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Multiple methods for multiple futures: Integrating qualitative scenario planning and quantitative simulation modeling for natural resource decision making

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ABSTRACT

Scenario planning helps managers incorporate climate change into their natural resource decision making through a structured "what-if" process of identifying key uncertainties and potential impacts and responses. Although qualitative scenarios, in which ecosystem responses to climate change are derived via expert opinion, often suffice for managers to begin addressing climate change in their planning, this approach may face limits in resolving the responses of complex systems to altered climate conditions. In addition, this approach may fall short of the scientific credibility managers often require to take actions that differ from current practice. Quantitative simulation modeling of ecosystem response to climate conditions and management actions can provide this credibility, but its utility is limited unless the modeling addresses the most impactful and management-relevant uncertainties and incorporates realistic management actions. We use a case study to compare and contrast management implications derived from qualitative scenario narratives and from scenarios supported by quantitative simulations. We then describe an analytical framework that refines the case study's integrated approach in order to improve applicability of results to management decisions. The case study illustrates the value of an integrated approach for identifying counterintuitive system dynamics, refining understanding of complex relationships, clarifying the magnitude and timing of changes, identifying and checking the validity of assumptions about resource responses to climate, and refining management directions. Our proposed analytical framework retains qualitative scenario planning as a core element because its participatory approach builds understanding for both managers and scientists, lays the groundwork to focus quantitative simulations on key system dynamics, and clarifies the challenges that subsequent decision making must address.

1. Introduction

Resource managers are regularly confronted by changing conditions arising from external forces that limit their ability to fulfill

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demands and meet established economic, social, and/or ecological targets. While set apart to conserve species, ecosystems, and processes, protected areas are likewise not immune to stressors such as invasive species, altered fire and hydrologic regimes, pollution, and habitat fragmentation. The semi-permeable boundaries of protected areas allow the influx of these stressors – over which managers have varying degrees of control – but also constrain managers' options for reacting to them. Regardless of resource type, climate change adds to this challenging situation by exacerbating the impacts of other stressors (e.g., Buckland et al., 2001; Fisichelli et al., 2014) or conversely, by other stressors aggravating climate change impacts (e.g., Krushelnycky et al., 2016). Incorporating these climate-stressor interactions into management decision making and planning is complicated by uncertainties regarding the magnitude, and for some aspects, direction, of climate change, as well as the complex and incompletely understood reactions of individual and interacting components of ecosystems to a changing climate.

Ecosystem managers may find this combination of uncertainties, limited control, and competing demands on their time and resources to be a barrier to implementing adaptation plans (Archie et al., 2012; Archie, 2013), or frustrating enough that incorporating climate change into planning becomes a low priority. However, managers who fail to incorporate climate change into their planning risk failure in achieving desired outcomes. To avoid this risk, managers require tools to sort through the complexities of climate change and ecosystem response, disentangling the more and less certain aspects in the context of other existing change drivers. These tools must be flexible enough to be useful in diverse decision-making contexts, and to both stimulate and answer questions.

Scenario planning is a tool well suited to climate change planning, where uncertainties about consequential factors are high but decision makers have little control over those uncertainties (Peterson et al., 2003). Scenarios are internally consistent storylines that incorporate uncertain, external forces and the system's and managers' responses to these forces (Rowland et al., 2014). The traditional 'predict then act' approach to planning typically uses scientific models to calculate probabilities of future events to build consensus around a single estimate of the future and the appropriate management response. In contrast, the scenario planning process develops a set of divergent, plausible, relevant, and challenging future conditions centered on a focal issue and constructed around impactful uncertainties (National Park Service, 2013). The initial storylines are designed to flex participants' thinking about how the future will unfold, taking a "what if" rather than a forecasting approach (Searce and Fulton, 2004).

Since the late 2000s, the U.S. National Park Service (NPS) Climate Change Response Program has used the scenario planning process to empower decision makers to take action and manage under uncertainty. Following the "intuitive logics" school for generating and using scenarios (Bradfield et al., 2005), the NPS approach has been largely qualitative and relied on expert elicitation to build scenarios. Over the course of more than two dozen scenario planning exercises, the focus of these workshops has transitioned from raising climate literacy to informing specific planning and management decisions. However, qualitative scenarios confront limits to resolving realistic responses of complex systems to altered climate conditions. In many cases, managers prefer quantitative, often spatially explicit, representations of the impacts hypothesized in qualitative narratives, as well as tools for simulating the outcomes of management responses, to increase scientific credibility and manager confidence in taking actions that differ from current practice (Alcamo, 2008; Rickards et al., 2014).

Combining qualitative and quantitative approaches in scenario planning is not new (Alcamo, 2008), even in its more recent applications to climate change issues in natural resource management and land use planning (e.g., Mahmoud et al., 2011; Sheppard et al., 2011; Vargas-Moreno and Flaxman, 2012; Byrd et al., 2015). Qualitative and quantitative methods are naturally complementary. When the two are combined, as in the story and simulation approach to scenario planning, the two key components offer outcomes necessary to achieve different policy ends (Alcamo, 2008; Mallampalli et al., 2016). Qualitative exercises stretch perspectives and expose participants' assumptions about divergent and challenging futures, while quantitative models focus on understanding, and in some cases projecting, system dynamics. For example, Miller and Morisette (2014) suggest an analytical framework that integrates scenario planning with species distribution modeling and simulation modeling to support climate-informed decision making. Simulation of a set of descriptive storylines reproduces complex relationships and can be used to quantitatively explore spatially explicit "what if" scenarios. This approach allows identification of surprising dynamics, verification of internal consistency of qualitative narratives, and testing of policies, strategies, or specific actions.

Whether qualitative narratives or quantitative simulations, scenarios are not predictions about the likelihood of any particular set of conditions occurring in the future. The significant challenge of integrating the implications of several divergent scenarios into traditional planning and decision-making processes toward climate change adaptation action remains (Rickards et al., 2014). Here, we use a case study from Wind Cave National Park (WCNP) to compare and contrast management implications derived from qualitative scenario narratives to those derived from quantitative simulations, as well as managers' acceptance of these implications. Based on this experience, we then describe an approach for integrating qualitative scenario planning with quantitative simulations to improve the direct utility of the results for management planning.

2. Methods

Previous publications (King et al., 2013a,b; Symstad et al., 2014) provide detailed methods of and results from the separate qualitative scenario (QLS) and quantitative simulation modeling (SM) approaches used for WCNP. Here, we summarize and highlight features that illustrate the complementarity of the two approaches toward advancing climate change adaptation.

2.1. Background and setting

WCNP was established in 1906 to protect the park's namesake – one of the longest caves in the world – and includes a 13,500-ha protected landscape in the Black Hills of southwestern South Dakota, USA (43.5° N, 103.5° W). Wind Cave's subterranean lakes and the park's surface water resources are strongly influenced by the area's karst geology. For example, Beaver Creek is WCNP's largest stream, but in most years all of its flow sinks below ground about halfway through its course through the park. Although most of WCNP's springs and streams are small and intermittent, large wildlife depend on them for water. The vegetation of WCNP includes a diverse mixture of northern mixed-grass prairie and ponderosa pine (*Pinus ponderosa*) dominated woodlands that fulfill additional habitat and forage needs. The park's enabling legislation requires maintenance of viable populations of American bison (*Bison bison*), elk (*Cervus elaphus*), and pronghorn (*Antilocapra americana*). Wildlife grazing and browsing, as well as prescribed and wild fire, create a shifting mosaic of plant communities and a dynamic prairie-woodland border (Bock and Bock, 1984; Detling, 1998; Brown and Sieg, 1999; Ripple and Beschta, 2007). Fencing that surrounds the park restricts free movement of large wildlife to access water and forage. Bison and elk population sizes are not constrained by large predators, and park staff depend on periodic captures and transfers to manage wildlife populations and their effects on vegetation.

Both short- and long-term climatic conditions influence these resources. The park's climate is continental, with cool, dry winters, hot summers, and half of annual precipitation falling in May-July. Year-to-year variability in precipitation is high and, with temperature, these patterns influence surface water flow from daily to 2-year time scales (Long and Mahler, 2013). Aquifer and cave lake levels are comparatively steady, with the climate of the previous century influencing long-term averages, and smaller short-term fluctuations lagging 1–2 years behind aboveground weather patterns (Long and Mahler, 2013). Annual grassland primary productivity is strongly influenced by the current and previous year's April-June precipitation (Smart et al., 2007) and therefore varies substantially from year to year. In contrast, the relative abundances of warm- and cool-season grasses in the prairie, and of grassland and woodland in the landscape, are influenced by longer-term temperature and precipitation patterns – both directly through the physiological requirements of each species and indirectly through climatic effects on fire, insects, and disease (Epstein et al., 2002; Brown, 2006) – and grazing and browsing by the park's wildlife.

When this work began (2009), IPCC (2007) climate change models for the WCNP region consistently projected warming, with mean annual temperature increasing by 1.7–2.2 °C by 2050. The majority of projections suggested modest increases in winter precipitation (2–5%, or 0.7–1.8 mm), but there was little consistency in projections for growing-season precipitation (details in Symstad et al., 2014).

2.2. Qualitative scenario (QLS) approach

In 2009, the NPS engaged an experienced facilitator from the Global Business Network (GBN) to begin training NPS staff in the qualitative scenario planning process, and to explore its utility for incorporating climate change into park planning. WCNP served as one of two case studies for this training. At an initial workshop, 17 participants with general climate change expertise built qualitative scenarios (QLSs) using a "nested" approach. Global-scale, socio-political scenarios were developed first to provide a context for local, climate-driven ecosystem scenarios for each park (Cobb and Thompson, 2012). Here, we focus on the local QLS development.

Over the next three months the GBN facilitator led a small team of WCNP staff, scientists with regional expertise, and NPS trainees through scenario construction that focused on natural resources expected to be affected by climate change. Three key inputs to the process included:

- a table, developed from regional projections, of nine climate variables for the A1B emissions scenario (IPCC, 2007) that described the direction of change and range of values expected over the next 40 years, a comparison of the range to recent changes, changes to seasonal patterns, and a qualitative estimate of the confidence;
- a compilation of existing information about climate influences on WCNP's natural resources and ecosystem; and
- a list of climate-sensitive items identified by the team.

Based on these inputs, the group identified "Drought Severity" and "Precipitation Patterns" as the two climate drivers with the greatest uncertainty in direction or magnitude of change and potential impact on natural resources. These drivers formed a pair of qualitative axes, ranging from minor to major change from current conditions, that formed the framework for scenario development (Fig. 1). These axes and their endpoints were not based on individual climate projections but instead were simply informed by the quantitative information presented in the table mentioned above. Team members then developed four QLS narratives by imagining how conditions created by the different combinations of minor or major change in the two climate drivers would influence the structure, composition, and functioning of the WCNP's ecosystems and key resources. The four QLSs were given the descriptive names of "Mixed-grass Prairie" (the scenario of least change), "Shrubland", "Shortgrass Prairie", and "Novel Ecosystem" (Fig. 1).

Then, in a two-day workshop, participants considered the management implications of, and options for response to, the scenario set. Team members used their individual knowledge and expertise to develop management goals and practices appropriate for the conditions in each of the climate-ecosystem QLSs. In these discussions, WCNP managers faced questions about the park's mission if climate-driven changes in the ecosystem were drastic enough that, for example, the park could no longer support viable populations of bison, elk, and pronghorn, as in the "Novel Ecosystem" scenario. They also contemplated how much their current management practices, such as specific prescribed fire return intervals based on historical natural fire regimes, would influence the direction of ecosystem change in the climate scenarios. After discussing these issues for each QLS, the WCNP group examined important differences and commonalities among the QLSs in key resource and process responses (e.g., water, bison herd, fire), and the actions that park managers would need to take to address those responses. The team identified response options that were applicable, or "robust", across the QLSs. The workshop closed with a brief evaluation of the process in the NPS climate change-resource management context.

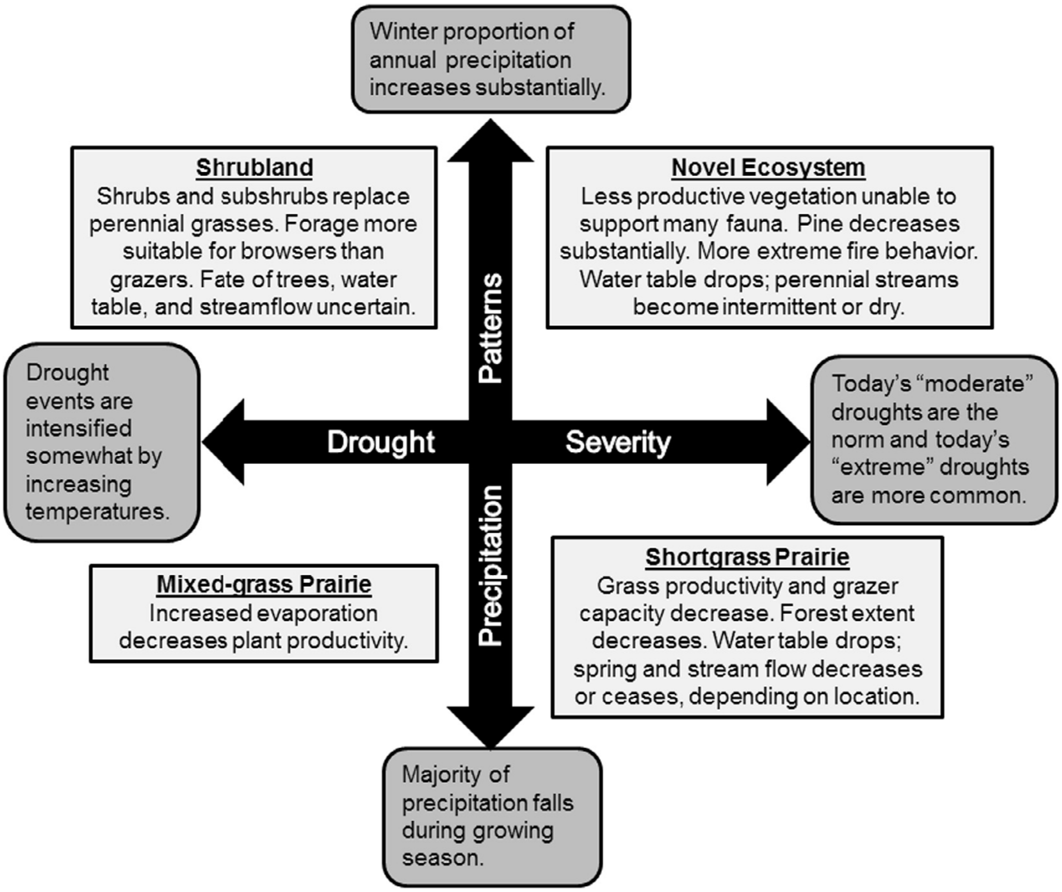

Fig. 1. Salient features of local climate-ecosystem QLSs used in the scenario planning exercise for WCNP. Arrows indicate climate drivers for which uncertainty about future patterns is high and that have a high impact on the ecosystem. Shaded boxes at ends of arrows describe alternative states of each climate driver, and scenarios (unshaded boxes) are the result of combining the two adjacent climate driver states.

2.3. Quantitative simulation modeling (SM) approach

The qualitative scenario planning exercise revealed incomplete understanding of how key ecosystem dynamics would respond to climate change and interact with management interventions (see "Evaluation of the QLS approach", below). Thus, when a funding opportunity arose, some QLS team members seized the opportunity to quantitatively validate the QLSs and test management options in various climate futures. Numerous simulation approaches are appropriate for representing scenarios and their impacts on natural resources (Miller and Morisette, 2014; Byrd et al., 2015). In this case study, the process-based Rainfall-Response Aquifer and Watershed Flow (RRAWFLOW) model (Long and Mahler, 2013), and the dynamic vegetation model MC1(Bachelet et al., 2001; King et al., 2013b) were selected to simulate hydrologic and ecological responses, respectively, during the process of assembling a science team for procuring the funding for the SM approach.

After procuring funding, the first step in the SM approach was a meeting between the science team and WCNP managers to exchange information, align expectations with model capabilities, and jointly determine the focal questions to address with the simulations ("Key Responses" in Table 1). This meeting and the subsequent discussions it spurred helped the scientists to better understand the WCNP system and its management and educated the managers about the functioning and limitations of the simulation models. For example, although managers were interested in the effects of the various climate scenarios on all the springs and streams in the park, scientists were limited to projecting Beaver Creek streamflow and cave lake level because the data required for calibrating the site-specific RRAWFLOW model (see Long and Mahler, 2013) were available only for these two hydrologic features. Similarly, while MC1 does incorporate differential effects of temperature on cool- vs. warm-season grasses, it did not distinguish between them with respect to the effects of atmospheric CO_2 on productivity and transpiration, an interaction that interested both managers and scientists. A modification of the model to address this issue was considered, but insufficient information was available in the scientific literature to make this improvement. On the other hand, scientists found park managers' data specific to the WCNP area valuable for calibrating MC1 to address other questions about ecosystem dynamics; this case-specific calibration was dubbed "MC1-WCNP" to distinguish it from the general model used elsewhere.

Participants in the initial meeting also decided that the SM approach would explore multiple future climates (through 2050)

Table 1
Climate input and key response variables for the two simulation models used in the WCNP case study.

Climate Input			Key Responses	
Abbreviation	Source model and downscaling	Parameters	RRAWFLOW	MC1-WCNP
CCSM3	CCSM3GCM output bias-corrected for RRAWFLOW weather stations	• Daily precipitation • Daily mean air temperature	• Streamflow • Cave lake level	
WRFc-Hydro	CCSM3GCM output dynamically downscaled at 36 km resolution with WRF, then bias-corrected for RRAWFLOW weather stations			
WRFc-Eco	CCSM3GCM output dynamically downscaled at 36 km resolution with WRF, then statistically downscaled and bias-corrected to 30 arc-second (~800 m) resolution	• Monthly precipitation • Mean monthly minimum air temperature • Mean monthly maximum air temperature • Mean monthly vapor pressure deficit		• Grass production (annual and seasonal) • Standing tree biomass • Fire frequency
CSIRO	CSIRO GCM output statistically downscaled and bias-corrected to 30 arc-second (~800 m) resolution			
Hadley	Hadley GCM output downscaled as for CSIRO			
MIROC	MIROC GCM output downscaled as for CSIRO			

derived from the A2 emissions scenario (the closest to actual trajectories since the emissions scenarios were developed), with each future climate being represented by a discrete time series of global climate model (GCM) output (a "projection") downscaled for the SM to better capture local dynamics. Daily precipitation and mean air temperature were statistically downscaled and bias-corrected, for the two weather stations used for RRAWFLOW calibration, from a projection from the Community Climate System Model, version 3 (Collins et al., 2006); we refer to this climate input dataset as CCSM3. In a project-specific innovation, the same CCSM3 projection was dynamically downscaled using the Weather Research and Forecasting (WRF) regional climate model at a 36-km grid spacing (Stamm et al., 2015). Daily precipitation and mean air temperature data from this downscaling were also bias-corrected for the two weather stations used for RRAWFLOW calibration; we refer to this climate data input dataset as WRFc-Hydro. CCSM3 and WRFc-Hydro served as climate input for RRAWFLOW simulations of Beaver Creek streamflow and cave lake level (Table 1).

MC1-WCNP required different climate parameters at a different temporal and spatial scale compared to RRAWFLOW (Table 1). Consequently, a different downscaling and bias correction method was used on the WRF-downscaled CCSM3 projection to produce the WRFc-Eco climate input dataset for MC1-WCNP (Table 1; details in Symstad et al., 2014). This method was also used on projections straight from three additional global climate models – CSIRO Mk3 (Gordon, 2002); Hadley CM3 (Johns et al., 2003); and MIROC 3.2 medres (Hasumi and Emori, 2004) – as additional climate input for MC1-WCNP. Although dynamical downscaling is beneficial in areas like WCNP where topographic features not recognized by coarse-scale global climate models influence climate, it is computationally intensive and time-consuming and therefore was infeasible for all four global climate model projections. In summary, MC1-WCNP climate input consisted of monthly temperature, precipitation, and vapor pressure deficit data from the four downscaled climates. Additional input consisted of spatially explicit soil data (Kern, 1995, 2000) and the A2 emissions scenario CO_2 pathway.

Once MC1-WCNP was parameterized using data supplied by park managers (e.g., forest structure, grassland production), scientists collaborated with managers in selecting management options to quantitatively simulate with MC1-WCNP in the different

Table 2
MC1-WCNP simulations run for combinations of grazing and fire management options. Numbers in parentheses summarize the number of simulations resulting from each combination. Italic text indicates the simulation was run for a small portion of the park to reduce model run-time.

Grazing option*	Fire option		
	Natural fire*	Fire suppression*	Controlled burn*
25%	*One each for CSIRO, Hadley, MIROC (3)*	(0)	(0)
50%	*One each for CSIRO, Hadley, MIROC (3)*	(0)	(0)
70%	*One each for CSIRO, Hadley, MIROC (3)*	(0)	(0)
30%	One for each climate (4) *One for each climate with* $[CO_2]^{\dagger}$ *held constant (4)*	One for each climate (4)	One with 20% tree mortality at 11-yr fire return interval for each climate (4) For Hadley, one simulation each for 11-, 16, or 21-yr interval with 20% tree mortality (3); and one simulation each for 10% or 30% tree mortality and 16-yr interval (2)

* *Grazing*: Percent of growing-season live biomass production consumed each year by year-round grazing. *Natural fire*: Climate and simulated fuel moisture determine when fire behavior thresholds are exceeded and fire occurs. Fire behavior and effects are modulated by current vegetation type. *Fire suppression*: A fire occurs only when extreme fire metrics are exceeded, so that only ~5% of potential fires occur. Fire behavior and effects are modulated by current vegetation type. *Controlled burn*: Prescribed fire regimes are represented by specifying a fire's date and the tree mortality rate. Other fire effects are modulated by climate and simulated fuel moisture on that date.

† Atmospheric CO_2 concentration.

climate scenarios (Table 2). (RRAWFLOW results are independent of management options.) When all simulations were complete, scientists shared the results of the simulations and their preliminary list of implications with managers in a formal presentation and as a draft project report. Managers provided feedback and their own suggestions regarding these implications (e.g., for prescribed fire practices that maintain desired tree density) over the following months by commenting on the report and via in-person conversations. This process yielded jointly derived management implications that were included in the final report.

In the final step of the SM approach, the research team quantitatively compared the climate projections used in the simulations to the range of climate projections available at the time. This comparison provided an understanding of the SM results in the context of a range of potential future climates (Barsugli et al., 2013), as well as a framework for evaluating the plausibility of the ecosystem responses described for the four climate scenarios used in the QLS approach.

3. Results

Data presented here are available as a U.S. Geological Survey dataset (Symstad et al., 2017).

3.1. Evaluation of the QLS approach

The consensus at the end of the 2009 QLS planning workshop was that the approach was an appropriate tool to incorporate climate change into management planning for NPS units. Positive aspects of the process included the learning stimulated through its participatory approach (Cobb and Thompson, 2012). The consideration of four diverse futures, coupled with the inclusion of participants from outside the park, pushed WCNP managers and local scientists to critically examine and defend or change their way of thinking about ecosystem response and possible management actions. However, the self-evaluation also suggested that more work may be needed to validate the findings to ensure that the approach and the implications derived from it are credible for making decisions.

This caveat derived from the recurring concerns of some WCNP team members about the plausibility and internal consistency of the ecosystem responses to the regional climate change projections described in the local QLSs. For example, questions arose about how much change in drought severity or precipitation patterns would be needed to produce changes in streamflow significant enough to affect wildlife, or to result in substantially different vegetation over the 40-year time frame used for the exercise. The team was also challenged by the complex, interacting effects of atmospheric CO_2 concentration, temperature, and precipitation on the overall amount and seasonality of forage production, as well as by climate-fire-vegetation interactions. The critical role of fire regime in the relative distribution of prairie and forest in this region and the complexities of the influences of both climate and weather on this dynamic (Brown and Sieg, 1999; Brown et al., 2005, 2008) was a main concern. The WCNP team also realized that wildfire suppression and prescribed fire practices currently used in the park may determine whether the ecosystem responses in some scenarios could even occur. Some argued that maintaining the current prescribed fire regime, which is geared towards reducing ponderosa pine forest density and preventing pine encroachment into grasslands, could prevent summer drought-adapted shrubs ("Shrubland" scenario) or desert-like plants ("Novel Ecosystem" scenario) from becoming dominant. A situation like this, with management working in the opposite direction of climate changes, could produce a system highly susceptible to dramatic change (Millar et al., 2007). Following the workshop, these concerns hampered implementation of QLS-derived response options into resource management practices.

3.2. Evaluation of the SM approach

The WCNP SM project did not involve a deliberate, whole-group evaluation of the overall approach or specific processes used, as occurred in the QLS process, but one point for improvement was clear: greater coherence in climate inputs used for the two response models. Better understanding at the beginning of the project regarding the complexity of dynamically downscaling global climate projections would have made it clear how many projections could feasibly be produced this way. A single response model that integrated ecological and hydrological systems would also have reduced complications, but the complex geology of the region has hindered the development of such a model.

In place of a deliberate evaluation, project reports qualitatively addressed uncertainties inherent in the approach, including those associated with climate projections, dynamic global vegetation models in general, and MC1-WCNP specifically (King et al., 2013a,b), and quantitatively compared the climate projections used in the SM to the available range of plausible future climates (Fig. 2; Symstad et al., 2014). Both of these, along with discussions during the project, provided managers a better understanding of the limitations of the approach. Later evaluation of the process highlighted the fact that a formal sensitivity analysis investigating the relative effects of various model parameters would have provided a means for assessing the relative influence of the uncertainties associated with each model. Some elements of a sensitivity analysis were completed for MC1-WCNP via the large number of simulations (Table 2), but a more comprehensive analysis could have informed the process for selecting which future climates and management options to simulate.

3.3. Comparison of the QLS and SM approaches

The QLS and SM processes shared many similarities but also differed in significant ways. In both approaches, scientists and managers jointly determined the focal questions to address. Furthermore, multiple climate scenarios provided a broad range of future

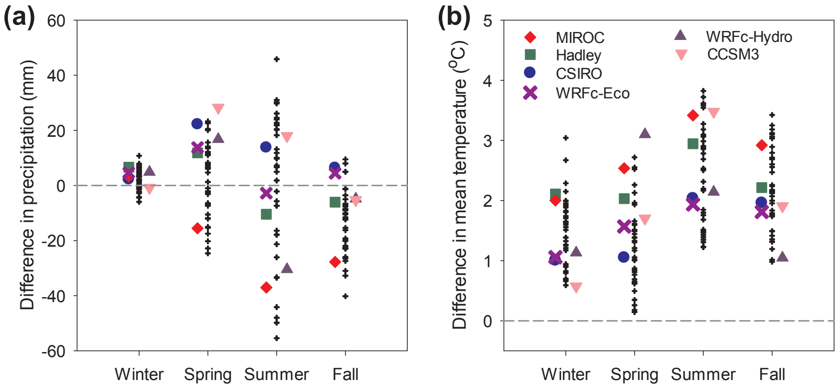

Fig. 2. Climate scenarios (2031–2050 mean) used in WCNP quantitative simulations (large shapes) compared to a broad range of CMIP3, A2 emissions scenario climate projections (small crosses; Reclamation, 2013). Climate scenarios are represented by their deviation in seasonal (a) precipitation and (b) average temperature from the 1980–1999 historical period mean for WCNP.

climates (Fig. 2) for managers to contemplate either qualitatively (QLS) or quantitatively (SM). However, the climate scenarios were selected for very different reasons. In the QLS approach, managers and scientists worked together to select qualitative, divergent climate scenarios based on assumptions about how their conditions would challenge management. In the SM approach, a team of scientists selected quantitative climate scenarios based on model fit, financial considerations, and data availability. The CCSM3 projection used as the basis for WRFc-Hydro and WRFc-Eco was selected because, of three climate models examined, it was the most highly skilled in estimating annual mean air temperature for central North America. The other three climate projections used in the vegetation simulations were selected by the MC1 development team long before the WCNP project because the climate input variables required by MC1 were available, and because they represented a spread of potential future climates for all of North America: "warm and wet" (CSIRO), "hot" (Hadley), and "hot and dry" (MIROC).

The approaches also differed considerably in their incorporation of management. In the QLS approach, management reactions to each climate scenario and their composite were derived via discussions comprising just one part of a two-day workshop. In the SM approach, scientists and managers collaborated to select fire- and grazing-management options, which were then tested under different climate scenarios over a period of months. The collaboration ensured that the management options were pertinent but challenging, in that they ranged from "worst" to "best" case conditions (e.g., from the elimination of all prescribed fire operations to prescribed fires occurring at currently desired, but not achieved, intervals). The iterative testing accomplished through the SM process allowed more time for the review of model results, consideration of implications, and incorporation of manager feedback into subsequent model runs than the QLS process. Noteworthily, the SM process likely would have been less interactive than the QLS process if not for the fact that one of the project scientists was co-located with park managers.

3.4. Comparison of the SM and QLS results

We highlight six major results from the WCNP case study:

1. SM confirmed concerns expressed during the QLS effort about surface water availability. Although the two climate projections used to simulate streamflow had annual precipitation equal to or greater than the historical period, warmer temperatures yielded

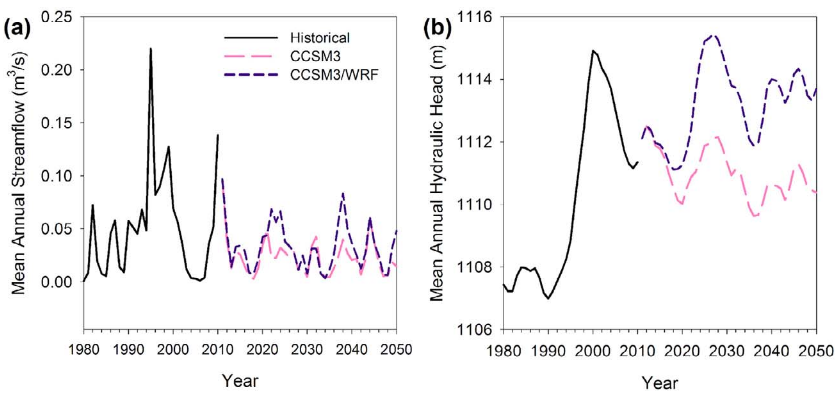

Fig. 3. Beaver Creek streamflow (a) and cave lake level (b) simulated by RRAWFLOW using historical climate and two future climate projections. Adapted from Symstad et al. (2014).

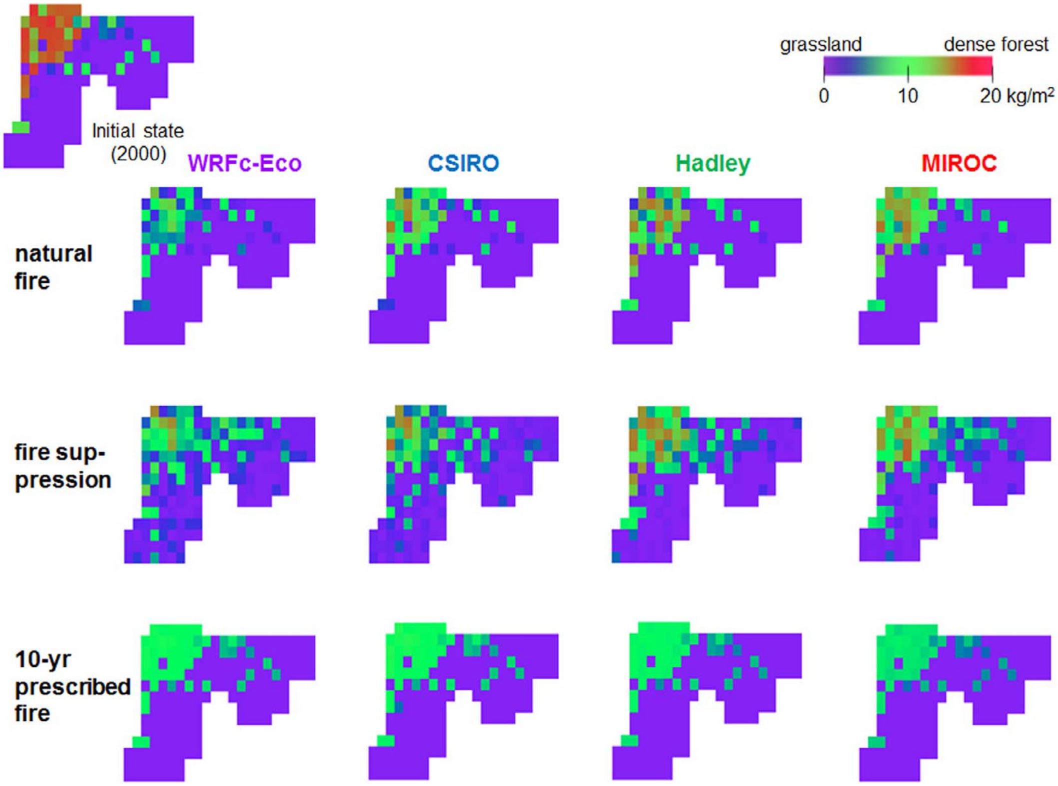

Fig. 4. WCNP tree biomass simulated with MC1-WCNP for historical conditions (year 2000, upper left) and four climate scenarios in three fire regimes. Each shape represents the polygon encompassed by the WCNP boundary in 2010. From Symstad et al. (2014).

significantly lower streamflow in both projections (Fig. 3a). More interestingly, SM revealed counterintuitive behavior of this complex system in that the climate projection with higher total annual precipitation (CCSM3 in Fig. 3a) yielded a greater decrease in annual streamflow because of its 1.3 °C-higher summer air temperature and much lower intra-annual variability in precipitation, both of which increased evapotranspiration.

2. Scenario planning participants generally assumed that cave lake level would drop as temperature-driven increases in evapotranspiration reduced recharge to the aquifer (Fig. 1). The SM supported this assumption in principle, but revealed that the aquifer has both a long system memory (~100 years) and a slow response to aboveground conditions. These characteristics can delay the effect of rising temperatures on cave lake levels over the next few decades (Fig. 3b). However, because the climate inputs used for hydrologic SM represented only the wet range of the spectrum of climate projections (Fig. 2a), further work would be necessary to understand potential changes with hotter and drier climate input.
3. In the QLS approach, half of the scenarios described substantial contraction of pine forest in WCNP based on projections made with continental-scale species distribution (climatic niche) models (Shafer et al., 2001; Rehfeldt et al., 2006; Fig. 1). In contrast, the WCNP-specific SM, which accounted for the role of fire in this ecosystem, showed reduced forest density overall, but the expansion of pine into current grasslands in a wide range of future climates unless approximately decadal fires occurred (Fig. 4).
4. While scientists and managers realized the importance and stochastic nature of individual severe fire events with regard to the prairie-forest balance using the QLS approach, determining how much the frequency of these severe events may change was only possible in the SM approach. Regardless of climate projection used in the simulation, the mid-century target period (2031–2050) had at least twice as many high-fire-danger days per year as the recent past (1980–2010). Moreover, the hottest, driest climate scenario showed even more high-fire-danger days than occurred during severe drought periods in the 1930s and 1950s.
5. All scenarios in the QLS approach described lower grass production by 2050 than has occurred historically, and in two of those scenarios grass production was too low to sustain bison, elk, and prairie dogs (Fig. 1). In contrast, in the SM approach the two hottest climate projections yielded grass production decreases of only 7 and 19%, not enough to require drastic reductions in herbivore populations. Although the climate scenarios in the QLS and SM approaches differ, this contrast does suggest that assumptions about grass production in the QLS approach may have been somewhat extreme.
6. The two QLSs developed for a higher winter:summer precipitation ratio described ecosystems that differ substantially from that of the park's current pine woodland-mixed grass prairie ecotone. The SM did not produce this biome shift, and the analysis of a broad range of climate projections (Fig. 2) suggested that the magnitude of precipitation change required to elicit such a vegetation response was outside the realm of plausible future climates for the time frame used in both exercises.

Table 3
Potential management actions for WCNP derived via the qualitative scenario planning process, and the refinements suggested in the quantitative simulation modeling process.

Management Challenge	Qualitative Scenario Planning	Quantitative Simulation Modeling
Water availability	Develop additional surface water sources for wildlife	Develop additional surface water sources for wildlife
Herbivore populations	Achieve current target population sizes for managed herbivores and prioritize wildlife species and/or populations that will be supported	Increase flexibility of major herbivore management; decrease response time of major herbivore management to current conditions to avoid long-term heavy grazing
Forage availability	Develop means for supplemental feeding of high-priority wildlife	Be prepared for the ecosystem impacts of drought years, high inter-annual variability of grass production, and lower late-growing-season grass production
Forest management	Reduce ponderosa pine forest density to reduce chances of widespread crown fire	Determine management goals for tree density in currently forested areas; implement prescribed fires in conditions conducive to fire-induced tree and seedling mortality to achieve these goals; monitor tree recruitment in currently forested areas
		Maintain an active prescribed fire program to maintain current grassland areas as grassland (burn grasslands every 10–20 years)
Fire management	Increase the number of fire staff and/or the length of the fire staffing season	Be prepared for more high-fire-danger days in a year, and more years of many high-fire-danger days, regardless of climate
Cave resources	Investigate climate change impacts on cave resources	Cave lake level will continue to be influenced by 1990s wet period through the middle of this century but could decrease even if precipitation increases

3.5. *Comparison of management implications derived via QLS and SM approaches*

Management actions derived via the QLS process were generally supported by the quantitative effort (Table 3). The latter suggested some refinements and additions, such as integrating the disparate results of two vegetation modeling approaches (Shafer et al., 2001; Rehfeldt et al., 2006 vs. this study) into a management strategy of continuing a prescribed fire program to prevent pine encroachment into prairie but closely monitoring pine recruitment in forested areas. The high agreement between the management implications derived from the two approaches can be attributed to at least two factors. First, despite a lack of literature on climate change impacts specific to the WCNP region, the QLS participants' collective expertise generally anticipated the direction of hydrologic and ecosystem changes even if the magnitudes of those changes in the target time frame were uncertain. Second, the potential management actions derived in the QLS exercise focused on those applicable across all scenarios (i.e., robust actions). Management actions derived to address just the more drastic of the QLSs – ceasing prescribed fire in grasslands to allow development of a shrub community, for example – were not included in the final list of recommendations. The ability to test such actions in a SM approach is valuable for planners contemplating riskier decisions, and the results of these tests could help guide their planning strategy.

4. Discussion

The results of the WCNP case study illustrate the added value of combining SM and QLSs for identifying counterintuitive system dynamics (results 1 and 3, above), refining understanding of complex relationships (1 and 2), clarifying the magnitude and timing of changes (4), and identifying and checking the validity of assumptions about resource responses to climate (5 and 6) (Miller and Morisette, 2014). While the QLS approach challenged managers to contemplate drastically different futures, the SM approach provided managers (and scientists) a better understanding of the degree of change to expect in key ecosystem metrics by 2050 with respect to historical means and variations.

Improved understanding can be pricey, however. For the WCNP SM, costs included ~$300,000 for five scientists' time calibrating, running, and interpreting the results from models specific to WCNP, as well as an untracked amount for the scientists' and managers' time in project meetings and preparing and reviewing documents over a period of ~4 years. In contrast, a typical QLS process in the NPS costs less than a third of the modeling effort, requires only weeks of preparation by 3–5 adaptation specialists and scientists, and the workshop typically lasts two days. Advantages of the longer time period of the SM approach included its fostering co-production of knowledge through iterative and sustained interactions among scientists and managers and providing the opportunity for all participants to process this knowledge and the simulation output into management implications. The combination of these advantages and the greater rigor and documentation of the process, including the assumptions and biases of the models, gave managers greater confidence in implementing those actions or in seeking the resources needed to do so (G. Schroeder, WCNP Natural Resources Division, pers. comm.).

The WCNP project did not evaluate whether the refinement of management implications and greater confidence in them justified the time and money invested. However, given the complementary findings of each approach described for the WCNP case study, and based on our experience with other QLS exercises, we believe that integrating qualitative scenario approaches with the quantitative decision-making needs of organizations wishing to address the unique issues posed by climate change will be justified in many instances. Therefore, we propose an analytical framework to achieve this. Our analytical framework is consistent with others that combine qualitative and quantitative approaches (e.g., Alcamo, 2008; Mahmoud et al., 2009; Miller and Morisette, 2014) but it

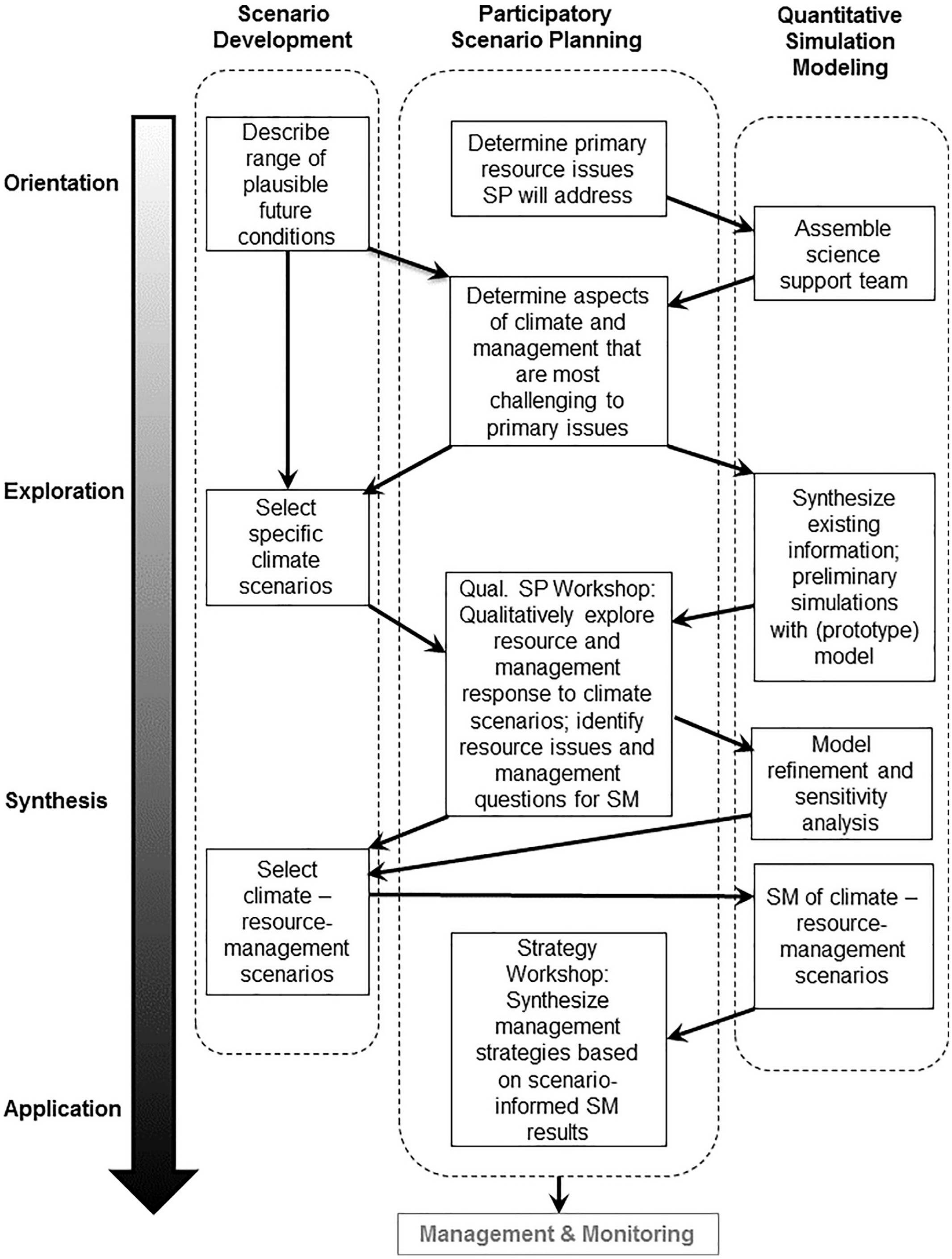

Fig. 5. The SP-SM (Scenario Planning with Simulation Modeling) framework described in the text.

provides a more detailed workflow for enhancing management relevance, and for bridging planning and action. Scenario Planning with Simulation Modeling (SP-SM) has three components – scenario development, participatory scenario planning, and quantitative simulation modeling – that interact through a process of orientation, exploration, synthesis, and application (Fig. 5).

Scenario development begins by determining key issues to address. This determination may be made when managers approach scientists with specific questions reflecting uncertainties about a high-priority topic such as an endangered species, or it may be made via a process of scenario planning experts' guiding of managers through an exercise to identify the most impactful uncertainties surrounding climate change for their management programs.

Identifying these issues up front clarifies the type of scientific support needed for the rest of the SP-SM process; thus, an appropriate science team is then assembled. This team includes expertise not only on the primary resource issue(s) and the capability for SM of these resources, but also on climate science, because the next step in the process requires understanding and describing the range of plausible future climate conditions for the geographic area of interest. A range of publications and easily accessed climate data sets (e.g., http://cida.usgs.gov/gdp/, Kunkel et al., 2013; Sun et al., 2015) have made this step less daunting than at the beginning of the WCNP project in 2009. This progress is reflected in the more quantitative climate scenarios currently used in NPS planning activities (e.g., Fisichelli et al., 2016) compared to those in the WCNP workshop. Scientists and managers then work together to determine which aspects of plausible future climates (i.e., climate parameters) are most relevant to the focal issues identified earlier.

Next, during exploration and early synthesis, the climate scientist leads the scientific team in developing three to five divergent, yet plausible, climate scenarios that form the basis for the QLS planning workshop. Historical climate data and data from specific future climate projections support the quantitative descriptions of internally consistent (i.e., physically coherent) climate scenarios for the location of interest. Raw climate data may additionally be described in terms of memorable, impactful climatic events to which workshop participants may more readily relate. For example, in the WCNP project, the climate scenarios could have been compared to droughts in the 2000s. Doing so may have made clearer the drastic climatic changes that would be necessary to produce the more extreme ecosystem scenarios.

Concurrently, the science support team assembles existing information on the response of the focal resources to various climatic conditions. Because information specific to the chosen climate scenarios and resources is often limited, the goal is to collect information relevant to discussions of the focal topics determined during the orientation phase. This information may also include indigenous knowledge, which often spans longer time periods and includes additional nuances and insights that are not captured by the western science tradition (Wildcat, 2009).

The science support team uses this information to build from scratch, or modify from existing stock, one or more simulation models to address the challenging climate and management issues identified during orientation. Working with existing simulation models has the advantage of reducing project costs and time. If no known model fits the SP-SM needs, scientists can improve project efficiency in resource-constrained situations by making a deliberate effort to minimize complexity of the models that need to be built by capturing only key system dynamics and documenting the simplifying assumptions (Miller et al., 2010). Preliminary output from the selected or constructed model(s), which may still be in prototype form or run for a subset of the study area, provides input for the next step, the QLS workshop.

It is critical that early discussions regarding the primary resource issues produce clear direction regarding the types of scientific and modeling expertise that will be needed. Although having this foresight is challenging, the benefits of including the science team as early as possible in the process are threefold: scientist-manager relationships have more time to develop, scientists provide managers with expertise on critical climate factors and resources, and managers educate scientists about their practices and the constraints they face in their management jurisdictions. The first is often critical to the other two, and the last is critical for designing challenging yet plausible management components of the scenarios to be simulated.

Participants in the QLS workshop include not only the managers and scientists involved in the orientation and exploration phases, but also additional stakeholders, scientists, and local experts identified during those phases. Including managers and stakeholders from a range of agencies and organizations can reveal areas of complementary experience and expertise and encourage future cooperation on shared challenges revealed during the workshop.

The workshop begins with facilitators explaining the scenario planning process, followed by presentations of the assembled information so that all participants can understand and contribute to discussions even on topics not in their primary area of expertise. Synthesis of the existing science and knowledge is critical for the construction of plausible scenarios. For example, in the WCNP exercise, publications available at the time suggested that climate would not be suitable for ponderosa pine in WCNP by 2040 (Shafer et al., 2001; Rehfeldt et al., 2006), described the results of experiments manipulating CO_2 and temperature in an ecosystem similar to that of WCNP's (Morgan et al., 2004, 2007, 2008), and explained the distribution of broad ecosystem types in relation to temperature and precipitation gradients (Epstein et al., 2002). Next, the climate scenarios and rationale for their selection are shared with the group, as are the results of the preliminary simulations. The latter are shared in order to inform, but not dictate, the outcome of the scenario construction given their preliminary nature. The workshop becomes truly participatory when the attendees integrate the presented information with their own expertise and experience to infer and describe in narrative form the responses of the focal resources in each of the climate scenarios; the result of these discussions are climate-resource scenarios. Participants qualitatively assess the effectiveness of current management practices in each of the scenarios and consider new management practices that may be necessary within and across scenarios. The final step in the workshop is a discussion of insight garnered during the workshop regarding necessary improvements to the simulation model.

QLS planning workshop participants may find sufficient value in developing divergent scenario narratives and considering options to begin addressing climate change in their management planning (e.g., Kicklighter, 2015). However, as experienced in the WCNP case, discussions during the qualitative exercise often generate three types of questions: What magnitude of change in the focal resources and other elements that affect them would be realistic in the provided climate scenarios? How would the management practices discussed interact with climate to influence the focal resources? What is the relative influence of climate and management on the future of these resources? These questions, as well as the discussion of the model at the end of the workshop, form the basis for a model sensitivity analysis. In this analysis, the science team evaluates the influence of parameter uncertainty on model performance. This analysis helps isolate the more important components of the model, which not only improves efficiency in determining which aspects of the model need the most attention for improvement, but also provides direction for the final phases of the SP-SM process, when synthesis leads to application.

The next step in the synthesis phase is to use the results of the QLS workshop and the sensitivity analysis to select the climate scenarios and management options that will be simulated. A greater number of quantitative simulations usually can be performed than the 3–5 climate scenarios created and applied to management in a QLS workshop. In the WCNP case, four climate scenarios were developed in the QLS process, in contrast to 20 climate-management-greenhouse gas combinations in the SM process (Table 2). In contrast to the QLS planning workshop, the goal of the final phases of the SP-SM analytical framework is not to explore the implications of deliberately divergent management options for a wide range of resources. Instead, simulation-informed strategizing in a second workshop is intended to build on the insights from, and address the limitations of, the preceding QLS effort by capitalizing on SM's capability to explore the relative effects of different climate scenarios and management options on important resources. This approach may involve examining the effectiveness of current management, testing the type and intensity of management required to achieve current goals, and ascertaining which goals are achievable with different levels of management capacity in a variety of climate scenarios. Because the ultimate goal of SM is to more thoroughly test options toward decision making, the process of selecting and running climate-resource-management scenarios may be iterative.

At the end of these iterations, scientists and managers reconvene in a workshop to build or refine management goals and strategies informed by a synthesis of the results from the simulations. One approach is to focus on actions that are robust (i.e., able to achieve management goals) across the future climate conditions, like those identified in the WCNP example. However, robust options do not always exist, and in some cases it may be desirable to identify suites of actions that are relevant to only some scenarios or a particular set of climate conditions. If such actions veer from traditional management practice or represent other risks (e.g., expensive or irreversible infrastructure development), it will be necessary to identify indicators of unfolding climate or resource conditions that would trigger the need for their implementation. SM is especially useful as a virtual laboratory to help identify indicators of approaching, potentially irreversible, system thresholds or tipping points (Carpenter et al., 2005). Because combining qualitative scenario planning with quantitative scenario output to operationalize adaptation is rapidly evolving, we anticipate the need for iteration to ensure deliberative and appropriate management responses over the long term.

5. Conclusions

Qualitative scenario planning coupled with quantitative simulation modeling (SP-SM) represents a comprehensive analytical framework for integrating highly uncertain and uncontrollable factors, such as climate change, into natural resource decision making. The outcomes of the two components are naturally complementary, as demonstrated by the WCNP case study, and serve to support managers in reviewing current actions and, if necessary, taking new or modifying existing actions in the face of ecosystem responses to changing climate conditions. The qualitative scenario component is essential because it builds understanding about the challenges climate change presents and clarifies the problems necessary to address through subsequent decision making. Although a qualitative approach alone is sometimes enough to motivate adaptation, in other cases it provides a framework for identifying management responses and, importantly, lays the groundwork to focus quantitative simulations on key system dynamics. As illustrated by the WCNP case study, these quantitative exercises can reveal nuances, surprising outcomes, and knowledge gaps associated with the interactions of climate, ecosystems, and management, and, when executed in a participatory environment, are effective in communicating the complexities that arise from the interactions of climate change and other factors. Additional SP-SM applications are essential for developing a greater understanding of managers' decision needs, refining the coordination of the qualitative and quantitative components, and building capacity for alternative planning processes, all toward a seamless integration with decision making.

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