Environmental Modelling & Software 85 (2016) 80–97

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

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

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A R T I C L E I N F O

Article history:
Received 18 April 2016
Received in revised form
2 August 2016
Accepted 15 August 2016

Keywords:
Scenarios
Biophysical modeling
Social-ecological systems
Watershed
Climate change
Land use change

A B S T R A C T

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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http://dx.doi.org/10.1016/j.envsoft.2016.08.008
1364-8152/

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