreted" manure, manure P, and manure N for all livestock types except lactating cows was determined based on conversion factors (per animal unit) from the USDA-Animal Waste Management Field Handbook (2008). Annual manure P and N production for lactating cows was estimated using regression equations from Nennich et al. (2005) that use daily milk production per animal as a predictor of excreted manure, manure P, and manure N. Milk production has been and is likely to continue to be a key driver of change in the Yahara River watershed (Gillon et al., 2015). Therefore, linking manure production with milk production allows for a more mechanistic link between the role of dairy in each scenario narrative and the biophysical model.

The estimated excreted manure N was reduced by 70% at all facilities to account for ammonia volatilization and 1st year crop availability (Laboski and Peters, 2012) which can be highly variable depending on storage and collection characteristics as well as weather conditions (Powell and Rotz, 2015). Total manure, manure P, and manure N could potentially be distributed within a circle with a radius equal to the estimated maximum hauling distance and the livestock facility at the center. Cropland and pasture were the only land cover/use types with manure spreading. Appendix G explains the procedure for accounting for overlapping areas of manure spreading. Finally, a minimum manure application rate was enforced based on survey data from dairy farms in south-central Wisconsin (Powell et al., 2005). If the calculated application rate was below the threshold (23,000 kg/ha of manure), then the radius



STEP 1

Develop current (2010) livestock operation inventory and crop fertilizer application rate recommendations

livestock operation variables
- location and type
- number of animal units
- manure hauling distance
- county milk production

fertilizer rate factors
- crop type
- manure applied/not applied

STEP 2

Convert current manure and fertilizer application rates to phosphorus (P) and nitrogen (N) application rates and map

STEP 3

Use narratives to determine the agricultural context (diet & food demand, environmental policy, technology) for each scenario

STEP 4

Determine the changes in number of livestock operations, animal units, milk production, and fertilizer application rate for each scenario

STEP 5

Use values in STEP 4 to scale the current P and N application rates map

STEP 6

Determine the current and future nutrient loads from wastewater treatment plants based on population and policy context for each scenario

Fig. 4. Steps involved in the development of nutrient (nitrogen and phosphorus) model inputs for each scenario (photo credit for Step 6: Madison Metropolitan Sewerage District).

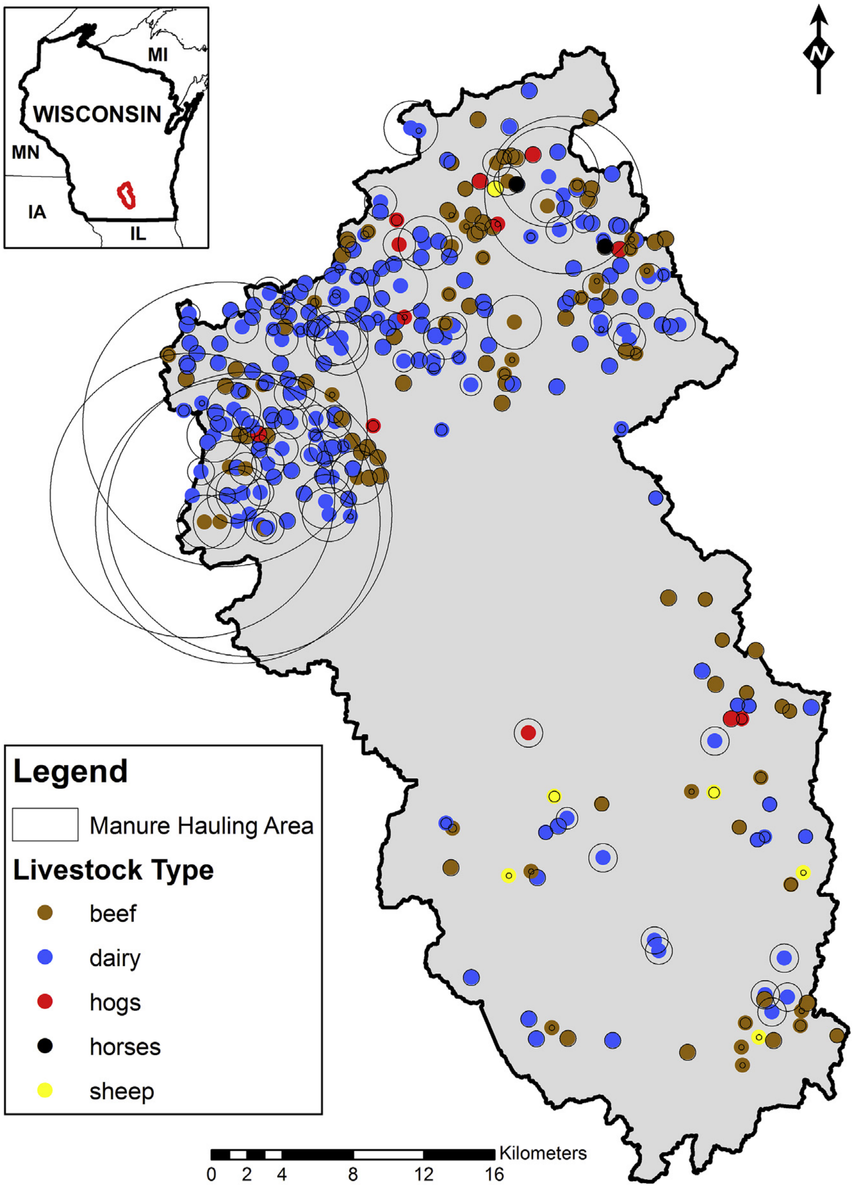


Fig. 5. Current (2010) map of all livestock operations by type showing estimated manure hauling areas.

of the potential manure spreading area would iteratively decrease until the threshold rate was reached.

After manure P and N application rates were determined, fertilizer P and N application rates were calculated for the following LULC types: alfalfa, corn, fruits/vegetables, small grains, and soybeans. Present-day (2013) fertilizer application rates were determined based on University of Wisconsin – Extension nutrient application guidelines (Laboski and Peters, 2012) assuming high yield potential soils, optimum soil nutrient status, and high yield goals (Table 2). For grid cells where manure had been applied, fertilizer was only applied, at a lower rate, if the LULC type was corn. Future application rates were determined by multiplying the present-day rates by a relative fertilizer rate, which varied according to each scenario's agricultural and policy context.

4.5. Model inputs – wastewater treatment plant effluent

Another important source of nutrients to water bodies in the Yahara River watershed is wastewater treatment plant (WWTP) effluent from three municipal systems: Madison Metropolitan Sewerage District (MMSD), City of Stoughton, and Village of Oregon. The first two discharge to Badfish Creek and the third to the lower Yahara River (Fig. 6). These are treated as point sources of water, phosphorus, and nitrogen to the THMB hydrologic routing model. Historical effluent volumes, phosphorus concentrations, and nitrogen concentrations were compiled from data provided by MMSD and the Wisconsin Department of Natural Resources. Effluent flow per capita was also determined based on current estimates of the MMSD service area population. Future changes in these effluent-related values for the scenarios were based on the themes and contexts of each narrative related to efficiency of water resources and water quality policy. Effluent flow per capita was first quantified and then multiplied by the service-area population (89.5% of the watershed population based on 2010 U.S. Census data) to get total effluent flow. Phosphorus and nitrogen concentrations were solely based on the water quality policy contexts of each scenario narrative.

5. Results

The biophysical model inputs created by the methods presented resulted in four highly contrasting scenarios of climate, LULC, and nutrient inputs. They each also reproduced the extremes related to climate (e.g., heavy rainfall, drought), LULC change (e.g., grassland-dominant landscape in AR), and land nutrient inputs (e.g., near elimination of livestock in AI) as detailed below.

5.1. Climate

Climate varied substantially among all four scenarios consistent with each narrative. Each climate scenario was derived using several different GCM projections (see Table 3). The most warming by 2070 occurs in AR (+5.5 °C), the least in AI (+2 °C), and CC (+3.5 °C) and NW (+4 °C) fall in the middle (Fig. 7A). The amount of warming in each scenario also drives increases in the growing season length and decreases in the date of spring onset (Appendix D).

Unlike air temperature, annual precipitation did not change monotonically in each scenario but interannual variability increased substantially in each one (Fig. 7B). All four scenarios generally continue the historical increasing trend in annual precipitation through the 2040s with AI and CC receiving higher than historical precipitation totals on average through the 2060s. AR experiences the wettest climate of all scenarios during the 2030s and 2040s; however, both AR and NW become drier in the final two decades, ultimately approaching historical averages by 2070.

Increases in the frequency of extreme events also tend to be related to the amount of warming. The warmest scenario (AR) experiences several heavy rainfall days and weeks, heat waves in the 2030s and 2040s, and more heat waves and droughts in the 2050s and 2060s. Even in the driest scenario (NW) a heavy rainfall event (260 mm in 11 days) occurs in 2070 as specified in the narrative. The wettest scenario in the 2060s (CC) also experiences three long dry periods (>40 consecutive days with cumulative precipitation less than 5% of 1948–2013 normal) during the growing season in that same decade. Appendix D provides time series for 6 temperature-related climate metrics and 4 precipitation-related ones for each scenario.

5.2. Land use/land cover

Land use/land cover (LULC) varied across the four scenarios, as the narratives advised, with strong divergence after 2030 (Table 4 and Fig. 8). The spatial distribution of these LULC changes determined by transition probabilities within a BBN framework produced contrasting maps for each scenario (Fig. 9). Agricultural lands increased slightly in one scenario (CC) and decreased in the other three, with AR experiencing the greatest decline (75%) in 2035 followed by a gradual rebound. Increased agricultural lands in CC reflects diet shifts and associated land conversion to less intensive and more diverse crops, such as vegetables/fruits, small grains and pasture both within the city (e.g., urban farms) and across the watershed. In AI, corn remains the dominant cover where it is used as a raw feedstock for the production of synthetic meat and dairy products. In the NW scenario, agricultural lands are transformed into natural covers through restoration and conservation efforts, and intensive crops such as corn and soybean are also converted into hays and grass for biofuel production in marginal areas. In the AR scenario, agricultural lands proximate to lakes are first abandoned around the 2030s due to the mass population reduction and migration, and rebound after the 2050s as small-scale farms (e.g., small grains, vegetables) around the scattered remnant settlements at the northern and southern tips of the watershed.

For urban lands, the AI scenario represents the largest increase in the urban land footprint as population increases without stringent restrictions on developing new residential land. Most newly developed urban areas occur in the fringe of adjacent towns, whereas the city of Madison follows an infill development pattern

Table 2
Fertilizer application rates from University of Wisconsin - Extension (Laboski and Peters, 2012) recommendations for different crop types.

Land-use/land-cover (LULC) type	Fertilizer P application rate [kg/ha] – present day (2013)	Fertilizer N application rate [kg/ha] – present day (2013)
Alfalfa	33.4	0.0
Corn	39.1	194.1
Corn – with manure	4.9	97.1
Fruits/Vegetables	19.6	107.8
Small Grains	17.1	75.5
Soybeans	24.4	0.0

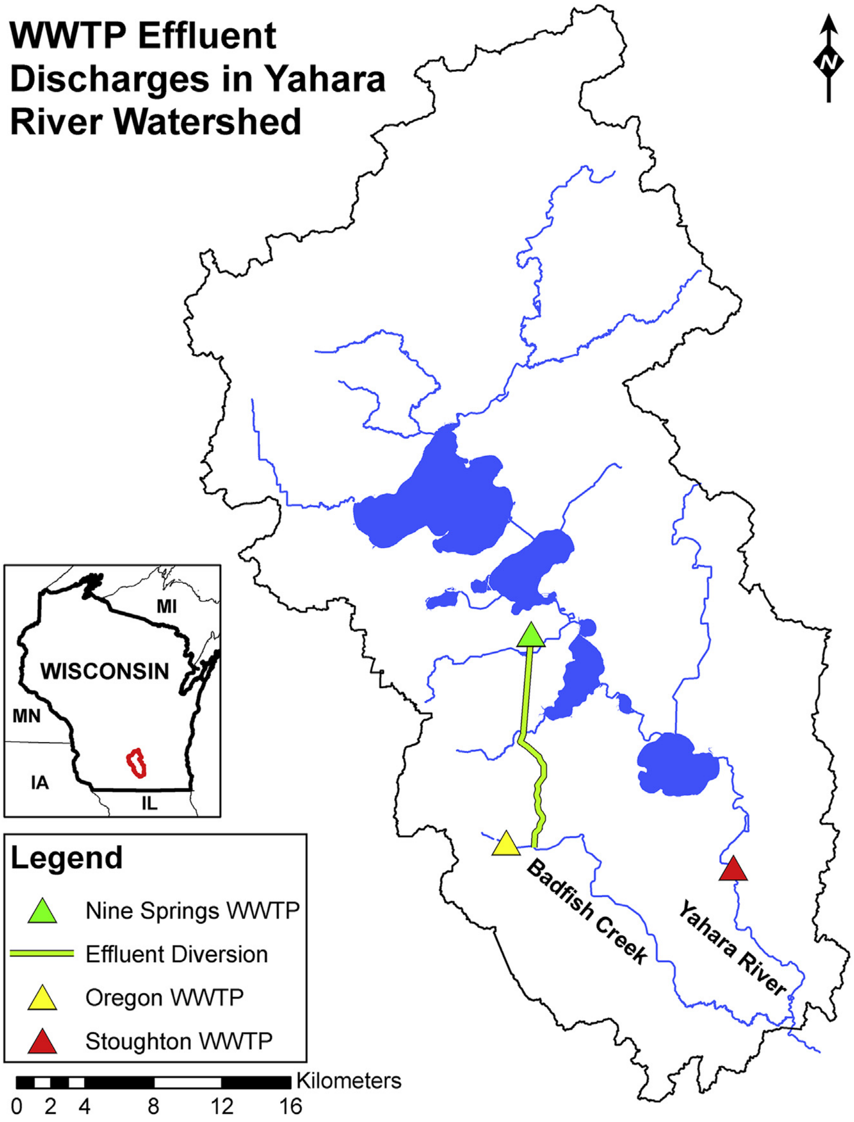


Fig. 6. Map of Yahara River watershed showing location of 3 wastewater treatment plants (WWTP) and the effluent diversion to Badfish Creek associated with the Madison Metropolitan Sewerage District WWTP (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

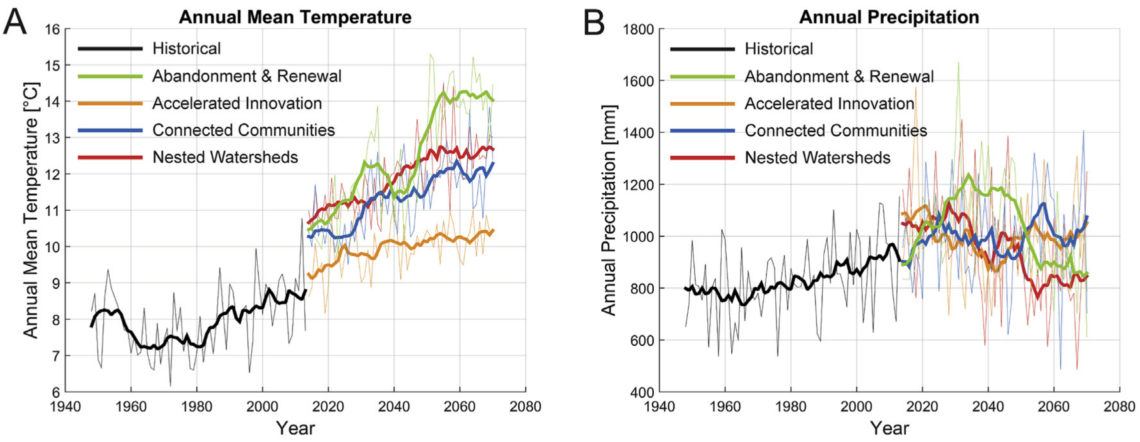


Fig. 7. Annual mean air temperature (thin line) and 9-year moving average (thick line) for each scenario (A). Annual precipitation (thin line) and 9-year moving average (thick line) for each scenario (B).

Table 3
Summary of each future climate projection used to seed the stochastic weather generator that produced the climate inputs for each scenario including associated emission scenario, general circulation model (GCM), and GCM time period.

Scenario time period	Abandonment & Renewal (AR)	Accelerated Innovation (AI)	Connected Communities (CC)	Nested Watersheds (NW)
2011–2030				
- emission scenario	A1B	B1	A1B	A1B
- GCM time period	2046–2065	2046–2065	2046–2065	2046–2065
- model ID	MRI-CGCM2.3.2	CSIRO-Mk3.0	GISS-ER	MRI-CGCM2.3.2
2031–2050				
- emission scenario	A1B	B1	A1B	A1B
- GCM time period	2081–2100	2046–2065	2081–2100	2081–2100
- model ID	GISS-AOM	MRI-CGCM2.3.2	CSIRO-Mk3.0	MRI-CGCM2.3.2
2051–2070				
- emission scenario	B1	A1B	A1B	B1
- GCM time period	2081–2100	2046–2065	2081–2100	2081–2100
- GCM model ID	MIROC3-2-HIRES	GISS-ER	MRI-CGCM2.3.2	MIUB ECHO-G

Table 4
Land classified as biophysically-distinct land-use/land-cover types for 2010 and for each scenario in 2070 (as % of watershed area).

Land use/cover category	% Of watershed area				
	2010	AR-2070	AI-2070	CC-2070	NW-2070
Corn	26.5%	1.3%	23.7%	6.4%	4.0%
Soybeans	8.5%	0.4%	8.1%	2.9%	0.6%
Alfalfa	8.6%	1.5%	2.0%	4.0%	2.9%
Small Grains	1.6%	3.8%	0.8%	4.0%	2.4%
Fruits/Vegetables	0.3%	8.7%	5.8%	10.7%	2.2%
Hay	0.2%	1.6%	0.4%	5.3%	18.3%
Pasture	0.9%	2.7%	0.5%	12.3%	3.4%
Developed/High Intensity	1.4%	0.8%	3.8%	3.1%	2.6%
Developed/Medium Intensity	3.9%	3.9%	8.5%	5.9%	5.5%
Developed/Low Intensity	9.7%	2.5%	11.5%	5.2%	8.1%
Developed/Open Space	11.7%	1.8%	12.8%	7.7%	12.1%
Deciduous Forest	6.5%	15.3%	5.9%	7.4%	11.6%
Grassland	6.1%	39.8%	2.6%	8.2%	7.1%
Wetlands	6.6%	8.4%	6.1%	9.4%	11.7%
Open Water	7.3%	7.3%	7.3%	7.3%	7.3%
Barren	0.2%	0.2%	0.2%	0.2%	0.2%

with increased density. The urban lands in NW remain stabilized, and decline substantially in both CC and AR (>25% of the watershed area towards 2050s). Declines of urban lands in the CC scenario occur largely in the open space within the city; and in the AR scenario urban abandonment and reductions primarily take place in areas close to lakes because of the airborne cyanobacterial toxin.

Natural land cover increases most in the AR scenario with peak abundance ~70% of the watershed during the 2050s, and the NW and CC scenarios follow. AI experiences a decline in natural vegetation area from 20% to 15% of the watershed. Increases in natural vegetation, primarily grasslands and forests, in the AR scenario occur in abandoned urban and agricultural lands around the Madison lakes as a result of natural succession (Fig. 8). In the NW scenario, there are substantial increases in wetland restoration (mostly in hydric soils) and afforestation in the form of riparian buffers around the stream network and lakes. In the CC scenario, restored prairies and wetlands largely replace managed turfgrass and lawns in the city. In the AI scenario, conversion of natural covers, such as prairie and forest to corn and soybean production, occurs mostly in proximity to existing agricultural and human settlements.

5.3. *Land-applied nutrients*

As with land use/land cover, the spatially varying land-applied nutrients in each scenario begin with a baseline in 2013 and then evolve into highly divergent pathways guided by differing human decisions related to the role of livestock in agricultural production and use of agricultural fertilizers in each scenario. The number of animal units (equivalent to 454 kg of animal weight) generally decreases for each scenario, but varies in magnitude (Fig. 10A). The AR scenario includes an intensification of agriculture into the mid-2030s, which results in a 40% increase in animal units, but then the abandonment in 2035 reduces the number by 95%. Livestock numbers steadily increase during the ‘renewal’ phase of AR but by 2070 are only 28% of the size in 2013. In the AI scenario, animal units also increase (8%) by 2030 but then swiftly decline to 3% of 2013 levels by 2060 as synthetic meat and dairy products replace those from animals. The remaining animals serve the demand of ‘real’ meat and dairy products from counter-culture communities.

The CC scenario starts with an increasing rate of decline in animal units that results in a 43% decrease by 2045 as the consumption of meat and dairy lessens due to a values shift. However, livestock numbers slightly increase (11%) over the remaining time as pasture-based meat and dairy operations increase in popularity. The NW scenario also includes a slight increase (5%) in the number of animal units by 2035 but then livestock is largely removed from the landscape due to new water quality regulations. By 2070, the number of animal units is only 11% of the 2013 value. Changes in milk production from cows are nearly proportional to the changes in animal units for each scenario (Fig. 10B).

The number of livestock operations decreases overall for three of the four scenarios with the only increase seen in the CC scenario. Initial decreases occur to 2035 in all scenarios – following the historical trend (MacDonald and McBride, 2009) – with some differences in magnitude (Fig. 10C). Livestock operations decrease at

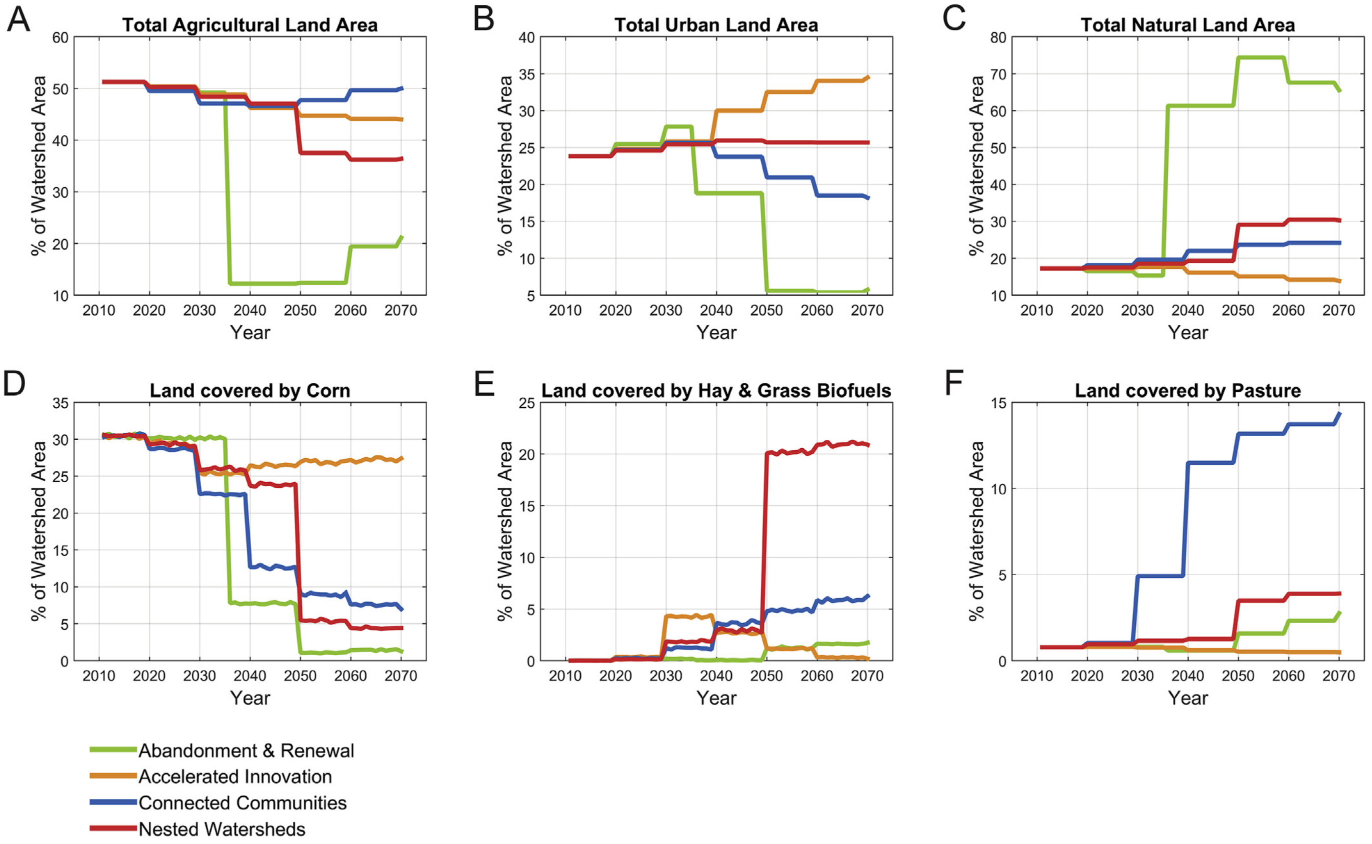


Fig. 8. Scenario driver curves for three dominant land-use/land-cover groups (A–C) and three representative types (D–F).

the highest rate in the AR scenario from 2014 to 2035 (35% decrease) and then plummet after the collapse in 2035 (only 16 remain in 2040). During the recovery phase, as more small farming communities appear, the number of livestock operations steadily increases over the rest of the time period (123 in 2070).

The number of livestock operations in the AI scenario steadily decreases throughout the scenario as farm consolidation continues. Eventually larger farms change to synthetic meat and dairy production and are no longer housing livestock. Only 13% of the original operations in 2013 remain in 2070. In the CC scenario, livestock operations also consolidate and reduce in number to 2035 (16% decrease) but then steadily increase throughout the rest of the time period as grass-based meat and dairy products from small farms gain in popularity. Finally, the NW scenario also sees a slow decrease in the number of operations to 2040 (12% decrease), but water quality policies that limit livestock densities are implemented after 2040, causing the number of operations to drop by 45% between 2040 and 2050. This number holds steady to 2070.

The relative fertilizer rate (RFR) – the factor that is multiplied by the application rate recommended by the University of Wisconsin-Extension in 2012 – generally decreases over each scenario (Fig. 10D), with the only increase occurring in the AR scenario during the period of agricultural intensification (2014–2035). By 2070, the highest RFR (0.65) belongs to the CC scenario, which still requires fertilizer for vegetable, small grains, corn, and soybean production. The 2070 RFR for the NW scenario is slightly less (0.56), reflecting stricter water quality regulations, and is even smaller for the AI scenario (0.4) as technology has enhanced plant nutrient use efficiency (particularly nitrogen).

Combining the above drivers of farmland nutrient applications leads to total manure and fertilizer phosphorus (P) and nitrogen (N) applied in the watershed (Fig. 10E–H). Changes in manure P and N match the changes in animal units and milk production explained above (Fig. 10E–F). However, changes in fertilizer P and N are nearly identical to each other (Fig. 10G–H) but do not match those for manure because fertilizer changes are a product of changes in the relative fertilizer rate and the extent of fertilizer-demanding crops. Overall, the total amount of fertilizer P and N applied decreases in each scenario with the exception of the period of agricultural intensification in the AR scenario (2014–2035). By 2070, the AI scenario represents the highest total fertilizer P and N applied due to the large extent of corn and soybean, despite a relatively low RFR. The second highest amount occurs in the CC scenario, which has the highest amount of land devoted to agriculture, with substantial areas devoted to vegetable and corn production. The NW scenario is next in order with approximately half of the amount of fertilizer applied as in the CC scenario. The majority of the agricultural area in the NW scenario is devoted to perennial biofuel crops that do not receive fertilizer. Finally, the least amount of fertilizer applied occurs in the AR scenario, which has the least amount of land devoted to agriculture and farmers with limited access to industrial fertilizers.

The total (manure + fertilizer) P and N applied to farmland generally follow the rank order for fertilizer as the majority of the sum commonly comes from fertilizer (66% for year 2013). The large exception is for the CC scenario, which overtakes the AI scenario for the highest total P applied in 2070 (Fig. 10G) due to the high amount of manure P applied in the CC scenario and very low amount applied in the AI scenario (Fig. 10E). The CC and AI scenarios are essentially tied for the most total N applied in 2070 because 1) the impact of the relative differences in manure between the scenarios for nitrogen is dampened due to manure N loss

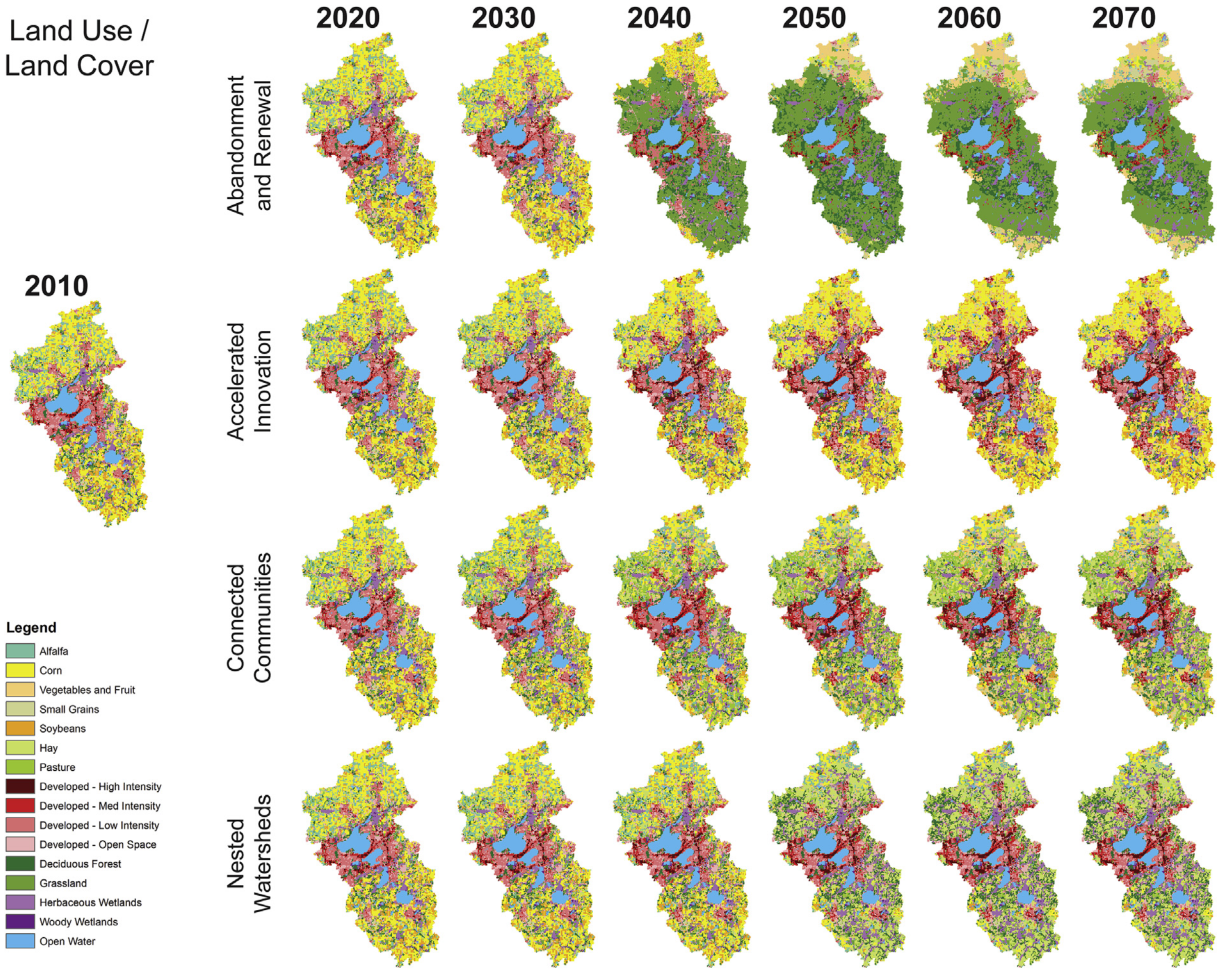


Fig. 9. Land-use/land-cover maps for 2010 baseline and subsequent decades of each scenario.

from ammonia volatilization and 2) the agricultural area in AI is primarily devoted to production of relatively high N-demanding crops like corn and soy. Manure applied exceeds fertilizer applied in the AR scenario, but it still holds its rank at the bottom of both total P and N applied due to the small amount of land devoted to agriculture.

The spatial distribution of manure and fertilizer P and N varies across each scenario based on the total watershed values described above as well as the locations of active livestock operations and different agricultural land types (Fig. 11). In the AR scenario, total phosphorus intensifies across the watershed through 2020 and 2030 as more animal units and fertilizer are added to the landscape. After the abandonment, only small regions far from the lakes are subject to small applications of fertilizers with a slow increase in intensity as more livestock are added by 2070. The AI scenario has a less extreme intensification than AR through 2030 as livestock operations consolidate, but then total P inputs reduce to a fairly uniform and lower application rate across all agricultural areas when livestock are largely eliminated from the landscape beginning in 2040, resulting in fertilizer as the source of nearly all N and P.

Total P applied in the CC scenario is slowly reduced and becomes more distributed as small livestock operations start to dominate in 2030 and 2040. But the remaining livestock operations result in local hotspots of manure P application primarily in the northern half of the watershed. Finally, the NW scenario also sees only moderate changes to 2040, but then P application rates decrease substantially across the watershed following the enactment of strict water quality regulations. Many areas convert to perennial bioenergy crops that do not receive any nutrient applications. Appendix H provides separate decadal maps for manure P and N, fertilizer P and N, and total N for each scenario.

5.4. *Wastewater treatment plant effluent*

Wastewater treatment plant (WWTP) effluent flow and P & N concentrations also vary widely across the scenarios. Effluent flow per capita continues the historical decline – driven by increases in household water efficiencies – for all scenarios in the 2020s and early 2030s (Fig. 12A). Effluent flow per capita is similar for the AI, CC, and NW scenarios but are driven by technological water efficiency improvements, values-driven water consumption decreases, and water consumption regulations, respectively. Effluent flow – the product of population and effluent flow per capita – reduces to zero for the AR scenario after the abandonment of all major infrastructure in 2035 (Fig. 12B). In contrast, effluent flow keeps increasing in the AI scenario as population increases faster than efficiency improvements.

Changes in effluent P and N concentrations for a given scenario follow the same pattern and are driven by technological innovation and water quality policies within each scenario (Fig. 12C–D). The focus for the CC scenario is on values-driven declines in

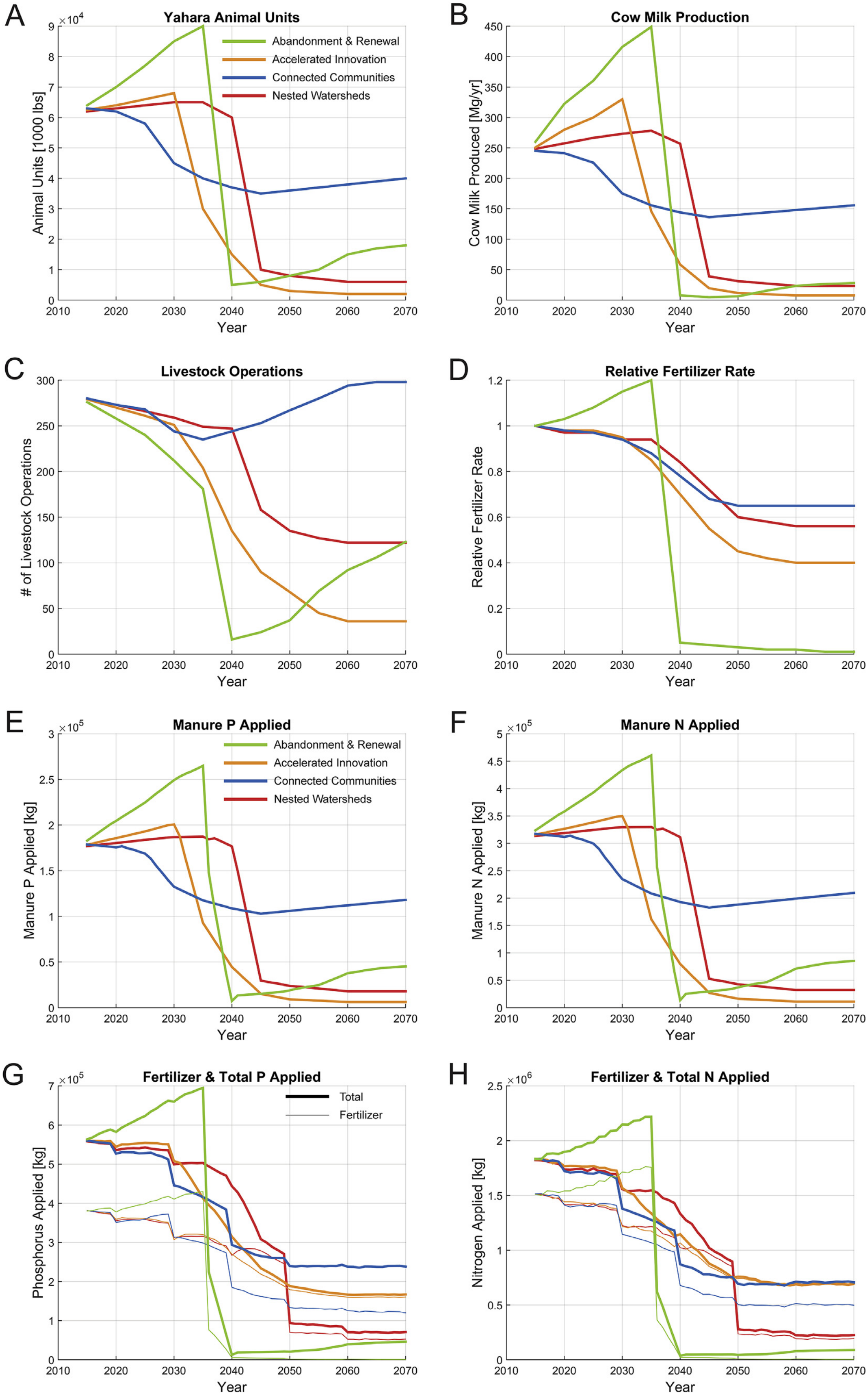


Fig. 10. Drivers of farmland-applied nutrient inputs including watershed animal units (A), total milk production (B), number of livestock operations (C), and relative fertilizer rates (D). Farmland-applied nutrient inputs of manure phosphorus (E) and nitrogen (F) and fertilizer (thin lines) and total (thick lines) phosphorus (G) and nitrogen (H).

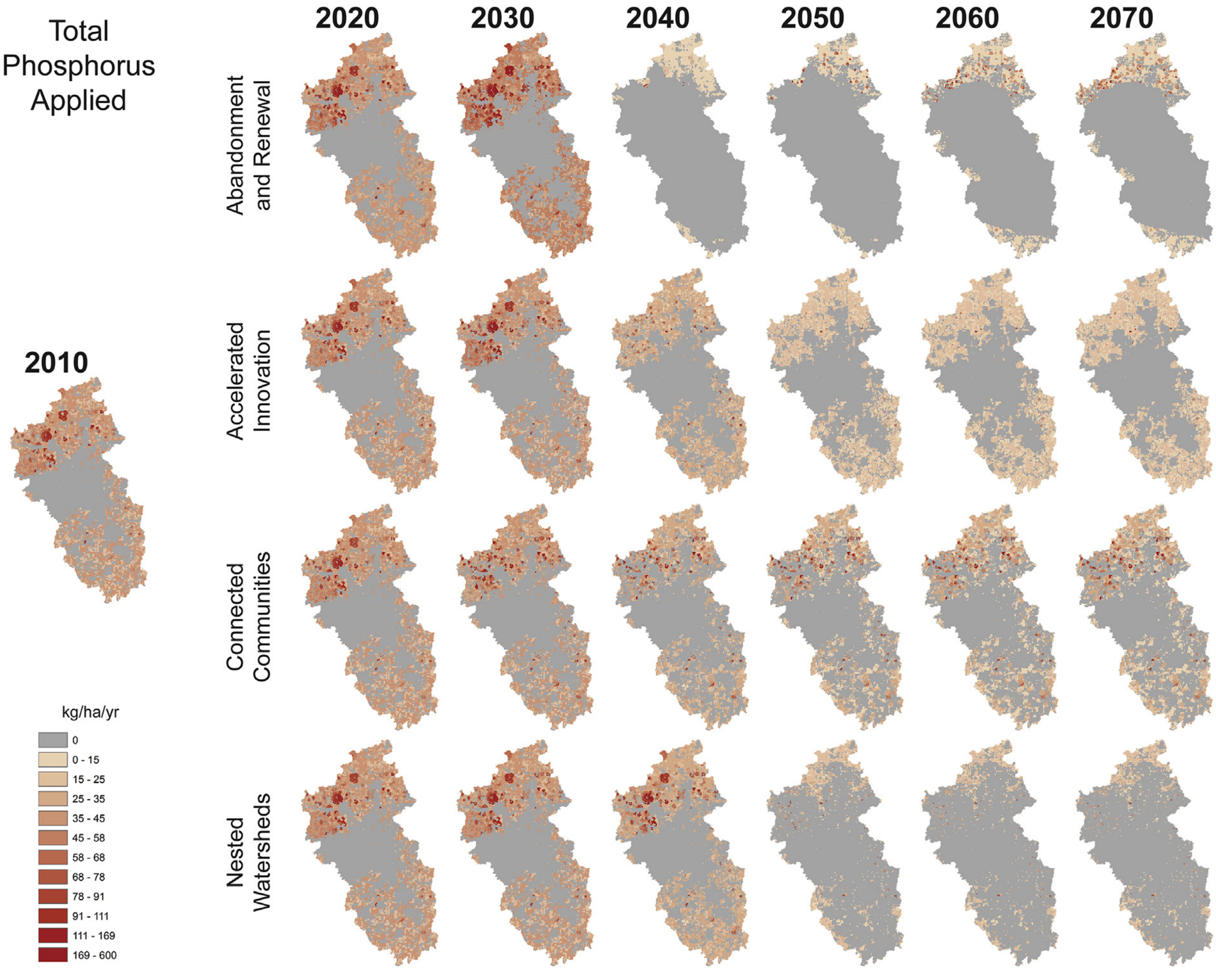


Fig. 11. Maps of total phosphorus applied for the 2010 baseline and subsequent decades of each scenario.

consumption but not necessarily changes to wastewater treatment technology. Therefore, effluent P and N concentrations remain constant at 2010 levels. A 33% decline in effluent N and P concentrations in the NW scenario is driven by strict water quality regulations on any point source. Conversely, technological innovation is the major factor for a 50% reduction in effluent N and P concentrations in the AI scenario. Finally, the WWTPs in the watershed are all taken off-line following the abandonment in 2035 and effluent N and P loads are set to zero.

6. Discussion and conclusions

Scenarios are gaining popularity as a useful approach for anticipating and envisioning the future of complex social-ecological systems. However, scenarios that translate narratives to biophysical model inputs are often performed too simply, focusing on only one driver of change (e.g., climate), and poorly documented. Our study advances the scenarios research field by presenting a transparent and reproducible roadmap to translate qualitative scenario narratives into detailed quantitative drivers that vary spatially and through time so that they can be used with biophysical models at the regional or watershed-scale. We have developed a suite of methods that produce spatially and temporally continuous drivers capable of representing the dynamic nature of social-ecological systems. Our approach is transferrable to other regions and systems that seek a sustainability transition—ensuring human wellbeing while maintaining the life-support systems of the planet in the face of global environmental changes (Kates and Parris, 2003; NRC, 1999). While the quantitative drivers for the Yahara case study were designed with the modeling suite determined *a priori*, our method is adaptable to any spatially-explicit and transient biophysical model that requires climate, LULC, and nutrient inputs.

We have accounted for the spatially explicit and temporally dynamic nature of a large set of system drivers, including both biophysical and social changes (such as shifts in values) that are rarely represented in regional quantitative scenarios. This process relies on the development of watershed-scale changes in land use/land cover and nutrient inputs as an intermediate step to bridge the qualitative and quantitative scenarios. Our method also specifically incorporates extreme climate events such as drought and heavy rainfall, which are highly plausible and foundational to several scenarios, by combining the credibility of global climate model projections with the flexibility of a stochastic weather generator. Other specific innovations incorporated include the implementation of the feedback of urban heat island with high-development scenarios and spatio-temporal distribution of manure applications.

A challenge associated with our qualitative-quantitative scenario translation method is the need to integrate disparate datasets that are constrained by time, space, and public access. For example, manure application inputs required a dataset of livestock operation locations, number of animal units per location, and estimated

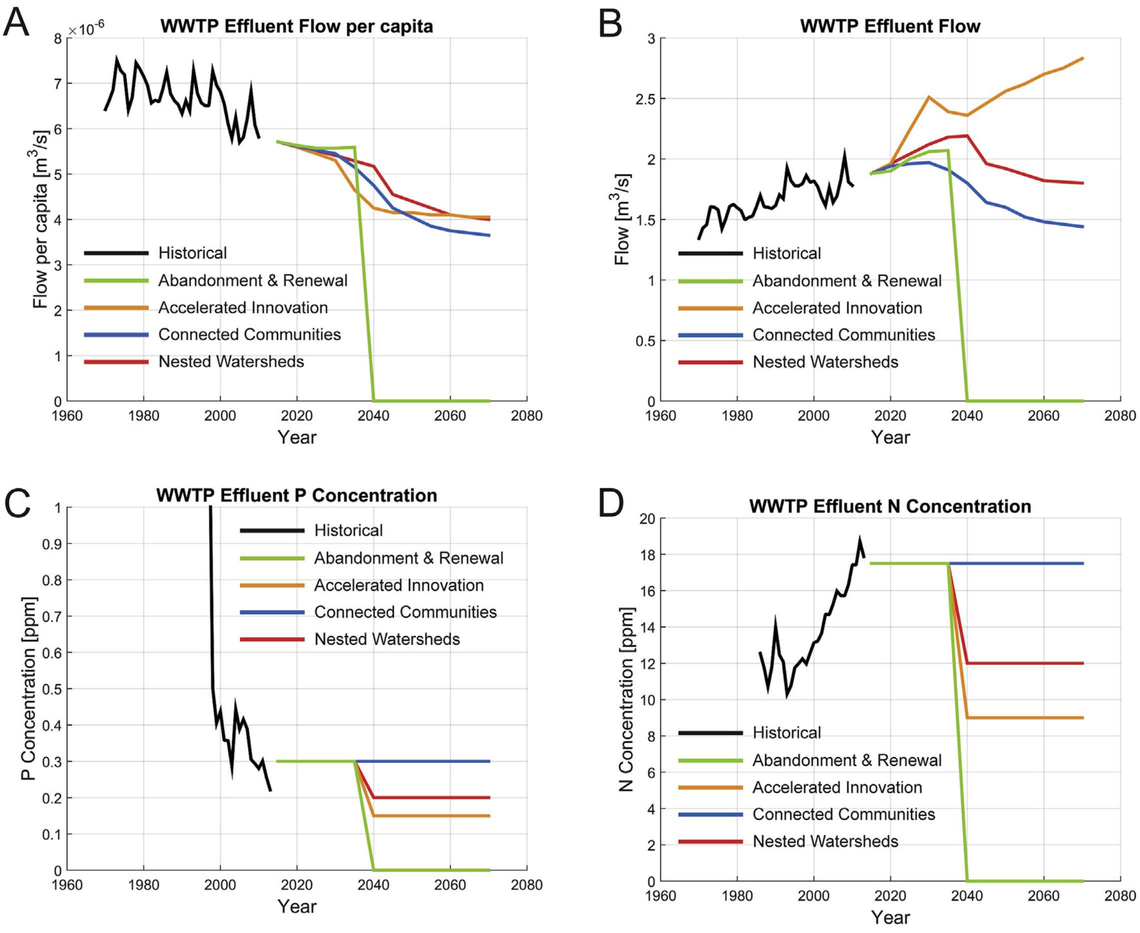


Fig. 12. Wastewater treatment plant (WWTP) effluent flow per capita (A), WWTP effluent flow (B), WWTP effluent P concentration (C), and WWTP effluent N concentration (D) for historical period and each scenario.

manure hauling distance. Fortunately, such a dataset had been developed by local county staff and was accessible. However, such data are increasingly difficult to obtain due to privacy restrictions, especially in the United States. In contrast, other environmental datasets — notably those collected via remote sensing — with high spatial and temporal resolution are expanding rapidly and constitute a major focus for government agencies and academic institutions (Vitolo et al., 2015).

An important lesson learned from our study was the need for iteration between the scenario narrative writer, the biophysical modeling team, and a smaller group of individuals who engaged with both qualitative and quantitative features of the scenarios. Consistent with interdisciplinary research, communication among these groups is especially critical for producing integrated scenarios that are plausible, contrasting, and internally consistent. Good communication also facilitates a transparent development process because the modeling team is not forced to make decisions that may ultimately impact the character of the scenario when they encounter details from the narrative that are too incomplete to adequately create a set of inputs required by the model. For instance, we found that modeling decisions about land-use/land-cover could not be adequately made until more details on energy and human diet were provided in the narrative. The narrative writer would then serve as a translator of the stakeholder suggestions relevant to this needed change without requiring the stakeholders to engage with the details of the model. This allowed the stakeholders flexibility to design the storyline while providing sufficient quantitative information for the models. The communication and iteration needs of our method also point to the importance of having research team members with skills and training that enable them to work comfortably across disciplines and understand and connect both the qualitative and quantitative aspects of the scenario.

Our novel method for producing climate inputs for each scenario could be readily transferred to other applications including studies with a narrower focus on climate as the only source of change. Combining the well-validated nature of GCM projections with the flexibility of a stochastic weather generator allows for the production of customized climate time series that are consistent with pre-defined qualitative scenarios. This concept of tailored climate scenarios has already been suggested for use in hydrological impact assessments (Ntegeka et al., 2014). As is the case with other studies, the quantitative scenario drivers that our method has developed are not necessarily meant to be used to test specific scientific hypotheses or determine attribution of environmental change, as may be more common in other biophysical scientific studies. Rather, the scenarios — after integration with biophysical models and determination of ecosystem service outcomes — are seen as a vivid and holistic integrated package designed to build public engagement through storytelling and expanding the imagination of what is possible in the future. They are also intended to challenge biophysical models to simulate highly divergent environmental conditions and extreme weather events. We firmly believe that such a strategy will lead to better and more useful modeling tools, but only if there are adequate methods for integrating qualitative and quantitative scenarios such as those presented in this paper. We call on the biophysical and environmental modeling community to recognize the growing value and popularity of scenarios and continue to research and develop new tools that better integrate stories and models. This perspective is also consistent with recent calls to better engage the biophysical scientific community with the humanities to help foster a sustainable future (Castree et al., 2014).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2016.08.008.

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