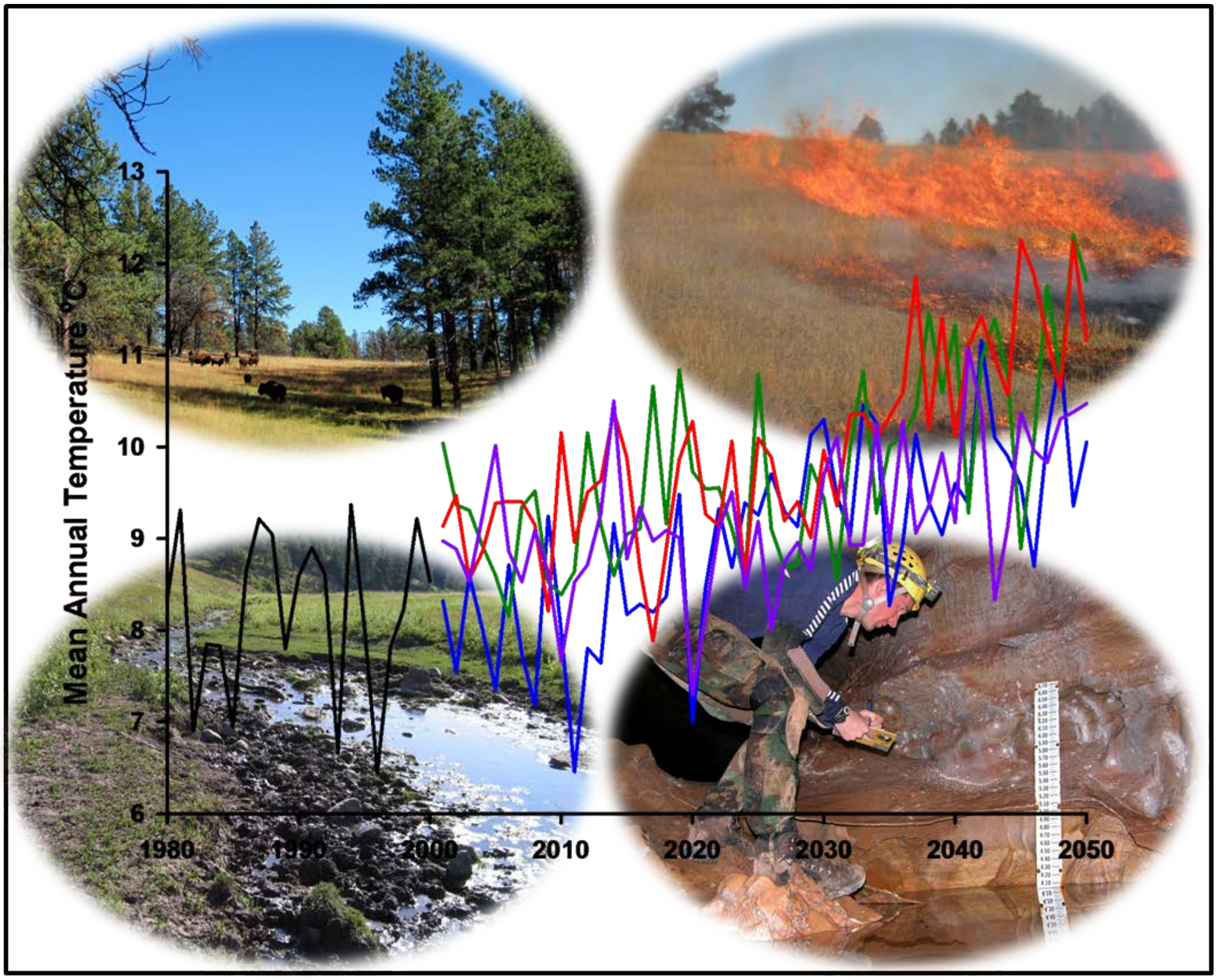
**National Park Service**
**U.S. Department of the Interior**

**Natural Resource Stewardship and Science**

# Two Approaches for Incorporating Climate Change into Natural Resource Management Planning at Wind Cave National Park

Natural Resource Technical Report NPS/WICA/NRTR—2014/918



**ON THE COVER**
Grass, ponderosa pine, bison, and surface and cave water are major concerns of resource management in a changing climate at Wind Cave National Park. Graph shows historical (black) and projected (four colors, each representing a different climate projection) annual mean temperature at the park.
Photographs by Dominique Bachelet (upper left) and Wind Cave National Park (others).

# Two Approaches for Incorporating Climate Change into Natural Resource Management Planning at Wind Cave National Park

Natural Resource Technical Report NPS/WICA/NRTR—2014/918

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# Executive Summary

Wind Cave National Park (WICA) protects one of the world's longest caves, has large amounts of high quality, native vegetation, and hosts a genetically important bison herd. The park's relatively small size and unique purpose within its landscape requires hands-on management of these and other natural resources, all of which are interconnected. Anthropogenic climate change presents an added challenge to WICA natural resource management because it is characterized by large uncertainties, many of which are beyond the control of park and National Park Service (NPS) staff.

When uncertainty is high and control of this uncertainty low, scenario planning is an appropriate tool for determining future actions. In 2009, members of the NPS obtained formal training in the use of scenario planning in order to evaluate it as a tool for incorporating climate change into NPS natural resource management planning. WICA served as one of two case studies used in this training exercise. Although participants in the training exercise agreed that the scenario planning process showed promise for its intended purpose, they were concerned that the process lacked the scientific rigor necessary to defend the management implications derived from it in the face of public scrutiny.

This report addresses this concern and others by (1) providing a thorough description of the process of the 2009 scenario planning exercise, as well as its results and management implications for WICA; (2) presenting the results of a follow-up, scientific study that quantitatively simulated responses of WICA's hydrological and ecological systems to specific climate projections; (3) placing these climate projections and the general climate scenarios used in the scenario planning exercise in the broader context of available climate projections; and (4) comparing the natural resource management implications derived from the two approaches.

Scenarios explored in the 2009 scenario planning exercise were developed by nesting four park-level, ecosystem scenarios derived from critical uncertainties about future climate (drought severity and precipitation patterns) within four high-level, societal scenarios. However, management implications were largely derived based on the four ecosystem scenarios. These ecosystem scenarios, which were named for the type of vegetation assumed under the four combinations of two alternative states each of drought severity and precipitation pattern, were Mixed-grass Prairie (the base-case scenario), Shortgrass Prairie, Shrubland, and Novel Ecosystem.

The follow-up quantitative study used projections from climate models as input for a hydrologic model and an ecosystem model, both of which were calibrated for WICA resources. The Weather Research and Forecasting (WRF) model was used to dynamically downscale the Community Climate System Model, version 3 (CCSM3) global climate model. This projection and the CCSM3 projection were used as climate input to simulate streamflow in WICA's largest perennial stream and the level of a cave lake with the Rainfall-Response Aquifer and Watershed Flow model. The CCSM3/WRF climate projection and three other global climate model projections (CSIRO Mk3, Hadley CM3, and MIROC 3.2 medres) chosen to span a range of future temperatures were used as input to simulate tree biomass, grass production, and various components of fire with MC1, a dynamic vegetation model. All projections were for the A2 emissions scenario.

Annual mean air temperature of the climate projections in the mid-21st century significantly exceeded that of the recent past (1986-2005) by 1.5–2.7 °C (2.7 – 4.9 °F). Precipitation patterns varied considerably among the projections, with mean annual precipitation change between these periods ranging from a 16% decrease to an 11% increase. Projections also differed in their intra- and interannual variability of temperature and precipitation. The four projections used for the ecosystem response modeling represented a major portion of the range of climate projections available, whereas the two projections used for the hydrologic response modeling both had relatively high annual precipitation compared to the range of projections available.

Results of the quantitative simulations suggest that, even in a future with precipitation higher than historically, streamflow of Beaver Creek could decrease compared to that of the historical period because of warmer temperatures. The simulations also revealed that cave lake level is likely to be influenced by the historically wet 1990s through the middle of the 21st century. One climate projection yielded an increase in lake level of nearly 2 m (6 ft) by 2050, whereas the other projection yielded no trend in lake level. Lake level might decline in a drier climate projection than those used in this study. Results of the ecosystem simulations suggest that the strongest effect of climate change on WICA's vegetation will be through rising temperature's effecting increasing fire frequency. The simulations also suggest that, in the absence of prescribed or natural fire, ponderosa pine could expand into current grasslands, thereby reducing park-wide grass production, regardless of future climate. Only the hottest climate projection produced a substantial decline in mean annual grass production by 2050, but even the wettest climate projection had drought years with grass production like that of the most severe climate projection.

Results from the quantitative simulations supported some assumptions made during the 2009 scenario planning exercise, including higher fire danger and stationary or decreased streamflow in most plausible future climates. However, the simulations and quantitative evaluation of future climate projections suggest that the Shrubland and Novel Ecosystem scenarios used in the exercise are unlikely for the mid-21st century timeframe targeted by both approaches, and that declines in grass production assumed in all scenarios may not be as strong as assumed. The simulations also demonstrated the importance of differences in intra- and inter-annual variability in precipitation on streamflow and cave lake level, effects that drive seemingly counter-intuitive results when only mean values of precipitation are compared.

Although the quantitative simulations did not support all of the scenarios used in the scenario planning exercise, the management implications derived from this approach and the quantitative simulations did not differ strongly, at least partly because the scenario planning exercise focused on management activities appropriate for any of the four scenarios considered. Both approaches suggest the following potential management actions:

- Develop additional surface water sources for wildlife.
- Avoid long-term, heavy grazing by achieving target population sizes of managed herbivores.

- Be prepared for high inter-annual variability of and lower late-growing-season grass production by developing means for supplemental feeding, prioritizing wildlife species or populations, and/or reducing response times of herbivore management programs.
- Anticipate the impacts of declining cool-season and increasing warm-season grass production.
- Maintain an active prescribed fire program to maintain current grassland extent and production, but ensure fire effects in forested areas are amenable to achieving park goals regarding forest structure.
- Be prepared for more high-fire-danger days in a year and more years of many high-fire-danger days.
- Monitor surface water and associated vegetation; wildlife health; grassland vegetation composition, production, and phenology; mountain pine beetle impacts; and ponderosa pine recruitment.

Although WICA completed activities recommended in the NPS Climate Change Response Strategy in an order different than that recommended by this strategy, the consistency in management implications between the park’s scenario planning exercise and the quantitative assessment of hydrologic and ecosystem responses indicates that WICA now has the rigorous information needed to produce and implement climate change adaptation strategies. Developing widely applicable, affordable means for incorporating quantitative simulations into scenario planning exercises would provide an efficient mechanism for translating climate change science into management actions for other NPS units and natural resource management agencies.

# Acknowledgments

We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.  The 2009 scenario planning training described in this report was funded by the U.S. Geological Survey's Northern Prairie Wildlife Research Center.  Funding for the quantitative projections project was provided by the National Park Service's Climate Change Response Program.  Putting the climates used in the quantitative projections project in context was inspired by J. Barsugli and A. Ray of the National Climate Predictions & Projections Platform through a project funded by the Department of Interior's North Central Climate Science Center.  N. Fisichelli, D. Weeks, and A. Ray provided valuable input for improving an earlier version of this document.

# 1. Introduction

## 1.1 Background and Setting

Wind Cave National Park (WICA) was the first national park established to protect a cave resource, and the park's namesake is one of the longest caves in the world. In addition, the park has been recognized as exemplary for having large amounts of high quality, native vegetation and a majority of natural processes in place (Marriot 1999). The park's enabling legislation requires it to maintain viable populations of bison, elk, and pronghorn, all of which depend on the availability of forage and surface water. Consequently, these four items – cave and karst features, native vegetation, native wildlife, and water resources – are identified as four of WICA's five fundamental resources (Wind Cave National Park et al. 2011). Managing for these fundamental resources in a relatively small area (~13,500 ha or 33,300 acres) is challenged by climate change.

Although biota are sparse in the cave system at WICA, other aspects of the cave system can be highly sensitive to changes in its environment. The genesis, growth, and erosion of speleogens such as boxwork and speleothems such as helictite bushes, quartz formations, frostwork, and fragile growths of gypsum are influenced by cave temperature, humidity, and water flow. Water in the cave drips from hundreds of locations underneath surface drainages, flows down small streamlets on cave floors, and accumulates in cave pools and lakes. An unusual feature of this cave is that, at its lowest point, Wind Cave intersects the water table of the Madison aquifer to form subterranean lakes. The level of these lakes rises and falls with the aquifer's water table and thus is susceptible to fluctuating aquifer recharge rates, which are in turn susceptible to climate change.

Surface water resources are strongly influenced by the area's karst geology, in which the underlying limestone actively conducts groundwater and is gradually dissolved by the water it transports. This geology and its subsurface channels result in numerous small springs, as well as streams that disappear from the surface, within WICA's boundaries. These springs and streams, most of which are small and intermittent, provide not only water for wide-ranging, upland wildlife, but also habitat for aquatic and wetland plants and animals. Both short- and long-term climatic conditions influence the flow and availability of these critical water sources to wildlife and, therefore, the degree to which wildlife concentrate their use of individual sources.

Upland wildlife also require habitat and forage. WICA's vegetation, which is comprised of at least 480 native plant species plus additional non-native species and is a mixture of warm-season ($C_4$) and cool-season ($C_3$) grasslands, and forests or woodlands dominated by ponderosa pine *(Pinus ponderosa*) (Figure 1-1), provides these for at least 180 resident or breeding vertebrate animals (http://imtest/im/units/ngpn/parks/wica.cfm). The wildlife also shape the vegetation. Grazing by the park's bison (*Bison bison*) and elk (*Cervus elaphus*) herds influences grassland structure and composition. Browsing by wild ungulates affects recruitment and growth of deciduous trees and shrubs and therefore their extent on the landscape (Ripple and Beschta 2007). Constant, widespread clipping of vegetation, as well as more localized ground disturbance, within black-tailed prairie dog (*Cynomys ludovicianus*) towns creates unique plant communities that support wildlife species – including the critically endangered black-footed ferret (*Mustela nigripes*) – adapted to these special conditions. Finally, much of WICA's diversity stems from its location at the southeast edge of the Black Hills (Figure 1-1). Here, the dynamic border between prairie and ponderosa pine forest or woodland is highly dependent on fire (Bock and Bock 1984; Brown and Sieg 1999).

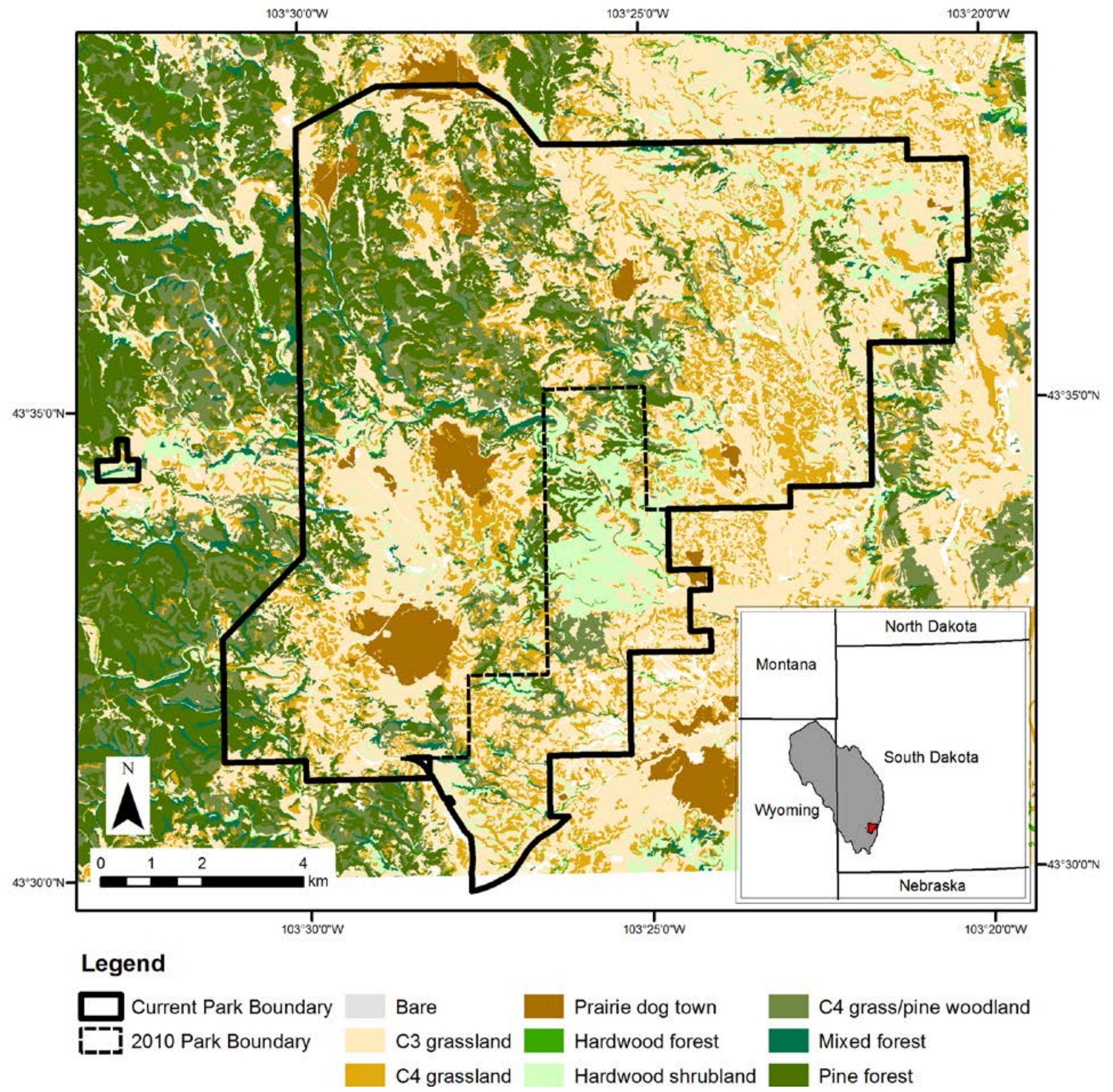

**Figure 1-1.** General vegetation types at Wind Cave National Park based on vegetation mapping from 1997 aerial imagery (Cogan et al. 1999).

Inset shows location of park (red) within the Black Hills (gray). Coordinate System: NAD 1983 UTM Zone 13N. Alternative grayscale image in Appendix A.

All of these interactions are affected by short- and long-term climatic conditions. Grassland plant production is highly responsive to precipitation (Webb et al. 1983; Sala et al. 1988; Smart et al.

2007). Trees germinate and establish during wet periods and die from drought or climate-induced pest or pathogen outbreaks (Brown 2006; Negrón et al. 2008; Allen et al. 2010). Animals succumb to diseases influenced by climate (Harvell et al. 2002; Snäll et al. 2008). Finally, fire frequency, severity, and extent react to fuel loads, fuel moisture, vegetation structure, air temperature, wind, and lightning ignitions.

### 1.2 Natural resource management in a changing climate

WICA's relatively small size and unique purpose within its landscape requires hands-on management, particularly of aboveground natural resources. Exotic plant management targets undesirable species with chemical, mechanical, biological, and fire treatments (National Park Service Northern Great Plains Parks 2005). The size and demographic makeup of the bison herd, which is critical to the conservation of the species because of its high levels of unique genetic variation and low level of introgression of cattle genes (Halbert and Derr 2007; Halbert et al. 2007), is managed with periodic culling (National Park Service 2006a). Elk are chased out of the park to reduce their grazing and browsing pressure on the park's vegetation (National Park Service 2009). Prairie dog towns are treated with pesticides to prevent plague outbreaks, but towns' extent may also be reduced via poisoning to reduce conflicts with park neighbors or if towns exceed the target extent set to maintain forage for other wildlife species and preserve diverse vegetation types within the park (National Park Service 2006c). All wildland fires are suppressed as soon as possible because of the park's small size, but a prescribed fire program aims to restore and maintain native vegetation by applying fire under controlled conditions (National Park Service 2006b).

A rapidly changing climate presents an added challenge to the management of all of these WICA natural resources because it is characterized by large uncertainties. These uncertainties come in many forms. First is the uncertainty about the climate itself, stemming most importantly from uncertainty about future greenhouse gas emissions, but also from incomplete understanding of how global, regional, and local climate will respond to these emissions over the coming decades. This incomplete understanding is reflected in the fact that different climate models – each of which has a unique combination of assumptions and processes – produce different climate projections for a given time period and location even when the same future emissions scenario drives the simulation. For example, increasing temperatures are virtually certain in the WICA region, with warming even in the coolest models, and there is general agreement among models and emissions scenarios that summers will warm more than winters (Kunkle et al. 2013; Lukas et al. 2014). The degree of warming is uncertain, however. For a moderate increase in greenhouse gas emissions, projected increase in mean annual temperature between the end of the 20th century and the middle of the 21st century for the WICA area ranges from ~1 to 3 °C, or 2 to 6 °F (Lukas et al. 2014). Changes in precipitation are even more uncertain, not only because it is more difficult to represent the complex factors contributing to precipitation patterns in climate models, but also because high historical variability in precipitation (the standard deviation is 24% of the mean for 1950-1999 at WICA) makes it difficult to detect trends driven by anthropogenic forces. Syntheses over multiple climate models project non-significant changes in annual precipitation for the WICA area by the middle of the 21st century, including generally wetter winters and springs but showing disagreement in the direction of precipitation change for summer (Kunkel et al. 2013; Lukas et al. 2014).

Second is the uncertainty about how basic, critical resources, such as water and vegetation, respond to climate change. Again, incomplete understanding of hydrological and ecological systems even in the current climate introduces uncertainty into projections of future water and vegetation. Land use changes, population growth, and a host of other factors also influence future water and vegetation and their reaction to climate change. Finally, there is uncertainty about the implications of many changes, certain or not, for critical park resources and values, including foundational resources and the visitor experience.

Many uncertainties related to natural resource management planning and climate change are beyond the control of those doing the planning. In this situation – when uncertainty is high and control of this uncertainty is low – scenario planning is an appropriate tool for deriving future actions or policies (Peterson et al. 2003; Figure 1-2). In the scenario planning process, a set of plausible, future scenarios centered on the focal issue are constructed around key uncontrollable uncertainties. Scenarios are internally consistent storylines that incorporate the uncertain, external forces and the system's and managers' response to these forces. The set of scenarios is purposely chosen to expand and challenge thinking about the system, and the scenarios often diverge markedly from each other to reflect the range of uncertainty in the system. These storylines are then played out to either assess how existing practices would fare in different scenarios, or to identify actions that would perform well in most or all of the scenarios (Peterson et al. 2003). The actions in the latter approach are often referred to as "no-regrets actions".

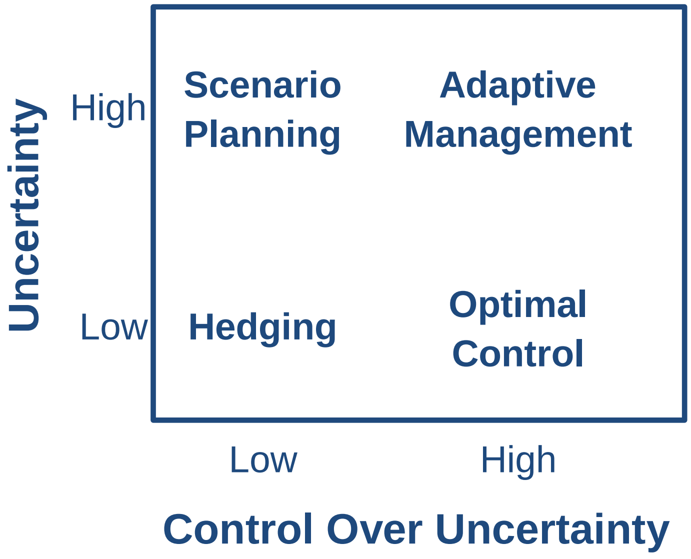

**Figure 1-2.** Approaches appropriate for future strategizing vary depending on the degree of uncertainty and control over factors or processes that create that uncertainty.

Adapted from Peterson et al. (2003).

The National Park Service (NPS) began exploring the use of scenario planning for resource management planning in a changing climate in the late 2000s. In 2009, NPS obtained formal training in the scenario planning process from experts at Global Business Network (GBN). WICA served as one of two case-study parks for this training, which culminated in a multi-day workshop in April of that year.

Although the primary goal of this training was to teach planners and resource managers in federal agencies (primarily NPS) the scenario planning process, participants from WICA did take home some idea of no-regrets actions to incorporate into their natural resource management planning. However, products resulting from this workshop (Global Business Network 2009; Cobb and Thompson 2012) lacked the detail WICA natural resource management staff desire for using the exercise's results in natural resource planning.[1]

Furthermore, the 2009 exercise also raised many questions, particularly regarding the plausibility and internal consistency of the scenarios used in the exercise. Because the emphasis of the 2009 exercise was learning the process of scenario planning, funding and time were not sufficient for rigorous testing and validation of the scenarios used for the case studies – testing that would be required, and is the general practice, when the outcome of the scenario planning is the emphasis (Peterson et al. 2003; National Park Service 2013). Not surprisingly, then, participants in the April 2009 workshop concluded that the qualitative expert opinion used to determine how hydrological and ecological systems would react to given climate scenarios lacked the scientific credibility needed for major NPS natural resource management decisions and the National Environmental Policy Act (NEPA) environmental assessment process through which they must pass.

This report addresses these shortcomings by (1) providing a thorough description of the process of the 2009 scenario planning exercise, as well as its results and management implications for WICA[2]; (2) presenting the results of a follow-up, scientific study that quantitatively simulated the responses of WICA's hydrological and ecological systems to specific climate projections, including one projection developed specifically for WICA's locale; (3) placing these climate projections and the general climate scenarios used in the scenario planning exercise in the broader context of available climate projections; and (4) comparing the natural resource management implications derived from the scenario planning process to those derived from the quantitative simulations.

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[1] The workshop's final report (Global Business Network 2009) was in the form of a PowerPoint slidedeck and lacked in-depth descriptions of many aspects of the exercise; Cobb and Thompson (2012) provided a social scientist's evaluation of the process but did not address the management implications.

[2] This description draws heavily from Global Business Network (2009), but it is supplemented by (1) notes taken at and documents produced before and during conference calls and meetings of the WICA core team, which the first author on this report led; and (2) important points from conversations among WICA park staff and the WICA core team lead after the April 2009 workshop.

# 2. Scenario Planning for Resource Management in a Changing Climate

## 2.1 Scenario Planning Background

As described above, scenario planning is appropriate when uncertainty about the future is high and control of forces that will determine that future is low. Originating in military applications, scenario planning became more widely known and used in a variety of sectors after Shell Oil Company used it to anticipate and emerge strong from the 1970s oil crisis (Bradfield et al. 2005). The method is often contrasted to the more traditional approach of reducing uncertainty, in which scientific models are refined and probabilities of future events are calculated with the goal of improving predictions and building a consensus around a reasonable estimate of the future. In contrast, scenario planning aims to account for low probability, but still plausible, occurrences that could have a high impact on the outcome of the issue being addressed (Jones and Preston 2011). It also aims to more easily consider social, technological, economic, environmental, and political factors over a relatively long time frame (Kass et al. 2011) while allowing for social and biological adaptation, as well as changing ecological relationships and novel ecosystems (Brooke 2008).

Although various methods are used for generating and using scenarios for planning, the school of thought following Shell Oil's methods (called "intuitive logics") is perhaps the most widely known in business, partly because it was widely promoted by the company (Bradfield et al. 2005). Global Business Network (GBN), the company hired by the NPS to provide formal training in scenario planning, is a direct descendent of the Shell Oil group. Therefore, the scenario planning process reported here follows this school. GBN's version consists of five steps; the first three build the scenarios, the fourth derives the implications of the scenarios for what actions to take, and the fifth is follow-up monitoring.

## 2.2 Building the Scenarios

The first three steps in GBN's scenario planning process are orientation, exploration, and synthesis.

### *2.2.1 Orientation*

The first step in the process was orientation – focusing the topic around a single strategic issue. Park management in the face of climate change was the issue pre-determined by the organizers of the training, who also chose WICA to be one of the case study parks. However, later in the process, WICA staff and others focusing on the WICA case study narrowed the issue further to emphasize natural resources over cultural resources, visitor protection, and maintenance for this exercise.

### *2.2.2 Exploration*

The second step was exploration – determining critical, driving forces ("drivers") that affect the future of park management in a changing climate. This process began with a workshop of 17 representatives from the NPS, U.S. Geological Survey (USGS), U.S. Forest Service (FS), U.S. Fish and Wildlife Service (FWS), and GBN in January 2009. Most participants had general expertise related to climate change, not to the two case study parks (WICA and Assateague Island National Seashore, or ASIS). After much discussion, participants in this workshop decided that drivers fell into two broad categories, societal and climatic/ecosystem response. Because of the importance of and great uncertainty about many of the driving factors in both of these categories, workshop participants also decided to use a "nested" approach for building scenarios for the two case study parks. Local-level, climate/ecosystem scenarios would be constructed by individuals with expertise relevant to the individual parks based on the most important and uncertain forces for those locations, whereas higher-level scenarios focusing on societal forces would be constructed by participants in the January workshop.

Therefore, in answer to the question, "What will be the social and political landscape around climate change in the next 25 years?", January workshop participants identified two critical drivers with great uncertainty about their direction in the future. For each of these drivers, the group characterized the uncertainties by describing two different alternative states (Table 2-1). The "Nature of Leadership" driver described the degree of commitment senior leaders (i.e., decision-makers for nations) have toward reducing climate change and its impacts; how much nations align on approaches to dealing with climate change; and whether short- or long-term concerns have the higher priority in decision-making. The "Degree of Societal Concern" driver described the degree to which individuals feel the impact of climate change on their lives, and therefore how concerned they are about climate change compared to other issues.

**Table 2-1.** Alternative states for two societal drivers used in building high-level scenarios.

| Driver | State 1 | State 2 |
|---|---|---|
| Nature of Leadership | Political forces and controversy lead some national leaders to lack commitment to reducing climate change and its impacts, but this degree of commitment and therefore decisions and actions vary widely across nations. Governments and business focus their attention on other concerns that appear more immediately important. | Political leaders consistently make tough decisions to address the long-term challenges from climate change, working together in coordinated, global approaches. This commitment is reflected in budgets, priorities, and inter-agency cooperation. The media holds politicians and business leaders accountable for climate change impacts. |
| Degree of Societal Concern | Climate change impacts are considered minimal, with effects on energy and other resources being felt only by a small proportion of the population. The public is generally not interested in, or feel incapable of, making a difference through their individual actions, being more concerned about other pressing issues seen as unrelated to climate change. | Climate change is having a high impact on the majority of individuals. Effects are felt through energy demand, resource constraints, and population movements. Public reaction to weather phenomena and images of global change is powerful, and individuals feel able to make a difference in how much these impacts will continue into the future. |

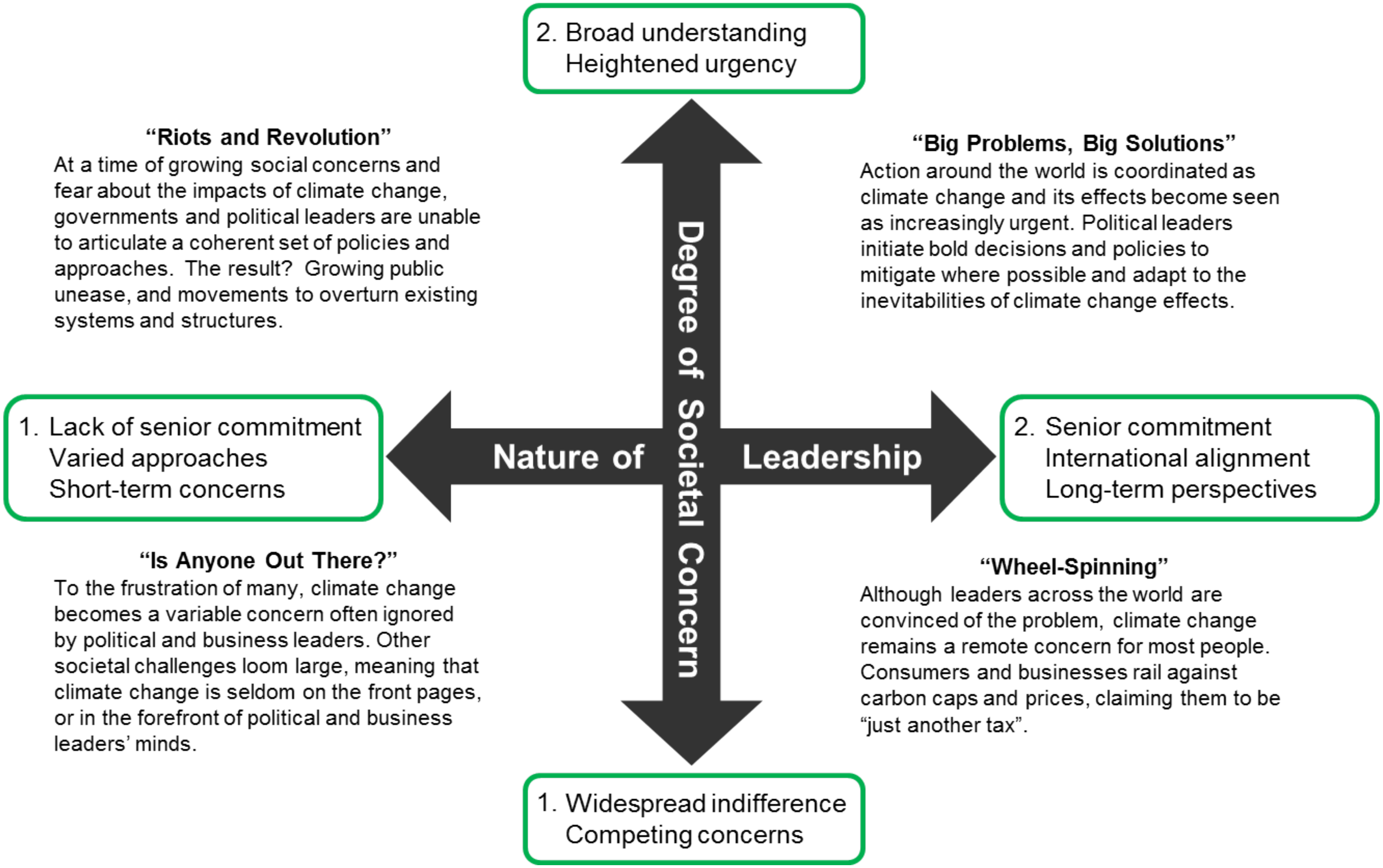
Critical driving forces relevant to WICA's local ecosystem were then determined through a series of meetings and conference calls of the WICA ecosystem response team. This team consisted primarily of WICA natural resource staff and a local USGS scientist, but it also included other WICA staff (superintendent, chief of interpretation), other USGS scientists, GBN trainers, and regional- or national-level NPS experts.

The process began with team members constructing a table of items expected to be affected, directly or indirectly, by climate change (Appendix B). Items were arranged by areas of responsibility (sector) within the park. The natural resources sector had the longest list of items and included the sub-sectors of hydrology and water resources, the cave, air resources, paleontological resources, vegetation, wildlife, disturbance, and soil. Other sectors were cultural resources, facilities, visitor and resource protection, interpretation and education, and administration. Because natural resources dominated the table, the WICA team decided to focus their attention on this sector when determining what climatic variables were most important and uncertain. Team members then compiled available information about climate influences on the items in this sector, but a formal, organized literature review on the topic was not conducted.

Next, the team considered a table of climate drivers. This table was compiled by the Wyoming state climatologist from published climate projections (IPCC 2007). It described, for a variety of climate variables, the general direction of the change expected, a quantitative range of values for the expected change, and comparison of this range to recent changes, seasonal patterns of the change, and a qualitative estimate of the confidence in the information (Appendix C). To accommodate the climate information available, the time frame for these changes was longer (40 years) than that used for the higher level, societal drivers. Based on the climate drivers table (AppendixC), the list of climate-sensitive items (Appendix B), and the information compiled by team members, as well as guidance from GBN to focus on drivers with the greatest uncertainty and impact on the items in Appendix B, the team chose “Drought Severity” and “Extreme Precipitation Events” as the two critical climate drivers for WICA. This choice was influenced by two crucial assumptions: (1) Increasing temperatures will have a significant impact on many aspects of park natural resources. However, because increased temperatures are virtually certain, temperature was not chosen as a critical driver. Instead, increased temperatures were assumed in all scenarios. (2) Because of increased temperatures, it was assumed that effective precipitation (i.e., water available for plant, animal, and human use) will decrease. Thus, the Drought Severity driver was described in terms of degree of increase in drought severity (mild to extreme), and a “wetter” scenario was not considered.

### *2.2.3 Synthesis*

The third step in the GBN scenario planning process is to synthesize. In this step, the drivers chosen in the previous step are used as “axes” that, when crossed, produce divergent but plausible scenarios. The scenarios are then fleshed out with internally consistent storylines describing expected conditions and impacts in the given circumstances. Memorable names are assigned to the scenarios to capture their essence and to make them easily distinguishable and discussable. Four higher-level, societal scenarios resulted when the alternative states of “Nature of Leadership” and “Degree of Societal Concern” were combined (Figure 2-1).



**"Riots and Revolution"**

At a time of growing social concerns and fear about the impacts of climate change, governments and political leaders are unable to articulate a coherent set of policies and approaches. The result? Growing public unease, and movements to overturn existing systems and structures.

**"Big Problems, Big Solutions"**

Action around the world is coordinated as climate change and its effects become seen as increasingly urgent. Political leaders initiate bold decisions and policies to mitigate where possible and adapt to the inevitabilities of climate change effects.

**"Is Anyone Out There?"**

To the frustration of many, climate change becomes a variable concern often ignored by political and business leaders. Other societal challenges loom large, meaning that climate change is seldom on the front pages, or in the forefront of political and business leaders' minds.

**"Wheel-Spinning"**

Although leaders across the world are convinced of the problem, climate change remains a remote concern for most people. Consumers and businesses rail against carbon caps and prices, claiming them to be "just another tax".

**Figure 2-1.** High-level scenarios for the future social and political landscape around climate change.

In developing the park-level, climate-driven scenarios, it became evident that the chosen drivers did not produce divergent-enough (following GBN's guidance) storylines. Consequently, the "Extreme Precipitation Events" driver was replaced by a "Precipitation Patterns" driver and alternative states for these two drivers described (Table 2-2).

**Table 2-2.** Alternative states for two climate drivers used in park-level scenarios.

| Driver | State 1 | State 2 |
|---|---|---|
| Drought Severity | Mean annual precipitation and interannual precipitation variability are similar to historical records, but some drought events and impacts are intensified by increasing temperatures. | Today's "moderate" droughts become the norm and today's "extreme" droughts become more common. |
| Precipitation Patterns | Precipitation seasonality, intensity, and frequency change little from historical patterns. | Annual precipitation remains about the same, but seasonality shifts so that the proportion falling in winter increases compared to the proportion falling in summer. Summer events are less frequent but more intense. |

The four park-level scenarios resulting from this iterative driver-scenario discussion were different ecosystems: "Mixed-grass Prairie", "Shortgrass Prairie", "Shrubland", and "Novel Ecosystem" (Figure 2-2). The WICA team derived these by finding a region of the country with a current climate that best matched the description of each quadrant in the figure resulting from crossing the two climate driver axes. The natural vegetation currently occupying each of those locations was then assigned to that scenario, and the WICA team used their professional expertise (and what literature they could find) to play out the consequences of that new vegetation type and the associated climate for other items on the "climate-sensitive list" of Appendix B.

Before describing these scenarios, it should be noted that, despite the extremely high importance of Wind Cave (the cave itself) to WICA's mission, identity, and visitation (and therefore staffing), none of the scenarios included changes to the cave. Because the air temperature in the cave is a function of the long-term mean annual outside air temperature and the temperature and flow rate of water ascending from below, it is highly likely that the air temperature in the cave will increase in a warming climate over the 40-year time frame of the scenario planning exercise. As in the aboveground environment, increased air temperature leads to higher evaporation rates in the cave, which in turn affect the composition and rate of the mineral deposits that make up the cave's speleothems. These deposits are also sensitive to the amount of water entering the cave, which depends on aboveground conditions. However, it is not clear how long it takes for the air temperature and humidity in this large cave to adjust to the more quickly changing aboveground world. Even though cave temperature and drip rates do react to climate change, WICA team members assumed that the impacts of their changes on speleothems would be unnoticeable within the 40-year time frame used for the scenario planning exercise because these features are formed and eroded on geological time scales (hundreds-millions of years). Cave biota would presumably be more sensitive. However, cave biota are limited to three categories (1) microbes found only along tour routes and therefore presumably not endemic to the cave; (2) individuals of essentially aboveground species whose occurrence is limited to the vicinity of above-ground interfaces; and (3) an extremely low-biomass but high-diversity microbial community located throughout the cave, including in the cave's lakes. The third category is of primary interest to natural resource management staff, but information about it was limited at the time of the scenario planning exercise and still is (Barton 2012).

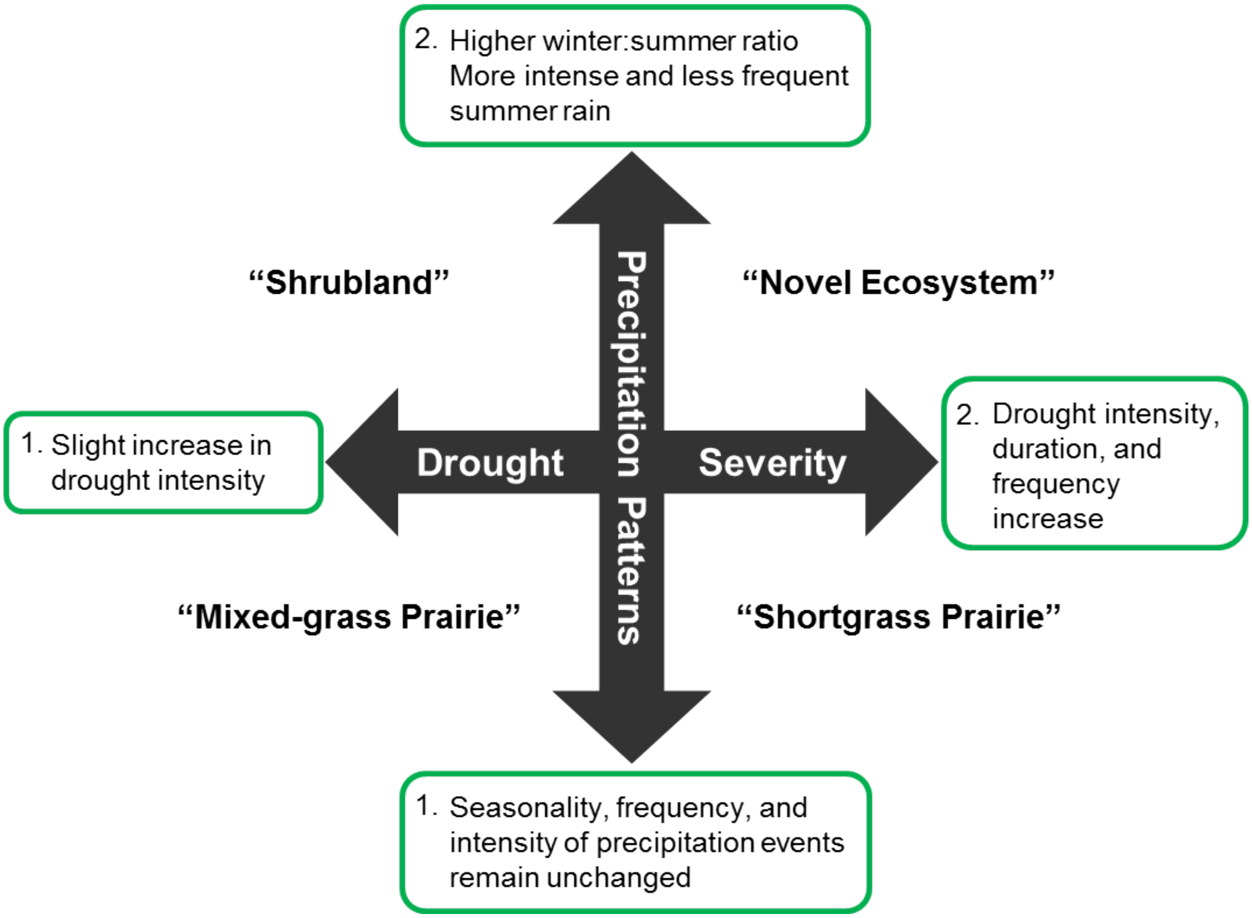


**Figure 2-2.** Park-level scenarios for future climates varying in precipitation patterns and drought severity. Full descriptions of the scenarios are in the text.

**Mixed-grass Prairie** served as the base case scenario – it included all the "very likely" changes described in the climate drivers table (increased temperature, evaporation, length of growing season, and heat events), but it assumed that these changes would be slow and mild enough that, for the focal 40-year time frame, they would remain within the range of variability that park managers and the current ecosystem (northern mixed-grass prairie and ponderosa pine woodland/forest) have experienced in the historical past. Even with these relatively mild changes, however, the increased evapotranspiration and higher temperatures would moderately reduce streamflow and surface water availability in general, increase moisture stress on trees (and therefore susceptibility to insect attack), increase the length of the fire season, decrease productivity of the grasses that feed the park's charismatic fauna (bison, elk, pronghorn, prairie dogs), and stress riparian vegetation. Consequently, park vegetation may gradually shift to more short-statured, warm-season grasses and fewer trees, but at a much slower pace than that assumed in the Shortgrass Prairie scenario.

In the **Shortgrass Prairie** scenario, greater temperature increases and perhaps decreased total precipitation would yield a hotter, drier climate similar to that of current-day northeastern Colorado. Short-statured, warm-season grasses such as blue grama (*Bouteloua gracilis*) and buffalo grass (*Bouteloua dactyloides*) characteristic of the shortgrass steppe region would become dominant. Although these species are well-adapted to grazing, they are less productive than some of the mid-height, cool-season grasses that currently dominate much of WICA (Smart et al. 2007). Therefore, the park's vegetation would be able to support fewer grazers, including bison and other charismatic fauna. Frequency or severity of wildlife diseases could increase. Forest, both the dominant ponderosa pine (*Pinus ponderosa*) and the already small stands of deciduous trees, would be more restricted by moisture availability, more susceptible to pests and pathogens, and at greater risk for stand-replacing fire; its extent would decrease. Greater evapotranspiration would cause a drop in the Madison aquifer (and therefore the cave's lake) and a noticeable decrease or disappearance of stream and spring flow. Reduced surface water availability would stress any currently existing riparian vegetation (which is rare) both directly and indirectly as animal trampling is concentrated into smaller areas.

The **Shrubland** scenario was based on the climate currently more characteristic of central and southwestern Wyoming, where winter snows provide a larger proportion of the annual precipitation than in the southern Black Hills, largely because of substantially lower summer precipitation. Spring snowmelt and precipitation, followed by a summer dry period, leads to water being stored deeper in the soil horizon than in the grassland ecosystems to the east; deep-rooted shrubs like big sagebrush (*Artemisia tridentata*) therefore dominate regions with this precipitation regime (Paruelo and Lauenroth 1996; Schlaepfer et al. 2012). Thus, in this scenario, shrubs like big sagebrush, and possibly subshrubs already common at WICA (fringed sage, *Artemisia frigida*, and broom snakeweed, *Gutierrezia sarothrae*) would increase to become dominant as currently abundant perennial grasses would decrease. This precipitation regime and the more open ground of sagebrush systems are conducive to invasion by exotic annual grasses, particularly cheatgrass (*Bromus tectorum*), which already occurs at WICA. Thus, this scenario assumed these would become more abundant as well. The shift in dominant plant lifeform would force shifts in the type and numbers of wildlife the park could support, with browsers (e.g., pronghorn) becoming more common than grazers (e.g., bison, elk). More clumped vegetation, with greater areas of bare ground, would lead to greater soil erosion. The WICA team was not comfortable describing the consequences of this scenario for the water table. Some decrease in stream and spring flow would be consistent with the greater evapotranspiration associated with higher temperatures, and more intense flash floods would be consistent with more intense summer storms and less vegetation on the ground to slow water flow. The team was not sure how this climate scenario would impact ponderosa pine vigor and extent directly.  Indirect effects via fire were also uncertain, given that fuels would be drier (and therefore fires more severe) but less continuous (and therefore less likely to carry a fire).

Finally, the most drastic scenario was the **Novel Ecosystem**.  This scenario assumed that the climate changed quickly, becoming something like that of the southwestern United States by the year 2050.  Climate change would be so rapid that species migration would not keep up.  Many species, particularly those associated with cooler and wetter climates (such as deciduous trees and tall prairie grasses) would disappear as the small number of species currently at WICA that are adapted to this climate increase in their dominance.  Cosmopolitan weeds and invasive species could fill empty niches, creating a novel combination of plant species.  Drier conditions would cause a temporary intensification of the fire regime; together, these would drive widespread loss of tree species.  Fire intensity and frequency would eventually decrease, however, when fuel loads became low or discontinuous enough that fire no longer spread.  Greater amounts of exposed soil would make it more susceptible to wind and water erosion.  Surface and ground water would decrease substantially, to the point that there were no perennial streams in the park.  Lack of water, along with drastically decreased forage availability for bison, elk, pronghorn, and many other important wildlife species, would prevent the park from sustaining these species without major intervention (e.g., supplemental feed and water).

These park-level scenarios, which received the most time and attention of all the scenarios in this training process, were then nested in the higher-level framework at the April 2009 workshop.  At this workshop, the WICA ecosystem team was joined by a few new participants in deciding which of the 16 possible nested scenarios would be explored for the final steps of deriving management implications.  The new team members were not familiar with WICA and therefore offered new perspectives not only in making this decision but also in deriving those implications.  Four scenarios were chosen to span a range of change in ecosystem and the social/political landscape (Table 2-3).  Due to the limited amount of time at the workshop, these scenarios were not fully developed story lines, but they did provide sufficient material for considering the broader picture of how natural resource management could be influenced by the social and political landscape in addition to climatic drivers.

**Table 2-3.** Storylines for "nested" scenarios, combining higher-level social and political scenarios with park-level climate scenarios, chosen for further exploration at the April 2009 workshop.

| Nested Scenario | Storyline |
|---|---|
| "Left High and Dry"<br>Riots and Revolution X<br>Shortgrass Prairie | Society is greatly concerned about climate change but there is little global or national leadership to address the associated challenges. At the same time, WICA is finding it difficult to maintain its foundational wildlife species at desired population sizes and to deal with more difficult fire seasons. Visitors and park staff are impacted by more fire restrictions (i.e., while camping), area closures when fires are occurring, and heat-related health issues and incidents. |
| "Managing Expectations"<br>Big Problems, Big Solutions X<br>Mixed-grass Prairie | Climate change issues are high profile around the world, leading international and national leaders to impose more regulations and encourage action related to climate change. In contrast, at WICA, there is not much discernible effect from climate change. The local community is concerned about the intrusiveness and relevance of international and national policy into their lives. Although park staff are challenged with following new policies in a manner that is relevant to their situation, high-level attention to climate change does allow for proactive management of its impacts. Park interpretation and community interactions would need to emphasize to the public that climate change is still an issue while at the same time acknowledge public concerns about high-level intrusiveness. |
| "Endless Problems, Endless Opportunities"<br>Big Problems, Big Solutions X<br>Novel Ecosystem | Climate change has turned everything on its head. Societal concerns are high and national and international political leadership is committed to solving or limiting the consequences of climate change. At WICA, climate change effects have drastically altered the ecosystem to the point that tough decisions about the mission of the park for above-ground resources must be made. Fortunately, the support of high-level authorities provides a great deal of opportunity for park managers to adopt radical approaches and policies to deal with the challenges. Park interpretation messages would need to address these changes and decisions, but with the proper message, visitor experiences could be maintained. |
| "Passive Reactive"<br>Is Anyone Out There? X<br>Mixed-grass Prairie | Concerns about climate change are low at both the global and local level because the effects appear minimal, or at least slow in happening. Consequently, leaders and managers focus their concern on more noticeable, short-term issues and do little planning that incorporates climate change effects. Park interpretation could emphasize how park natural resource monitoring is tracking climate change effects. |

## 2.3 Determining Appropriate Actions

In many cases, the ultimate goal of a scenario planning exercise is to determine what actions an organization should take when facing great uncertainty. To do this, the WICA group examined important differences and commonalities among both the nested and park-level scenarios – differences and commonalities not only in key resource or process responses (e.g., water, bison herd, fire), but also the actions that park managers would need to take to deal with those responses. Two key differences relating to natural resource management stood out: the amount of lead time WICA staff would have to educate the public and build support for its actions, and the degree of hands-on management of wildlife. GBN then assisted the group in organizing the actions that would be appropriate under any scenario into four categories:  resiliency, research and study, indicators to monitor, and capacity-building.[3]

Robust, no-regrets actions geared towards improving resiliency – the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain function, structure, identity, and feedbacks (Walker et al. 2004) – focused on natural resources.  **Achieving current target population sizes for managed herbivores** (bison, elk, prairie dogs) would reduce pressure on the existing mixed-grass prairie vegetation.  **Developing surface water sources and means for supplemental feeding** would enable the maintenance of high-priority wildlife (i.e., bison) through drought periods, at least in the short term. These would involve a marked departure from current park management practices, which are largely limited to reducing populations when necessary, and may require more resources than are available or may not be deemed acceptable practices.  Consequently, **prioritizing species and/or populations** by management importance would provide for a deliberate, well-planned reaction if/when conditions make it impossible for in-park resources to support the current target population sizes of all managed species.  **Thinning the park's ponderosa pine forest**, probably via prescribed fire, would reduce its susceptibility to crown fire and mountain pine beetle infestation.  **Emphasizing more drought-tolerant species in seed mixes** when restoring vegetation in disturbed areas would improve the long-term viability of these plantings.  **Controlling invasive plant species** that compete with native vegetation and may not provide wildlife forage would reduce the stress on native plant species.  **Restoring and enhancing riparian vegetation** would buffer streams from flood events.

Three types of actions were included in the research and study category.  **Investigating and evaluating options for surface water development and supplemental wildlife feed**, as well as **assessing streams, springs, and seeps** (quantity of water, susceptibility of surrounding vegetation), would provide critical information for implementing some of the actions in the resiliency category. **Photo documentation of cultural resources, collecting voucher specimens of biota now in the park, and making historical records easily accessible** (i.e., stored and served electronically) would help establish baselines or reference conditions.  Knowing these baselines could be useful in two ways:  (1) restoring resources to those conditions in the immediate future might make them more resilient to climate change; or (2) it may reveal that some resources are unlikely to be sustainable into the future because of their reliance on a very specific, past climate (Baron et al. 2009).  **Achieving better understanding of climate change impacts on cave resources** represented a desire for better understanding of how climate change will impact park resources in general, but it also highlighted the discomfort of some other workshop participants with the WICA team's assumption that cave resources would not be impacted in the target timeframe.

Actions for building capacity focused on partnerships and park staff.  **Building and strengthening partnerships with neighboring individuals and communities** could help provide resources for

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[3] A few of these actions do not appear in in GBN's final report (Global Business Network 2009) because they were identified by park staff in conversations shortly after the workshop.

alternative water sources and other responses needed as climate change impacts are felt. **Increasing the number of fire staff and/or the length of time they are active** would provide greater protection in the case of wildfire and enable WICA and other parks in the region to achieve prescribed fire objectives. **Incorporating climate change into all staff training**, such as at the annual park-wide training when summer interpretive staff arrive, would improve awareness of climate change issues within park staff and get the message out to the public through interpretive programs.

**Increasing staff and financial support for monitoring various park resources** is not only a capacity-building action in that it would improve the park's ability to detect climate-change related changes and react to them before critical thresholds are crossed, but it would also improve WICA's ability to follow through with the fifth step of the GBN scenario planning process. In this monitoring stage, WICA would evaluate which scenarios or aspects of scenarios are the most valid and determine whether actions are having their desired effects. Actions could then be adjusted according to this and any other new information available. **Important indicators to monitor identified at the workshop were mountain pine beetle-infested trees, invasive plants and other pest species, surface and cave water quantity and quality, and archaeological and paleontological sites.** This list focused on items without dedicated monitoring efforts at the time of the workshop. Monitoring of park-wide plant community composition and structure, bison and elk herd sizes, prairie dog colony extent, and streamflow in Beaver Creek were already or soon to be implemented.

## 2.4 Evaluation of the Scenario Planning Exercise

The final portion of the April 2009 workshop focused on asking whether scenario planning, particularly as taught by GBN through the WICA and ASIS case studies, could be a useful tool for incorporating climate change into NPS natural resource management planning. The answer to the question was "yes". Specifically, GBN's summary stated:

> "The scenario approach offers some promise in complementing existing technical and scientific information. Many felt that [the] scenario approach could help explain outcomes to management. … However, more work would need to be done in validating the findings to ensure that the approach had credibility." (Global Business Network 2009, p. 38)

Consequently, NPS has continued to use the GBN scenario framework since then and has recently published a handbook with guidance for its further use (National Park Service 2013).

One recommendation for follow-up work on the exercise was to "clean up and build out some of the scenarios further, paying particular attention to the testing and validation of the chosen scenarios" (Global Business Network 2009, p. 40). The first part of this recommendation may have stemmed from some issues that park-level teams struggled with during the scenario-building process. Specifically, the WICA team struggled to incorporate some important points regarding fire. Acknowledging that fire has played a critical role in prairie vs. forest distribution in this region (e.g., Brown and Sieg 1999), and that fire regimes in this region are highly sensitive to both climate (Brown et al. 2005) and weather, team members realized that a single, large crown fire in WICA's pine forest could have a greater effect on the fate of the park's forest over the next 40 years than could any but the most drastic (i.e., Novel Ecosystem) climate changes. Incorporating wild cards like this is a more advanced technique for building scenarios not used in the basic process followed in the 2009 exercise (National Park Service 2013). Furthermore, the WICA team also realized that the park-imposed fire regime (through wildfire suppression and prescribed fires) might also determine whether some scenarios could even occur. Maintaining the current prescribed fire regime, which is geared towards reducing ponderosa pine forest density and preventing pine encroachment into grasslands, could prevent shrubs like big sagebrush (Shrubland scenario) or desert-like plants envisioned for the 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 invasion. Specific management practices were not incorporated into the scenarios, however, given that the goal of the scenario planning exercise was to determine what the best management practices would be.

The second part of the recommendation was in part based on the discomfort some WICA team members expressed about the plausibility and internal consistency of the scenarios they developed. For example, they were not at all certain that climate changes within the range of what has been projected by quantitative climate models were capable of producing some of the scenarios described, particularly when ecological inertia of long-lived plants and animals is considered. Although this discomfort does not necessarily undermine the no-regrets actions derived from the scenario planning exercise, the exercise itself did leave park staff with lingering questions of what really is a plausible, mid-century future and how their management practices could impact that future. Therefore, some members of the WICA core team pursued a more quantitative approach for projecting impacts of climate change on the park’s natural resources.

# 3. Quantitative Projections of Climate Change Impacts

## 3.1 General Overview of Process

Quantitative climate projections come from models built on the first principles of physics (such as conservation of mass and energy) and calibrated and validated using historical, empirical data. Historical observations, measurements made in experiments, and principles of physics and biology provide the information necessary to build, calibrate, and validate models of hydrological and ecological systems. A hydrologic- or ecosystem-response model can then be used to project conditions of an assumed future climate and natural resource management scenario using quantitative data output by climate models.

Specifically, the basic input for projecting climate change impact is a global greenhouse gas (GHG) emissions scenario (Nakićenović and Swart 2000) or a representative concentration pathway (Moss et al. 2010). Emissions scenarios begin with realistic, internally consistent scenarios of demographic, economic, and technological driving forces; resulting GHG emissions are derived from these scenarios. In contrast, representative concentration pathways begin with radiative forcings (the change in balance between incoming and outgoing radiation to the atmosphere caused by changes in atmospheric components, such as carbon dioxide); the internally consistent sets of GHG emissions and concentrations that could produce these radiative forcings are independent of specific socioeconomic scenarios. Both emissions scenarios and concentration pathways provide GHG concentrations that serve as input for global climate models, also known as general circulation models (GCM's). GCMs dynamically simulate the flow of mass (e.g., air, water, GHG, particulate matter) and energy through the world's atmosphere and oceans (Figure 3-1, top).

The spatial resolution of these global-scale climate models – 125 to 400 km (78-248 miles) – is too coarse to capture topographic and other land-surface features that influence climate at a specific location. For example, the Black Hills strongly affect the climate at WICA, but GCMs do not simulate these effects because the Hills are smaller than the grid-cell spacing of the GCM – the model does not distinguish their higher elevation compared to the surrounding plains. Output from the GCMs therefore needs to be "downscaled" to account for these finer-scale features and provide the location-specific, fine-scale climate data needed by hydrologic- and ecosystem-response models (Figure 3-1, middle). Two techniques are used to do this; statistical and dynamical downscaling. Statistical downscaling derives statistical relationships between small-scale (e.g., at the level of a weather station), observed values of climate variables and the same variables simulated for a given place and time by the GCM. These relationships are then applied to the GCM's projected climate output to estimate the climate at a smaller scale than that of the GCM. This method assumes that statistical relationships based on past climate will remain the same (stationary) in the future. In dynamical downscaling, the equations of fluid dynamics and thermodynamics as used in a GCM are adapted to a smaller grid spacing over the area, or domain, of interest. The GCM's output serves as boundary conditions, defining the climate at the edges of the domain. Although this method might carry the original biases of the GCM through to the downscaled model and is much more computationally expensive, it avoids the stationarity assumption of statistical downscaling methods.

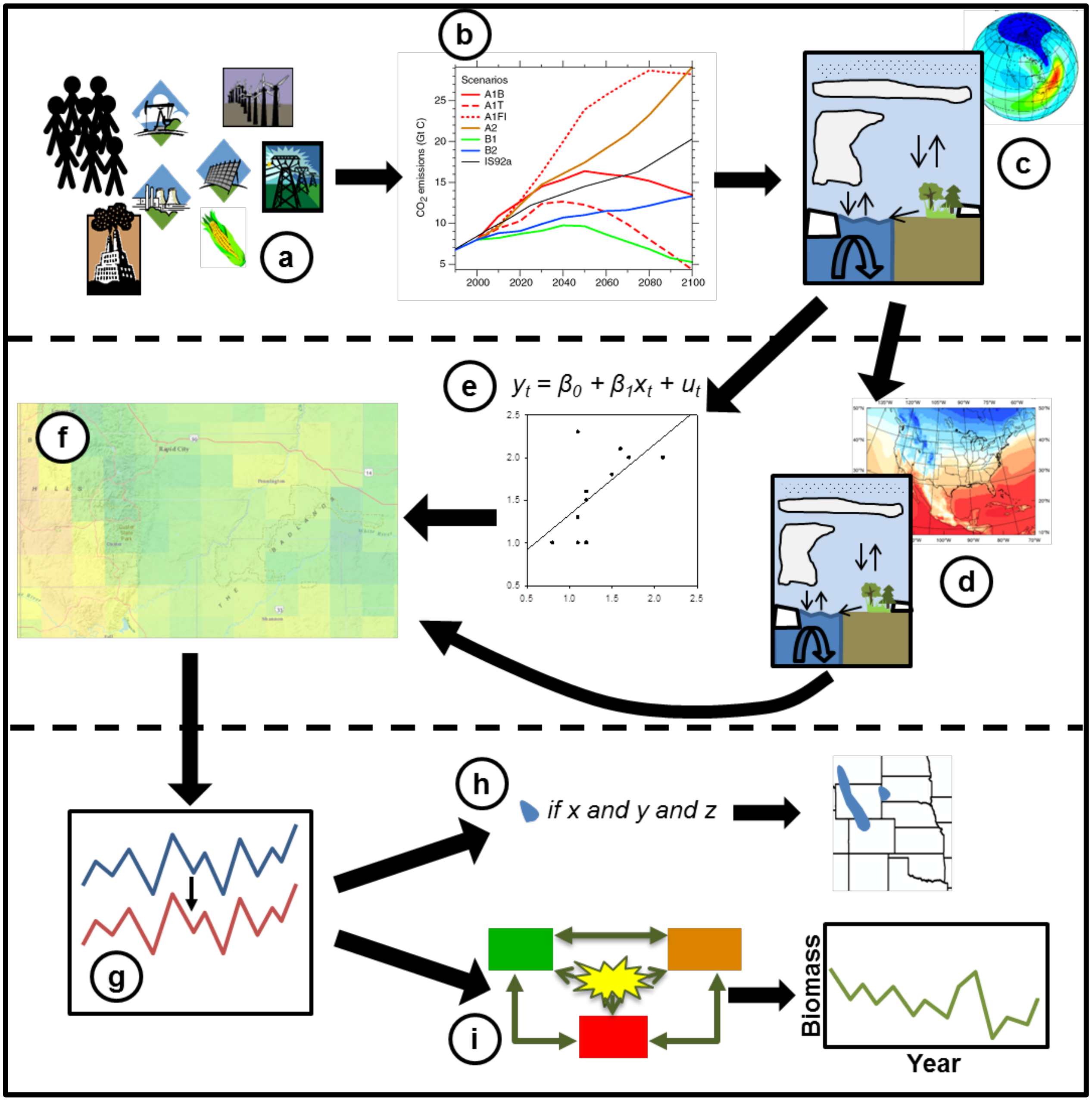

**Figure 3-1.** General schematic of process for quantitative climate change impact projections.

Uncertainty about changes in population, energy use and sources, and technology (a) are reflected in (b) different projections of future greenhouse gas emissions or concentrations (figure from Nakićenović and Swart 2000). Global-scale models (c) simulate contemporary and future climate using these emissions or concentrations and algorithms representing the physical and biological processes governing materials and energy exchange and cycling on a coarse scale. Global climate model output data are downscaled using either a dynamical (d) or statistical (e) approach, providing climate projections at a spatial resolution useful for local and regional planning (f). These projections often require bias correction (g), or adjustment to match the endpoint of historical data with the beginning point of the projection; this is done by comparing overlapping periods of the simulation and historical data. Bias-corrected data are then used in (h) statistical or (i) process-based impact models.

Downscaled climate data then provide input into hydrologic or ecosystem response models (Figure 3-1, bottom). Some response models resemble the statistical climate downscaling approach in that they apply relationships between climate and the responses of interest derived from past data to the future, thus assuming that these relationships remain stationary. Others simulate physical and biological processes that drive the responses of interest; their degree of complexity and computational requirements vary greatly. These process-based models often do not assume that the climate-response relationship will remain stationary. For example, dynamic, process-based ecosystem response models account for the fact that increasing atmospheric $CO_2$ concentrations alter the relationships between temperature or soil moisture and photosynthesis, and therefore plant growth and survival. The exact form of the climate input data for these response models varies. Some require full time series of multiple climate variables from the past to the future end point, others require only decadal mean values of one or two climate variables. Some require these values for just one or two specific locations (like a weather station), and others require these values for the full landscape of the area being simulated. In most cases, some form of bias correction is necessary to ensure consistency between historical, observed climate and future projections.

This project links statistically and dynamically downscaled GCM output to process-based hydrological and ecosystem response models. A GCM was dynamically downscaled using a regional climate model parameterized for the Great Plains region; this regional climate model has spatial resolution fine enough to capture some of the effects of the Black Hills on weather processes. The hydrological response model was calibrated for two specific hydrological features at WICA, Beaver Creek and Calcite Lake (WCL)[4]. The ecosystem response model was customized for the dominant vegetation types at WICA (ponderosa pine forest/mixed-grass prairie ecotone) and run using a variety of parameterizations representing different management scenarios. The results of these simulations provide information to help WICA natural resource managers plan for a changing climate.

## 3.2 Methods

We chose to base projected climate, hydrology, and ecosystem simulations on the A2 emissions scenario (Nakićenović and Swart 2000) used in the IPCC's Fourth Assessment Report (Solomon et al. 2007) to be consistent with regional climate model simulations published by other groups (http://www.narccap.ucar.edu, Hostetler et al. 2011), as well as with (or even somewhat conservative compared to) observed trends in atmospheric $CO_2$ emissions since the A2 scenario was described

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[4] Monitoring of the level of two cave lakes, Windy City Lake and Calcite Lake, began in 1986. Monitoring of Windy City Lake (USGS site 433302103281501) ceased in 1996 when the route to that lake became impassible due to rising water levels. The two lakes merged into one at about this time, after which cave lake levels modeled in this report are based on the Calcite Lake gage, with the exception of 1999-2004. During this 5-year period, when Calcite Lake was also inaccessible due to high water, cave lake level was estimated on the basis of a nearby Madison aquifer well (Long et al. 2012). Windy City Lake and Calcite Lake levels were nearly identical during the time in which both lakes were monitored (R. Horrocks, WICA physical sciences specialist, pers. comm., May 20, 2014). Thus, we refer to the site modeled in this report as "Calcite Lake (WCL)", with "WCL" being the site abbreviation used in previous publications (Long et al. 2012, Long and Mahler 2013).

(Manning et al. 2010). Figure 3-2 shows an overview of the process used to link climate, hydrologic, and ecosystem models in this project.

Most details of the methods used to develop and run each of the models are available in other publications. Stamm et al. (in press) describe the dynamical downscaling of the Community Climate System Model, version 3 (CCSM3; Collins et al. 2004) GCM using the Weather Research and Forecasting (WRF) regional climate model at a 36 km (22 mile) grid spacing. Long and Mahler (2013) describe the hydrologic model, subsequently named the Rainfall-Response Aquifer and Watershed Flow model (RRAWFLOW), and provide specific details about the parameterization and validation for the two WICA hydrologic sites. King et al. (2013b) describe the ecosystem model MC1, its adaptation to WICA conditions, and the results of simulations using climate data from three GCMs. In the rest of this section, we present a summary of the methods for each of this report’s three models (climate, hydrologic, ecosystem), plus the specific details relevant to the new results specific to this report. All projected simulations ran through the year 2050. This period is far enough in the future to expect substantial changes in climate, hydrology, and ecosystems, but close enough that it is within the timeframe for which park managers must plan at the present time, and it matches the time frame used in the scenario planning exercise (Section 2).

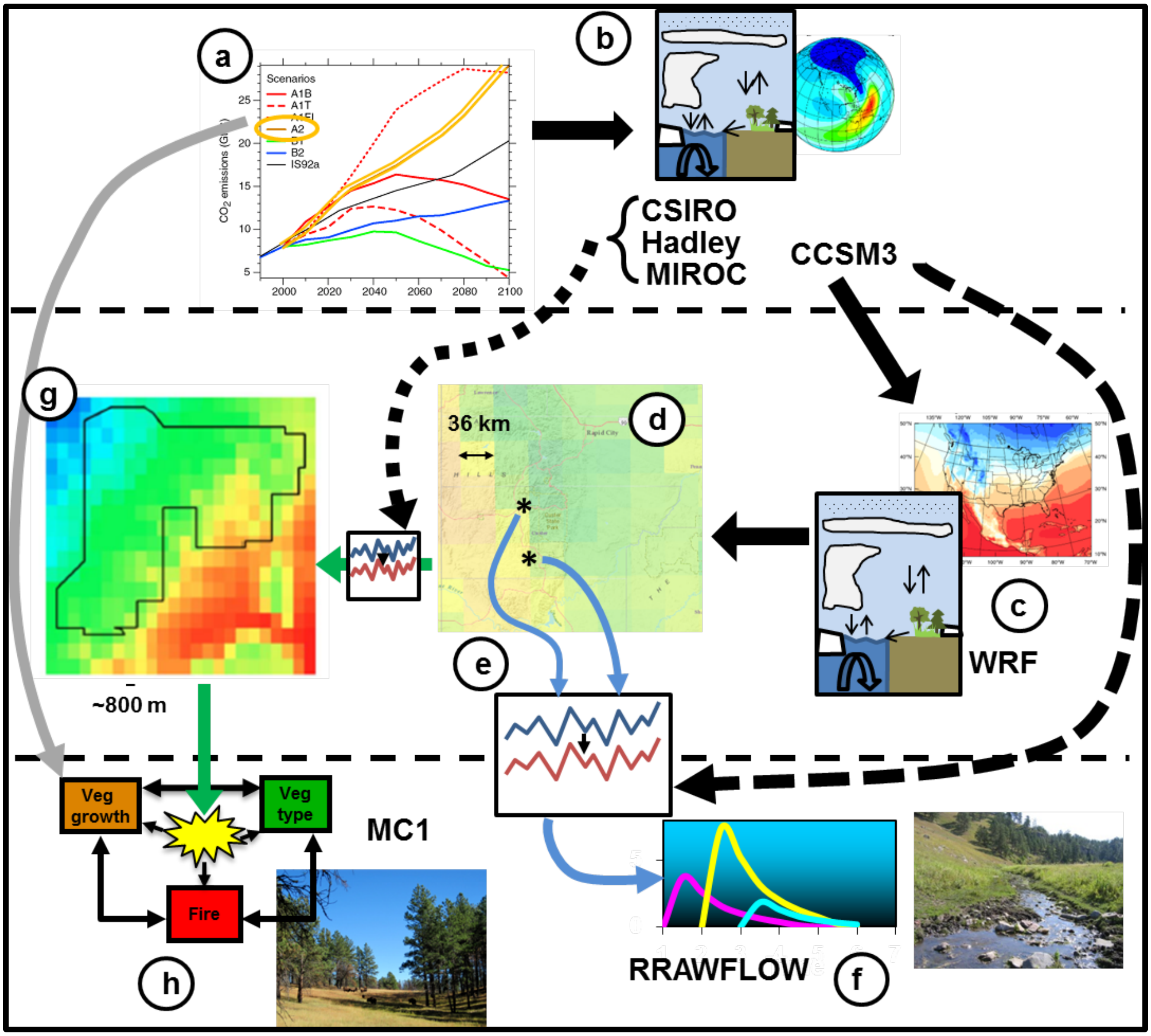

**Figure 3-2.** Schematic of specific quantitative model-linkage process used in this project.

(a) The A2 emissions scenario (highlighted in orange) drove (b) a single member of each of four GCMs. Output data from the CCSM3 model provided the boundary conditions for (c) dynamical downscaling using the WRF regional-scale climate model, which produced (d) a climate projection at 36-km (22-mile) spatial resolution for much of North America. Data from this projection were (e) bias-corrected for two weather stations (***** in d) used in (f) RRAWFLOW to simulate future flow of Beaver Creek and level of Calcite Lake (WCL). For comparison, we also simulated both hydrological responses using bias-corrected data from CCSM3 (dashed arrow). For vegetation response simulations, WRF output data were statistically downscaled and bias-corrected to an ~800 m (0.5 mile) grid cell resolution (g). Climate output from three other GCMs (b) were directly downscaled and bias-corrected to the same resolution (dotted arrow). These gridded data served as climate input for (h) MC1, the dynamic vegetation model used to simulate future vegetation and fire across WICA's extent (2010 park boundary). MC1 also used future atmospheric $CO_2$ concentrations of the A2 emissions scenario as direct input (gray arrow).

### *3.2.1 Climate Input for Hydrologic and Ecological Response Models*

Due to the high cost and long time required to run climate simulations at the high spatial resolution necessary, only one regional climate projection was simulated for this project. To maximize the utility of this single run, we first compared the skill of three global climate models in simulating contemporary climate of the Great Plains for the 1901-2012 time period. Compared to the Canadian Centre for Climate Modeling and Analysis General Circulation Model, version 3.1/T63 (CGCM3; Environment Canada 2013) and the Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1 (GFDL CM2; Geophysical Fluid Dynamics Laboratory 2013), CCSM3 was the most skilled in estimating annual mean air temperature compared to the Parameter-elevation Regressions on Independent Slope Model (PRISM; described by Daly et al. 2008) representation of the 1901-2012 period. All three models had a wet bias in precipitation, with CCSM3's bias being the middle of the three (Stamm et al. in press). Based on its performance for surface air temperature (2 m/6.56 ft height), we chose CCSM3 to serve as the global climate basis for our work. We downloaded the CCSM3 A2 scenario simulation from the Earth System Grid Federation (run number b30.042e; Program for Climate Model Diagnostics and Intercomparison CCSM3 SRESA2 Run 5) and used it to supply the boundary conditions to simulate climate at the regional scale using WRF.

The Advanced Research version of the Weather Research and Forecasting Model (WRF), version 3.4.1 (Skamarock et al. 2008), simulations for the northern Great Plains were based on physics and radiation schemes described by Stamm et al. (in press). One simulation for 1981-2010 (contemporary climate) and a second simulation for 2001-2050 (projected climate) were completed. Both simulations covered most of North America at a 36-km grid spatial resolution. Surface air temperature, precipitation, and vapor pressure (part of a suite of several hydrologic and atmospheric output variables) were output at 3-hour intervals and integrated to daily and monthly time steps for the hydrologic and ecosystem response models, respectively. For comparison, we also calculated daily total precipitation and mean air temperature from CCSM3 output for the grid cells of the global model that cover the WICA region.

Additional statistical downscaling and/or bias correction of the climate models' output was necessary to ensure a smooth transition between the historical and projected climate input used by the hydrologic and ecosystem models, both of which require a continuous time series of past climate connected to the future climate period. For RRAWFLOW, downscaling and bias correction were done for the two weather stations – one at Custer, South Dakota, and one at WICA (Table 3-1) – that provided the best climate information for RRAWFLOW simulations of Beaver Creek and Calcite Lake (WCL). CCSM3 output was downscaled by interpolating temperature and precipitation values from the four grid cells surrounding the weather station. No further downscaling was necessary for CCSM3/WRF output (where "CCSM3/WRF" refers to the WRF model driven by CCSM3 boundary conditions). For both climate models and weather stations, climate model bias was computed as the difference between the climate model output and weather station observations for the 1981-2010 period for the Custer weather station and for the 1984-2010 period for the WICA weather station. The truncated period was used for the WICA weather station because its observations were incomplete before this period. Bias was computed on an annual basis for average air temperature and on a monthly basis for total precipitation. Bias computed for the 1981-2010 CCSM3/WRF simulation was used as a bias correction to the 2001-2050 CCSM/WRF simulation. Once climate model (CCSM3 and CCSM3/WRF) output was adjusted to remove bias, a continuous time series for each weather station was constructed using weather station records through 2010 and projected through 2050 using bias-adjusted climate model output.

**Table 3-1.** Climate and hydrologic records used for bias-correcting climate model output and calibrating and validating RRAWFLOW for each hydrologic response site.

Weather Station # is National Weather Service Cooperative station identification number; Hydrologic Site # is U.S. Geological Survey site number; precipitation estimated from Doppler radar (NEXRAD) and Custer weather station data were used for the "spin-up" period of RRAWFLOW simulations of Beaver Creek prior to the WICA station start of record; Calcite Lake (WCL) level was partially estimated on the basis of an observation well near WICA (Long et al. 2012).

| **Weather Station Name<br>Location<br>Elevation** | **Weather Station #<br>Start of Record** | **Hydrologic Site<br>Type** | **Hydrologic Site #<br>Start of Record** |
|---|---|---|---|
| WICA Headquarters<br>43.5565° N, 103.4914° W<br>1,253 m (4,111 ft) | 399347<br>1 January 1984 | Beaver Creek<br>stream flow | 06402430<br>24 October 1990 |
| Custer, South Dakota<br>43.7744° N, 103.6119° W<br>1,670 m (5,480 ft) | 392087<br>1 January 1943 | Calcite Lake (WCL)<br>hydraulic head | 433302103281501<br>22 September 1986 |

For MC1, bias correction of CCSM3/WRF climate data was based on comparison with historical climate (1971-2000) from PRISM output (Daly et al. 2008) at 30-arc second spatial resolution [~670 m (0.42 miles) east-west x ~930 m (0.58 miles) north-south at WICA's location; henceforth abbreviated as 800-m resolution] and a monthly temporal resolution. CCSM3 output was not used in ecosystem response modeling. The CCSM3/WRF values for total monthly precipitation, mean vapor pressure, and mean daily maximum and minimum surface air temperatures, averaged over each month, were statistically downscaled and bias-corrected to the 800-m resolution using the delta method described by Rogers et al. (2011) and King et al. (2013a). A continuous time series of each climate variable was then constructed for each 800-m grid cell in the park's polygon for 1895- 2050 using PRISM historical output for 1895-2000 and downscaled, bias-corrected CCSM3/WRF output for 2001-2050. This process was also used to create climate input from three other climate simulations: CSIRO Mk3 (Gordon 2002), Hadley CM3 (Johns et al. 2003) and MIROC 3.2 medres (Hasumi and Emori 2004), hereafter referred to as "CSIRO", "Hadley", and "MIROC", respectively.

For climate output used as input for RRAWFLOW, trends in annual, winter (December, January, February), spring (March-May), summer (June-August), and fall (September-November) mean temperature and total precipitation were evaluated for three time periods for the WICA weather station and five time periods for the Custer weather station. For both stations the years 1985-2010 comprised the recent historical period, the projected period was 2011-2050, and the recent historical + projected period was 1985-2050. The longer record of the Custer weather station allowed for trends to be evaluated in a longer historical context, i.e., for the 1943-2010 historical period and the full time series of 1943-2050. Differences (referred to as "anomalies" in some climate change literature) in the same variables were tested between the historical and projected periods using two-sided Wilcoxon two-sample tests. Significance of trends was determined on the basis of the Kendall-tau non-parametric test applied to time series of variables. Probability of a type-I error ($P$) of 0.05 was considered significant and $0.05 \leq P < 0.10$ considered marginally significant. Statistical analyses of climate trends and differences between the historical and projected period for MC1 climate input were conducted similarly, except the historical period was 1950-2000 and the projected period 2001-2050, and analyses were limited to the single cell in which the WICA park headquarters lies.

### *3.2.2 Hydrologic Simulation Using RRAWFLOW*

RRAWFLOW is a time-series hydrologic model that simulates stream and spring flow or water-table level using daily mean air temperature and precipitation data as input. The model simulates two processes in series: the process of precipitation becoming recharge (precipitation that infiltrates the aquifer), and the transition of recharge into a hydrologic response. Recharge is simulated by estimating a daily soil moisture index, which depends on previous days' air temperature and precipitation, then multiplying this index by daily precipitation; snow is stored as snow pack until melt-inducing air temperatures occur. The transition of recharge into a hydrologic response is simulated using convolution. Convolution is the integration of the product of a forcing function (a series of impulses) and a time-lagged impulse-response function (IRF). For hydrologic modeling, a recharge event is an impulse. RRAWFLOW estimates the system memory, which is the amount of time between a precipitation event and the time at which that event has a negligible influence on the hydrologic system. RRAWFLOW also estimates the average time from a precipitation event to the peak response of the system (time to peak response).

In some cases, a single IRF can adequately represent the quick- and slow-flow components characteristic of karst hydrogeology, but in other cases a secondary IRF is useful. In this case, the primary and secondary IRFs are superposed to form a compound IRF. In addition, an IRF might vary between wet and dry periods. Therefore, as many as four IRFs may be necessary to adequately characterize the hydrologic response of a specific site to a recharge event. Since Beaver Creek sinks into the ground and is a direct source of recharge for Calcite Lake (WCL), its flow was used as an additional source of recharge (along with precipitation) for the lake, and the model for this site therefore included an additional IRF for sinking-stream recharge. Simulated Beaver Creek streamflow was used as input for the Calcite Lake (WCL) model for the period prior to the start of measured Beaver Creek flow.

RRAWFLOW is validated for a specific site in two steps, each using a different part of the observed records of impulse and response. Table 3-1 shows the source and period of record for observations used to validate the model for the two WICA sites. In the first step of validation, model parameters are optimized using the first portion of the observed record (calibration period). In the second step, the calibrated model is run using the remainder of the observed record (validation period). If the simulated responses of the validation period do not adequately fit the observed flow or lake level values (Nash-Sutcliffe coefficient of efficiency < 0.70; Nash and Sutcliffe 1970; Legates and

McGabe 1999), both steps are repeated, using different forms or combinations of IRFs, until the fit is adequate. A detailed description of this process is in Long and Mahler (2013).

Because of the long memory of the Calcite Lake (WCL) system, simulation for this site began at 1880 so that recharge prior to this date would have no effect on the simulated lake levels for the period of observation. This required longer-term climate data than available for the Custer station. Daily precipitation data for the Custer weather station began in 1911, but air temperature records did not begin until 1942 (Table 3-1). Thus, air temperature from a weather station in Lead, SD, for 1911-1941 was bias-corrected to the Custer weather station and used as an estimate. For 1885-1910, long-term average precipitation and air temperature were used as RRAWFLOW input .

The validated hydrologic model for each site was applied to historical and projected air temperature and precipitation from the appropriate weather station from the station's start of record through 2050 to simulate a continuous record of hydrologic response. Comparisons and assessments of historical and projected streamflow and lake level were made on simulated values because of the limited period of observed record, and for greater consistency between historical and projected periods. Statistical analyses of streamflow and lake level trends and differences between the historical and projected period were evaluated in the same manner as for the weather stations. To supplement the short climate record for WICA, on which the Beaver Creek simulations were based, the Beaver Creek RRAWFLOW model was also run using bias-corrected Custer weather station data from 1943-1983 to approximate Beaver Creek flow during this period. Statistical analyses did not include this period.

### *3.2.3 Ecosystem Simulation Using MC1*

MC1 is a dynamic global vegetation model that simulates vegetation distribution, biogeochemical cycling and fire in a highly interactive manner. We modified the standard version of the model so that, when using historical climate input, it adequately simulated the current spatial distribution of vegetation types, documented natural fire regimes, and measured grass productivity. Details of these modifications are provided in King et al. (2013b).

MC1 simulates carbon pool sizes, distributing the carbon among life forms (broadleaf or needleleaf, deciduous or evergreen trees; $C_3$ or $C_4$ grasses, where "grasses" includes all non-woody vegetation), fire events and fire's effects on carbon pools. Each grid cell is simulated independently, with no cell-to-cell communication. MC1's biogeography module translates the simulated carbon pools into potential natural vegetation type (e.g., temperate conifer savanna, $C_4$ grassland) as affected by soil type, atmospheric $CO_2$ concentration, grazing regime, climate, and fire.

In our application, soil data from Kern (1995, 2000) were downscaled to the same grid used for the climate data. Atmospheric $CO_2$ concentrations through time followed the A2 emissions scenario. We used a grazing regime of 30% removal of live grass production and 3% of standing dead grass in April-September, and 7% of live grass production and 15% standing dead grass removal in October-March.

Climate input is monthly total precipitation, monthly mean vapor pressure, and mean daily maximum and minimum air temperatures, averaged over each month. This report shows, for the first time, the results of MC1 simulations using the CCSM3/WRF model output. To put these results in a greater context, we include the earlier (King et al. 2013b) results of the same simulations using the three other projected climates (CSIRO, Hadley, and MIROC). These other three climates were available in the format needed for MC1 from earlier work, for which they were chosen specifically to represent the range of air temperature changes driven by the A2 emission scenario for North America. They also vary in their precipitation patterns, but they did not represent any of the specific scenarios in the scenario planning exercise.

MC1 is run in four sequential phases: equilibrium, spin-up, historical, and future. The equilibrium phase initializes the vegetation type and equilibrates the carbon pools for fixed, vegetation-dependent fire return intervals and monthly climate inputs averaged over 1895-1950. The spin-up phase is run for a repeating loop of detrended historical (1895-2008) climate data and allows for readjustments of vegetation type and carbon pools in response to dynamic fire. The historical phase is run with historical climate data (1895-2000), followed by the future run (2001-2050), which uses the bias-corrected, downscaled climate projection data described in section 3.2.1.

MC1 simulates the time of fire events and their effects using one of three fire modes. In the “natural” fire mode, input climate and simulated fuel moisture contents determine when fire behavior thresholds are exceeded; at this point a fire occurs (ignition sources are assumed unlimited). Fire behavior and effects (e.g., portion of cell burned, tree mortality rate) are modulated by current vegetation type. In the “suppression” mode, a fire occurs only when extreme fire intensity and behavior metrics are exceeded, so that only ~5% of potential fires occur. This rate is consistent with the fact that five of the 101 wildland fires that occurred at WICA from 1984 to 2010 accounted for 92% of all the area burned by wildland fires during that period (data from unpublished NPS Northern Great Plains Fire Management Office GIS files). In the “controlled burn” mode formulated specifically for WICA, prescribed fire regimes were represented by specifying the date of a fire and the tree mortality rate caused by that fire. In the application reported here, we ran MC1 in each of these three modes, with fire suppression beginning in 1941 for the fire suppression mode, and prescribed fires producing 20% tree mortality every 11 years beginning in 2001 for the controlled burn mode.

## 3.3 Results and Discussion

Slight differences in the periods treated as “historical” and “projected”, as well as larger differences in methods used for bias correction and final downscaling, of the climate data used in the hydrological and ecosystem response models requires discussing the results for these two components separately. Characteristics of the climate inputs are quantified in this section; they are compared to the broader array of climate projections available in Section 4.

### *3.3.1 Hydrologic Response*

#### 3.3.1.1 Climate Input for Hydrologic Response Simulations

Comparing trends and anomalies (projected minus historical) in RRAWFLOW’s climate input reveals largely similar patterns between the two weather stations over the recent historical period and for future projections. Comparisons of climate for the recent (1985-2010) and longer (1943-2010) historical periods for the Custer station place recent changes and projections into a more complete historical context (Table 3-2). Hereafter, annual or seasonal (such as winter) precipitation is the total for the year or season specified, respectively. Annual or seasonal air temperature is the mean for the daily mean air temperature for a year or season specified in a year, respectively. Means for a span of years are denoted as mean annual or mean seasonal (such as mean winter).

The recent historical period of 1985-2010 encompassed two dry periods (1987-1990 and 2001-2007) as well as 1992-1999, the wettest period on record for WICA and much of the Black Hills (Carter et al. 2002). There were few significant trends in climate over this period for both weather stations. Other than a marginal increase in spring precipitation at the WICA weather station, the only significant trend was a 2.7 °C (4.9 °F) increase in fall air temperature at the Custer weather station. However, trends are evident in the longer historical record of the Custer weather station. Since 1943, annual mean air temperature increased by 3.1 °C (5.6 °F). Winter and spring air temperature increased slightly more than summer and fall air temperatures (3.6 °C/6.4 °F and 3.4 °C/6.2 °F vs. 2.9 °C/5.2 °F and 2.6 °C/4.7 °F, respectively). Annual precipitation also increased marginally, driven by a significant, 5.1 cm (2 inch) increase in fall precipitation.

The CCSM3 simulation produced significantly increasing annual (1.9 °C/3.4 °F increase by 2050), and fall (3.2 °C/5.8 °F ) mean air temperatures for the projected period for both weather stations, as well as significantly increasing summer mean air temperature (2.0 °C/3.6 °F) for the WICA weather station and marginally increasing summer air temperature for the Custer weather station. For both weather stations, mean air temperatures were significantly greater in the projected period than the recent historical period for all seasons but winter, yielding significantly positive air temperature trends over the 1985-2050 and 1943-2050 time periods. Air temperature patterns were similar for the CCSM3/WRF projection, except that spring, not summer, values increased significantly through the projected period (1.6 °C/3.0 °F increase by 2050), and average projected air temperature did not differ from average recent historical air temperature for the fall season. Air temperature increases were also slightly lower than for the CCSM3 projection: 1.4 °C (2.6 °F) increase in annual mean air temperature and 2.3 °C (4.1 °F) increase in fall mean air temperature by 2050.

Neither the CCSM3 nor the CCSM3/WRF climate simulation had significant trends in annual or seasonal precipitation over the projected period for either weather station. However, the CCSM3 simulation had significantly higher annual and summer precipitation compared to the recent historical period for both weather stations, with annual precipitation being 14% (69 mm/2.6 inches) higher at the WICA weather station and 18% (89 mm/3.5 inches) higher at the Custer weather station. Three quarters of this increase was due to summer mean precipitation. CCSM3/WRF projected annual and seasonal precipitation differed from the recent historical period only for fall at the Custer weather station (23 mm higher in 2011-2050, $P = 0.023$), though projected precipitation tended to be higher than historical ($P \geq 0.14$). Furthermore, for the Custer station and compared to the longer historical period of 1943-2010, annual (100 mm/3.9 inches), summer (53 mm/2.1 inches), and fall (30 mm/1.2 inches) precipitation were significantly greater in the CCSM3 projection and annual (55 mm/2.2 inches), spring (18 mm/0.70 inches), and fall (44 mm/1.7 inches) precipitation were significantly greater in the CCSM3/WRF projection.

**Table 3-2.** Trends and differences in weather station historical climate and the CCSM3/WRF (abbreviated as WRF in table) and CCSM3 climate projections used as RRAWFLOW input.

▲ and △, significant and marginally significant upward trend, respectively; ▼ and ▽, significant and marginally significant downward trend; --, no significant trend; * and †, average for projected period significantly (*) different than average for historical period; significant, $P < 0.05$; marginally significant, $0.05 \le P < 0.10$

| **Station** | **WICA** | | | | | **Custer** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1985-2010** | **2011-2050** | | **1985-2050** | | **1985-2010** | **2011-2050** | | **1985-2050** | | **1943-2010** | **1943-2050** | |
| **Statistic** | | **CCSM3** | **WRF** | **CCSM3** | **WRF** | | **CCSM3** | **WRF** | **CCSM3** | **WRF** | | **CCSM3** | **WRF** |
| Mean air temperature | | | | | | | | | | | | | |
| Annual | -- | ▲ | ▲ | ▲* | ▲* | -- | ▲ | ▲ | ▲* | ▲* | ▲ | ▲* | ▲* |
| Winter | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | ▲ | ▲ | ▲* |
| Spring | -- | -- | ▲ | ▲* | ▲* | -- | -- | ▲ | ▲* | ▲* | ▲ | ▲* | ▲* |
| Summer | -- | ▲ | -- | ▲* | ▲* | -- | △ | -- | ▲* | ▲* | ▲ | ▲* | ▲* |
| Fall | -- | ▲ | ▲ | ▲* | ▲ | ▲ | ▲ | ▲ | ▲* | ▲ | ▲ | ▲* | ▲* |
| Total precipitation | | | | | | | | | | | | | |
| Annual | -- | -- | -- | ▲* | -- | -- | -- | -- | ▲* | -- | △ | ▲* | ▲* |
| Winter | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | △ | |
| Spring | △ | -- | -- | -- | -- | -- | △ | -- | △ | ▲ | -- | ▲ | ▲* |
| Summer | -- | -- | -- | △* | -- | -- | -- | -- | ▲* | -- | -- | ▲* | -- |
| Fall | -- | -- | ▽ | -- | -- | -- | -- | -- | -- | --* | ▲ | ▲* | ▲* |

Graphical representation of the historical records and projections (Figures 3-3 and 3-4) illustrate these results, as well as other important differences between the climate projections and the historical records. The CCSM3/WRF projection shows substantially more variability in precipitation than the CCSM3 projection, as shown by the much higher peaks and lower valleys in daily data in Figures 3-3 and 3-4. More quantitatively, in the CCSM3/WRF projection for the WICA weather station, 0.7% of daily precipitation events are > 25 mm (~ 1 inch) and only 25% of the days (average 92 days per year) have any precipitation, whereas in the CCSM3 projection only 0.1% of daily precipitation events are > 25 mm and 40% of the days (average 148 days per year) have some precipitation. These values are similar for the Custer weather station. In comparison, during the recent historical period, 0.7% (Custer) or 0.9% (WICA) of daily precipitation events were > 25 mm and 24% of days (87 days per year) had precipitation.

Differences between the CCSM3 and CCSM3/WRF projections themselves and between a projection and its associated historical period are further illustrated by comparing the exceedance values for daily precipitation. The 20% exceedance value is the amount of precipitation exceeded by 20% of the days in the record; this value is representative of a "typical" precipitation event during a given time period. The 1% exceedance value represents the magnitude of rare precipitation events; a higher value in the future period indicates that rare events are more extreme than in the past. As might be expected from examining Figures 3-3 and 3-4, the 1% exceedance value for the CCSM3 projection (13 mm at both stations) is lower than for either weather station during the recent or longer historical period (21-24 mm). The CCSM3/WRF projections for both the WICA and Custer weather stations produce 1% exceedance values (21 and 25 mm, respectively) more similar to the historical period. The two projections also differ in their 20% exceedance values, both of which are higher than in the historical records. For the WICA weather station, the CCSM3/WRF projection's 20% exceedance value is 1.4 mm and the CCSM3 projection's 20% exceedance value is 2.8 mm, compared to just 0.5 mm for the historical record. These higher values for "typical" precipitation events in the projections, particularly the CCSM3 projection, explain the significantly higher mean annual precipitation in the projected vs. historical time period. Furthermore, although it is difficult to accurately quantify 1% exceedance values or the frequency of rare events like 25-mm precipitation days with the relatively short recent historical period we use, for either weather station, these comparisons indicate that the CCSM3/WRF projection more closely resembles the historical period in daily precipitation patterns. In comparison, the mean change in the number of days with precipitation > 1 inch (~25 mm) between 1980-2000 and 2041-2070 for the Great Plains from 8 regional climate models is +17%, but less than half of the models in this analysis show a statistically significant change in this parameter for the WICA region (Kunkle et al. 2013).

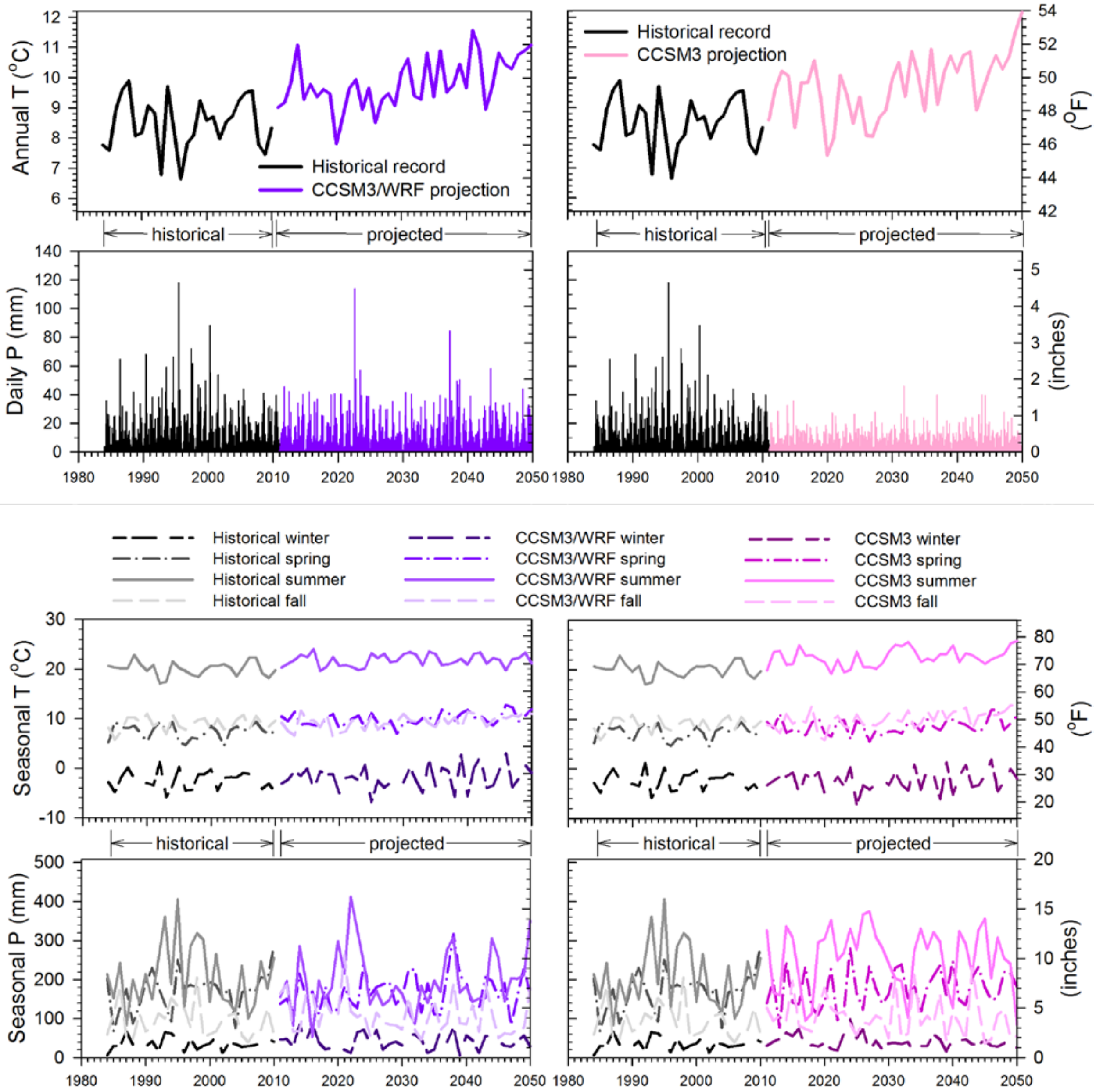

**Figure 3-3.** Historical and CCSM3/WRF- (left) or CCSM3- (right) projected air temperature (T) and precipitation (P) for the WICA weather station.

Air temperature is averaged by year (top) or season (bottom), and precipitation totaled by day (top) or season (bottom).

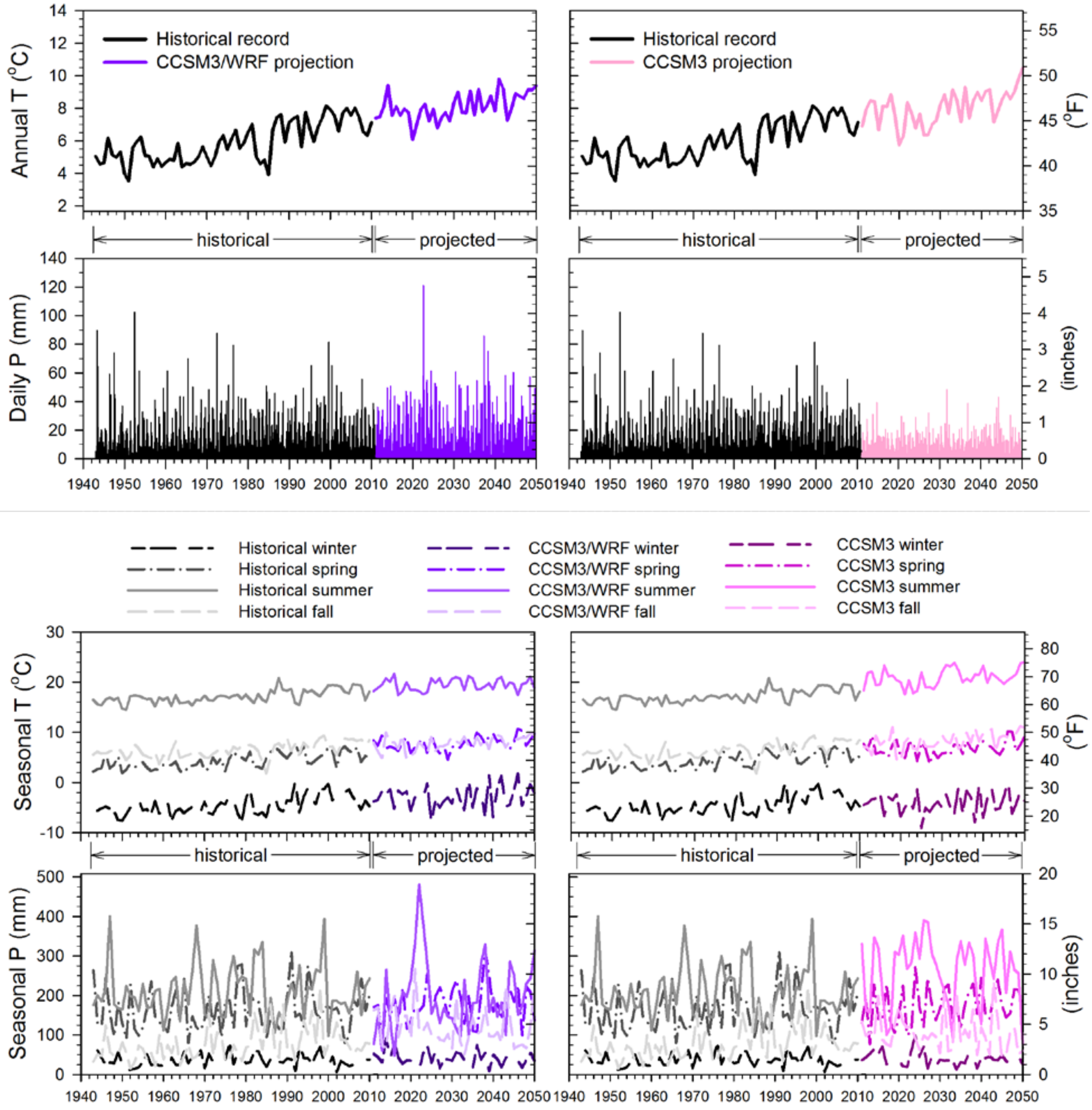

**Figure 3-4.** Historical and CCSM3/WRF- (left) or CCSM3- (right) projected temperature (T) and precipitation (P) for the Custer weather station.

Air temperature is averaged by year (top) or season (bottom), and precipitation totaled by day (top) or season (bottom).

Terrain can be a triggering mechanism for orographic and convective precipitation in dynamical climate models like the CCSM3 and the WRF model. The CCSM3 does not accurately represent the variability of terrain in the region of the Black Hills, or in the Rocky Mountains to the west, while the WRF model, given its higher spatial resolution of 36 km (22 miles), has a more realistic representation of terrain (Figure 3-5). The more complex terrain in part contributes to differences between the models and to the more realistic representation of precipitation in the Black Hills region by the WRF model.

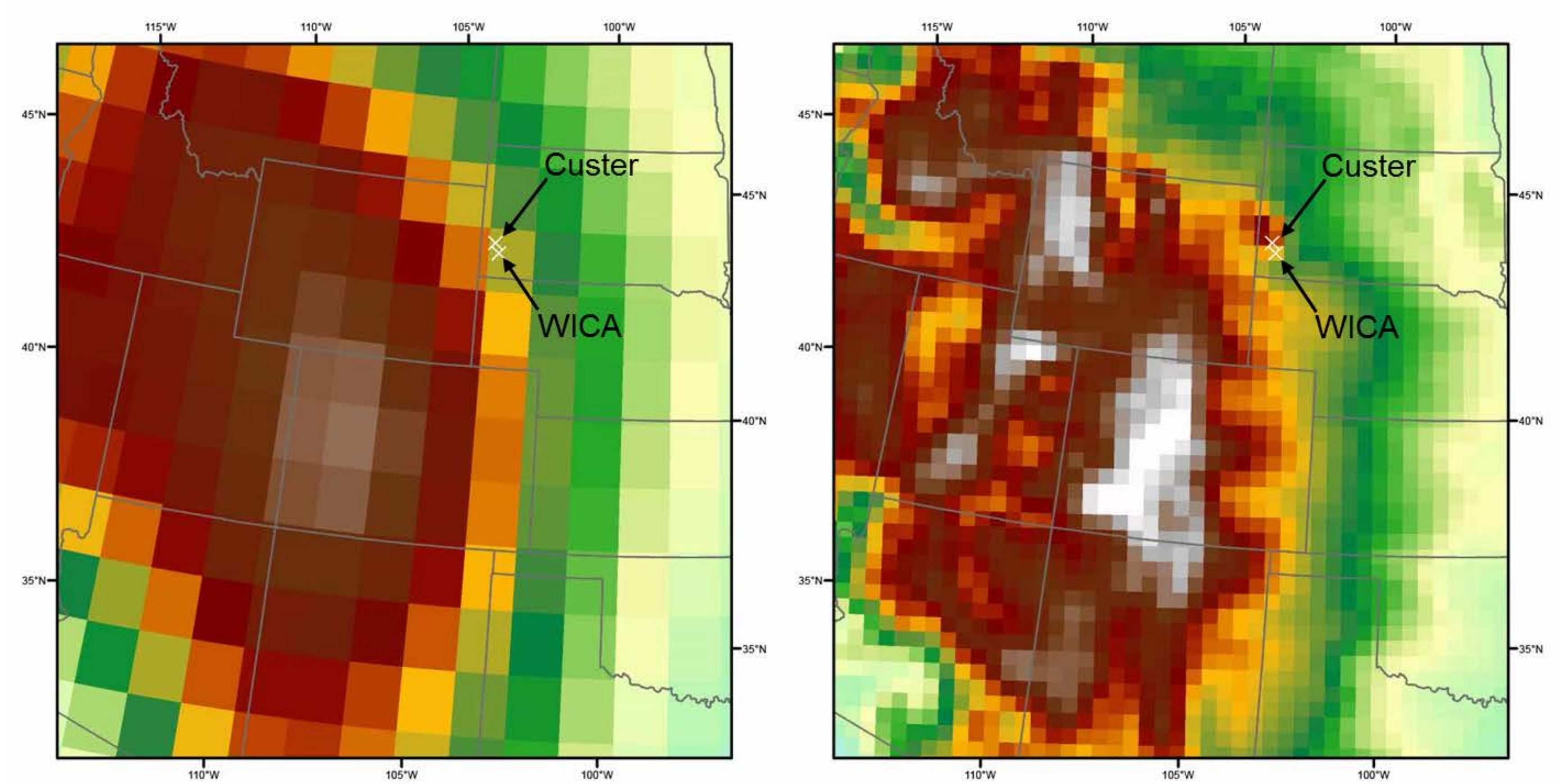

**Figure 3-5.** Elevation of the west-central United States as represented by (left) the Community Climate System Model, version 3 (CCSM3) and (right) the Weather Research and Forecasting (WRF) model as implemented in this project.

Locations of Custer and WICA weather stations are indicated on each map. Coordinate System: World Geodetic System, 1984. 3000 m elevation is 9,850 feet. Alternative grayscale image in Appendix A.

#### 3.3.1.2 Beaver Creek Response

The RRAWFLOW calibration for Beaver Creek illustrated that this stream responds quickly to precipitation events (time to peak response < 1 day), but it also has a memory of ~2 years (Long and Mahler 2013), which is displayed in the stream's continuing to flow during periods without precipitation. This base flow, primarily originating as groundwater inflow to a stream, is seen in the observed and simulated streamflow records at the bottoms of inter-peak troughs (Figure 3-6). RRAWFLOW simulations matched observed base flow values and timing of peak events well, though the magnitude of peak events differed somewhat between simulated and observed values. Calibration and validation also indicated that the creek responds to precipitation differently during wet and dry periods (Long and Mahler 2013).

Beaver Creek streamflow observations began just before the very climatically wet period of 1992-1999 (Carter et al. 2002). During the latter half of this period, base flow ranged from ~0.05 - 0.08 $m^3/s$ (1.8-2.8 $ft^3/s$), the highest observed peak flow (2.4 $m^3/s$, 85 $ft^3/s$) occurred, and peak flow rates > 0.2 $m^3/s$ (7 $ft^3/s$) occurred frequently (Figure 3-6). This pattern contrasts with the streamflow simulated using WICA weather station data from 1985-1991, when base flows were ~0.01 - 0.05 $m^3/s$ (0.3-1.8 $ft^3/s$) and peak flows never exceeded 0.5 $m^3/s$ (18 $ft^3/s$). Simulations using Custer weather station data for earlier periods (not shown) indicate frequent periods of near-zero streamflow rates, particularly for 1950-1963. Over the recent historical period (1985-2010), the 1% exceedance value for daily simulated flow was 0.42 $m^3/s$ (15 $ft^3/s$) and the median (50% exceedance) was 0.035 $m^3/s$ (1.2 $ft^3/s$). For comparison, when the very wet 1992-1999 period is excluded, 1% exceedance for daily flow was 0.28 $m^3/s$ (9.9 $ft^3/s$) and the median was 0.020 $m^3/s$ (0.071 $ft^3/s$). Nine percent of the days in the 1985-2010 historical period had simulated flow < 0.002 $m^3/s$ (0.07 $ft^3/s$), the low flows reached during the most recent dry period of the mid-2000s. There were no significant linear trends over the 1985-2010 period.

Beaver Creek streamflow simulated with the CCSM3/WRF projection (2011-2050) as climate input was characterized by several multi-year periods with continuous streamflow separated by short periods of low flow (< 0.01 $m^3/s$ or 0.4 $ft^3/s$). Although there were no significant trends in seasonal or annual flow over the 2011-2050 period ($P > 0.12$), other metrics indicate differences between the historical and projected periods with this climate projection. In contrast to the simulated historical period (1985-2010), only 2% of days during the projected period had flow < 0.002 $m^3/s$ (0.07 $ft^3/s$). Projected base flow was usually < 0.03 $m^3/s$ (1.1 $ft^3/s$), which is similar to the historical period outside of the wet 1990s whether compared to the shorter period for which WICA weather data are available (Figure 3-6) or the longer historical period using weather approximated from the Custer weather station (data not shown). Annual and summer streamflow simulated using the CCSM3/WRF projection as climate input were marginally significantly lower than the simulated 1985-2010 period ($P \leq 0.08$). All seasonal and annual flow means were similar to those of the historical period excluding 1992-1999 ($P \geq 0.35$). Projected peak flows were lower than historically (1% exceedance = 0.18 $m^3/s$, 6.4 $ft^3/s$), and the median flow resembled that of the drier portion of the historical period (0.024 $m^3/s$ or 0.85 $ft^3/s$).

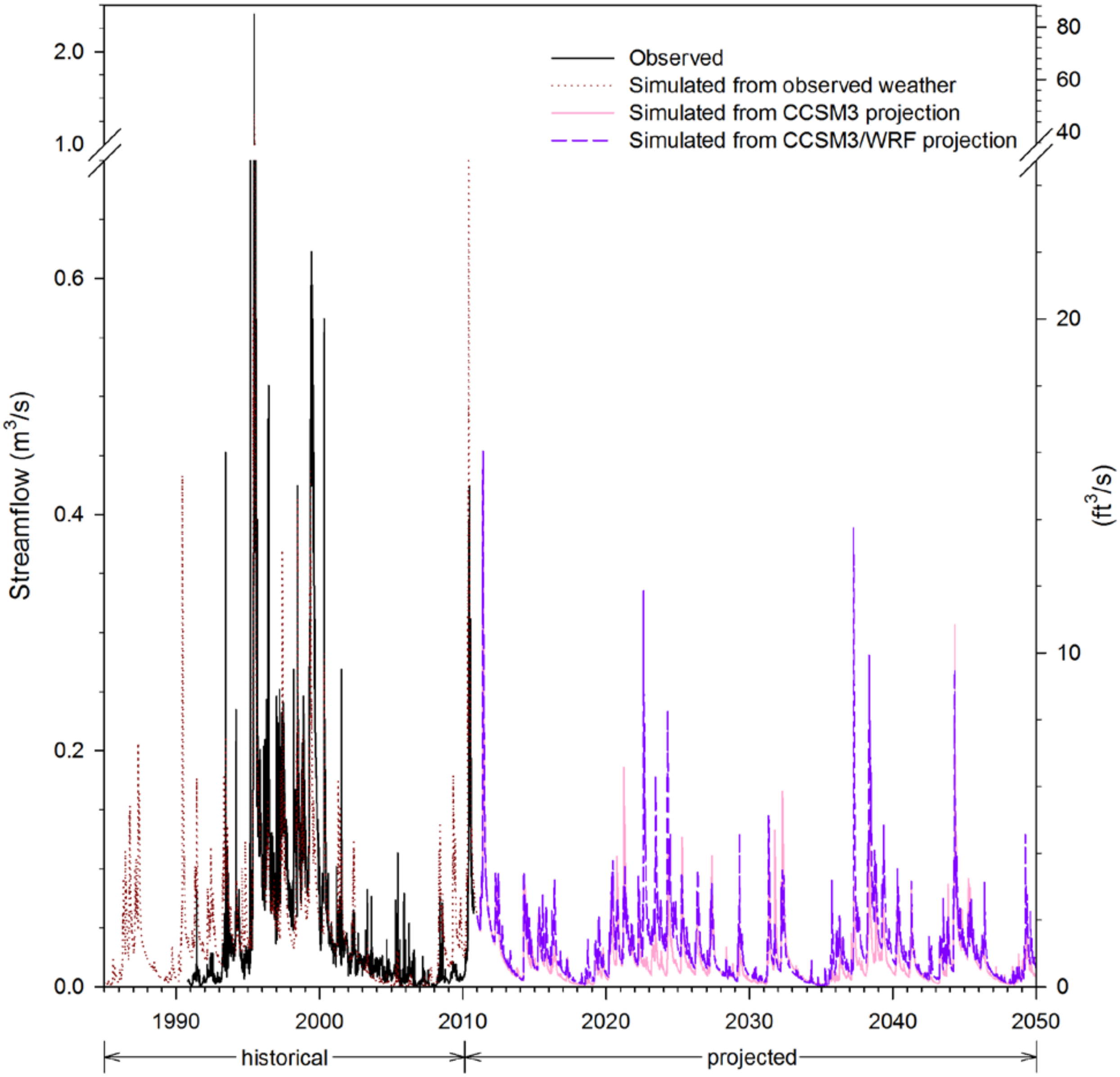

**Figure 3-6.** Daily streamflow at the gage on Beaver Creek in WICA – observed, simulated by RRAWFLOW on the basis of historical weather records, and simulated by RRAWFLOW on the basis of CCSM3/WRF and CCSM3 climate projections.

Streamflow simulated with the CCSM3 projection as climate input had somewhat lower variability in base flow and peak flows compared to the simulation using CCSM3/WRF climate input (Figure 3-6). Simulated base flow based on the CCSM3 climate was 0.01-0.02 $m^3/s$ (0.3-0.7 $ft^3/s$) for most of the projected period, but dropped lower than this range for short periods. As with the other climate projection, CCSM3-based simulated streamflow < 0.002 $m^3/s$ (0.07 $ft^3/s$) occurred in only 2% of days during the projected period. In contrast, CCSM3-based simulated peak flows generally fell within a relatively small range (0.10-0.20 $m^3/s$ or 3.5-7.1 $ft^3/s$; daily 1% exceedance of 0.12 $m^3/s$, 4.2 $ft^3/s$) compared to both the simulated historical period and the projected period simulated with

CCSM3/WRF climate input. Despite the significantly higher annual and summer precipitation of the CCSM3 climate projection compared to the historical period (Table 3-2), simulated mean annual streamflow for 2011-2050 was 58% lower than that of 1985-2010 ($P = 0.010$) and more closely resembled that of the drier portion of the historical period (i.e., excluding 1992-1999; $P = 0.39$). Simulated streamflow based on the CCSM3 projection was lower than the recent historical period for all seasons, with summer streamflow decreasing the most (71%).

In summary, for the WICA weather station, the CCSM3 projection had significant, 14% and 24% increases in mean annual and summer precipitation, respectively, as well as smaller but more consistent precipitation events and a 2.5 °C (4.5 °F) increase in summer air temperature, compared to the recent historical period. This yielded a 58% lower simulated mean annual streamflow, and a 71% lower simulated mean summer streamflow, in the projected vs. recent historical period. For the CCSM3/WRF projection, precipitation means and patterns of extremes were similar between the recent historical and projected periods, and the greatest air temperature difference (2.4 °C/4.3 °F) was in spring, not summer (1.7 °C/3.1 °F). This yielded less dramatic and less statistically significant decreases in simulated mean annual (40%) and summer (53%) streamflow compared to those based on the CCSM3 projection. These differences are visible in Figure 3-6, primarily as the difference in peak flows, as well as in base flows in the mid-2020s and late 2030s.

#### 3.3.1.3 Calcite Lake (WCL) Response

Calcite Lake (WCL) responds more slowly to precipitation events (time to peak response 1.5-2.0 years) than Beaver Creek, and it has a long (~100 years) system memory (Long and Mahler 2013). Also, Custer weather station data resulted in a better model fit for Calcite Lake (WCL) than did WICA weather station data. Both of these facts indicate that Calcite Lake levels (WCL) are influenced by distant recharge sources, such as on the western and southern sides of the Black Hills. The Custer weather station may represent the climate of this larger region better than the WICA weather station. As with Beaver Creek, calibration of RRAWFLOW for Calcite Lake indicated that lake level responds to recharge differently during wet and dry periods (Long and Mahler 2013). Simulations matched observed lake levels well between 1985 and 2000, but somewhat overestimated levels from 2000-2008 (Figure 3-7).

The slower time to peak response and longer system memory make Calcite Lake (WCL) level much less variable than Beaver Creek streamflow, but variations in recharge are still evident in its temporal fluctuations. Observed and simulated lake levels increased significantly ($P = 0.0002$) over the 1985-2010 historical period. The ~7 m (23 ft) rise from 1991 to 2000 coincided with most of the 1991-2004 period of high base flow in Beaver Creek (Figure 3-6). Lake level began to decline in 2001, however, which coincided with a drier period for the Custer weather station (Figure 3-4).

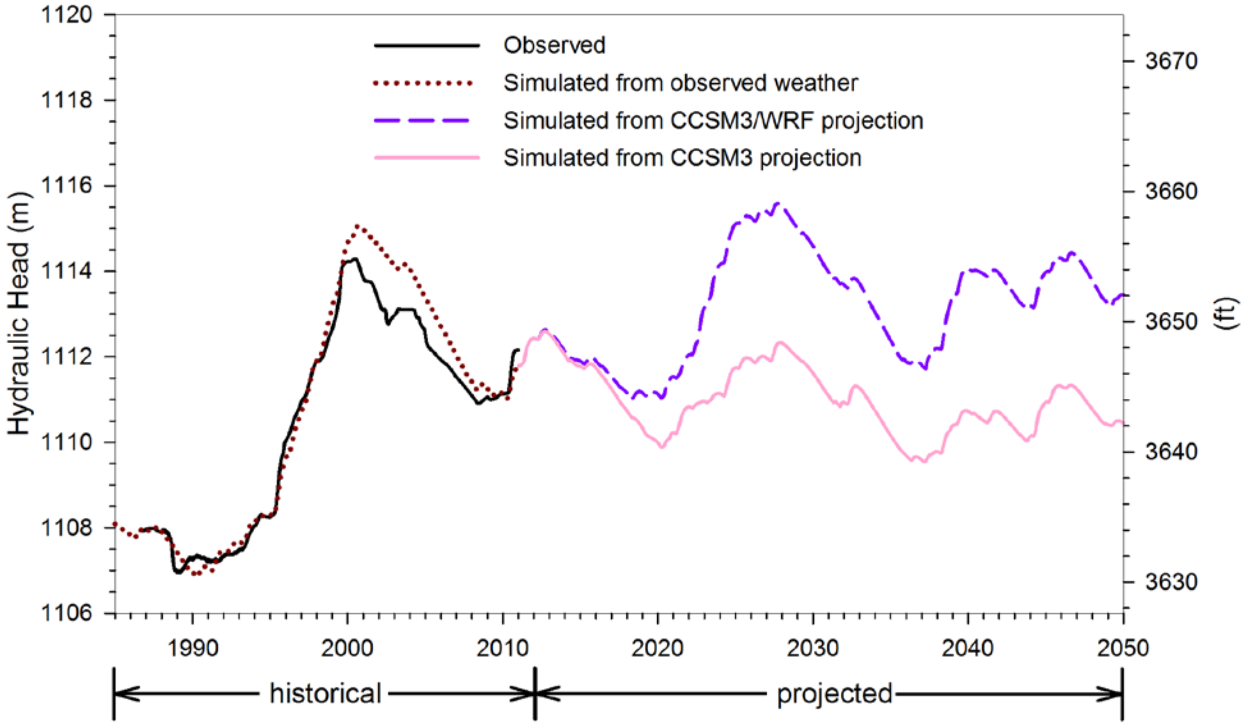

**Figure 3-7.** Daily lake level of Calcite Lake (WCL) in Wind Cave – observed, simulated by RRAWFLOW based on historical weather records, and simulated by RRAWFLOW based on the CCSM3/WRF and CCSM3 climate projections.

Hydraulic head is measured as the level above the North American Vertical Datum (NAVD) of 1988.

RRAWFLOW-simulated lake levels based on the two climate projections (2012-2050) share similar fluctuations but differ in their long-term trends. No fluctuations during the projected period are as large as the dramatic increase in lake level observed (and simulated) during the late 1990s. Simulated lake levels based on the CCSM3/WRF projection slightly exceeded historically observed lake levels for a portion of the projected period and did not drop below those observed since the beginning of the 21st century. In contrast, simulated lake levels based on the CCSM3 projection repeatedly dropped below the range of post-2000 observations, particularly later in the projected period. Consequently, simulated mean annual lake level increased by 1.8 m (6.1 ft) over the projected period for the CCSM3/WRF projection ($P = 0.03$) and decreased by 1.4 m (4.6 ft) for the CCSM3 projection ($P = 0.002$).

These two projections illustrate the complexities of hydrological response to climate change. The CCSM3 climate projection had a 1.6 °C (2.9 °F) higher mean annual temperature and 14% higher annual precipitation than the recent historical period (for the WICA weather station), but it yielded 58% lower simulated mean annual streamflow, other flow metrics that resembled the drier portion of recent history (Figure 3-6), and a declining cave lake level (Figure 3-7). The CCSM3/WRF projection had a slightly lower temperature anomaly (1.4 °C/2.5 °F) and no anomaly for precipitation, but it yielded 40% lower simulated mean annual streamflow compared to the recent past and an increasing cave lake level over the projected period. These counter-intuitive results can be explained by two primary factors, air temperatures and precipitation variability. Soil moisture varies directly with air temperature, which affects the soil drying rate; the lower air temperatures of the CCSM3/WRF projection compared to the CCSM3 projection resulted in more groundwater recharge in the former. High variability in precipitation, as occurred in the CCSM3/WRF projection, results in less average evapotranspiration (ET) and, thus, greater groundwater recharge compared to the low variability in precipitation exhibited by the CCSM3 projection. Specifically, during periods of very high precipitation, the soil has high moisture content, and most of the precipitation during a storm infiltrates below the root zone to recharge the aquifer. During dry periods, ET is limited because of limited availability of precipitation; during wet periods, ET is limited by the rate at which plants can consume water, and this limiting of ET results in more water available for groundwater recharge, on average, than for a scenario of low precipitation variability, as in the CCSM3 projection.

Observed values of both Beaver Creek streamflow and Calcite Lake (WCL) level declined after the wet 1990s, but the rate of decline for the Calcite Lake (WCL) level was much slower because of the long system memory and, in particular, the long tail of the IRF. If not for this, the lake level would be expected to decline much faster. Unlike flow in Beaver Creek, the large rise in lake level during the 1990s is projected to have long-lasting effects that could buffer the influence of rising temperatures.

#### 3.3.1.4 Implications

In order to provide WICA resource managers with a full, quantitative understanding of the possible futures for Beaver Creek streamflow and Calcite Lake (WCL) level, we would ideally run RRAWFLOW using a broad range of credible climate projections, then build a probability distribution of potential futures based on the outcomes. Through this project, we have gained an appreciation for the difficulty of producing even a small number of useable, credible climate projections that could be used in RRAWFLOW simulations. We admittedly overestimated the number of projections that we could produce given the project's funding and time frame, and we could not find alternative climate data sources with the full time series necessary for RRAWFLOW input.

Consequently, our assessment of hydrological response to climate change for Beaver Creek and Calcite Lake (WCL) is limited to one regional projection and the global projection from which it was dynamically downscaled. However, for either of these projections, annual precipitation was either equal to or greater than the historical period but mean streamflow was lower than the overall recent historical period that included both dry and wet cycles. A future climate with precipitation less than the historical record and/or greater temperature increases – plausible alternatives (see Section 4) – could have even lower mean streamflow than that simulated using the CCSM3/WRF model and CCSM3 projections. Given that Beaver Creek is a major water source for WICA wildlife, and this creek and its associated vegetation are already imperiled by high wildlife use (Burkhart and Kovacs 2013), planning for alternative sources of water for wildlife is warranted.

A substantial concern about future climate is an increase in extreme events, including intense precipitation events, flooding, and – at the opposite end – periods of very low stream flow. The CCSM3/WRF model's more realistic precipitation projection (compared to CCSM3) indicated neither a greater frequency nor intensity of extreme precipitation events than the historical period for the immediate WICA area, and the RRAWFLOW-simulated response to this projection had lower frequency and intensity of peak streamflow events. Moreover, the occurrence of very low flow events was less frequent in both projections than in the recent historical period. Further simulations with RRAWFLOW based on climate projections with more extreme precipitation characteristics could help managers better understand the behavior of Beaver Creek under these circumstances. Calcite Lake (WCL) level is buffered from short-term (days-long) extreme events, and our simulations suggest that the nearly decade-long 1990s precipitation event will continue to influence the lake's level until at least the middle of the 21st century regardless of future climate patterns. However, lake and aquifer levels could decline even if total precipitation increases, as illustrated by the CCSM3 projection.

### ***3.3.2 Ecosystem Response***

#### 3.3.2.1 Climate Input for Ecosystem Response Simulations

Trends and anomalies in seasonal and annual air temperature and precipitation for the climate projections used as input for MC1 are shown in Table 3-3. In contrast to the data from the Custer weather station used for RRAWFLOW input, the PRISM historical climate input for MC1 showed an increase in air temperature only for the spring. All four climate models projected statistically significantly higher annual mean air temperature in the projected period (2001-2050) compared to the historical period (1950-2000). The MIROC projection was the warmest, at 2.0 °C (3.6 °F) warmer than the historical period, followed by the Hadley (1.8 °C/3.2 °F), and CSIRO and CCSM3/WRF (1.2 °C/2.2 °F) projections. The pattern was generally the same for summer air temperature, a factor critical to fire behavior, with the MIROC and Hadley projections having summer air temperatures 2.1°C (3.8 °F) warmer than the historical period, and the CCSM3/WRF and CSIRO projections having summer air temperatures only 1.2 °C (2.2 °F) warmer than the historical period. Positive trends in air temperature over the projected period are spread throughout all seasons for the CSIRO and MIROC simulations, all seasons but fall for the Hadley simulation, and in summer and fall for the CCSM3/WRF simulation. When combined with the historical period, all climate projections yielded significant positive trends in mean annual or seasonal air temperature over the whole time series and significantly higher mean annual or seasonal air temperature in the projected future than in the historical period.

The historical climate input for MC1 showed a significant positive trend in annual precipitation (124 mm/4.9 inch increase over 1950-2000), driven by increases in spring and fall. With one exception, climate projections showed little or no trend in precipitation during the projected future period. The exception was that the MIROC model had a significant downward trend in summer, fall, and annual precipitation, yielding a decrease of 94 mm (3.7 inches) in annual precipitation over the 2001-2050 year period. Despite their general lack of trends during the projected period, the CSIRO and CCSM3/WRF projections had significantly higher average annual precipitation in the projected period than in the historical period (15 and 9% difference, respectively), and the full time series showed a significant trend of increasing precipitation for most seasons and the whole year for both these and the Hadley projection. In contrast, the significant downward trend in the MIROC projection did not yield a significantly drier (average precipitation) projected future than past, as the projected decrease essentially cancelled out the historical increase.

**Table 3-3.** Trends and differences in climate in the MC1 grid cell that includes the location of WICA's headquarters for the 1950-2000 historical period (derived from PRISM), as well as the 2001-2050 projected period and full time series (1950-2050) for the four climate projections used as input for MC1.

CCSM3/WRF abbreviated as WRF; ▲ and △, significant and marginally significant upward trend, respectively; ▼ and ▽, significant and marginally significant downward trend, respectively; --, no significant trend; *, average for projected period significantly different than average for historical period; significant, $P < 0.05$; marginally significant, $0.05 \leq P < 0.10$

| | 1950- | ------------------2001-2050------------------ | | | | ------------------1950-2050------------------ | | | |
|---|---|---|---|---|---|---|---|---|---|
| Statistic | 2000 | WRF | CSIRO | Hadley | MIROC | WRF | CSIRO | Hadley | MIROC |
| Mean air temperature | | | | | | | | | |
| Annual | -- | ▲ | ▲ | ▲ | ▲ | ▲* | ▲* | ▲* | ▲* |
| Winter | -- | -- | ▲ | △ | ▲ | ▲* | ▲* | ▲* | ▲* |
| Spring | ▲ | -- | ▲ | ▲ | ▲ | ▲* | ▲* | ▲* | ▲* |
| Summer | -- | ▲ | ▲ | ▲ | ▲ | ▲* | ▲* | ▲* | ▲* |
| Fall | -- | ▲ | ▲ | -- | ▲ | ▲* | ▲* | ▲* | ▲* |
| Total precipitation | | | | | | | | | |
| Annual | ▲ | -- | -- | -- | ▼ | ▲* | ▲* | ▲ | -- |
| Winter | -- | -- | -- | -- | -- | -- | -- | ▲* | -- |
| Spring | ▲ | -- | -- | -- | -- | △ | ▲* | ▲ | -- |
| Summer | -- | -- | ▽ | -- | ▼ | -- | -- | -- | ▽ |
| Fall | ▲ | -- | △ | ▲ | ▼ | ▲* | ▲* | ▲ | -- |

The climate projections also differed in their year-to-year variability in both air temperature and precipitation (Figure 3-8). The CCSM3/WRF projection's variability most closely resembled that of the historical period, whereas the CSIRO projection exhibited larger swings in growing season (spring and summer) precipitation than the historical period or any of the other projections. The Hadley projection displayed relatively muted interannual fluctuation in precipitation, as did the latter half of the MIROC projection.

In summary, the CCSM3/WRF and CSIRO projections provide relatively mild (smaller air temperature increases, higher precipitation) projected climate scenarios compared to the MIROC and Hadley climate projections used by King et al. (2013b).

#### 3.3.2.2 Vegetation and Fire Response

King et al. (2013b) discuss the results and implications of MC1 simulations of WICA vegetation and fire patterns in detail for the CSIRO, Hadley, and MIROC climate projections. Therefore, the results we present and discuss here concentrate on how simulations using the CCSM3/WRF projection as climate input compare to those discussed in the earlier report.

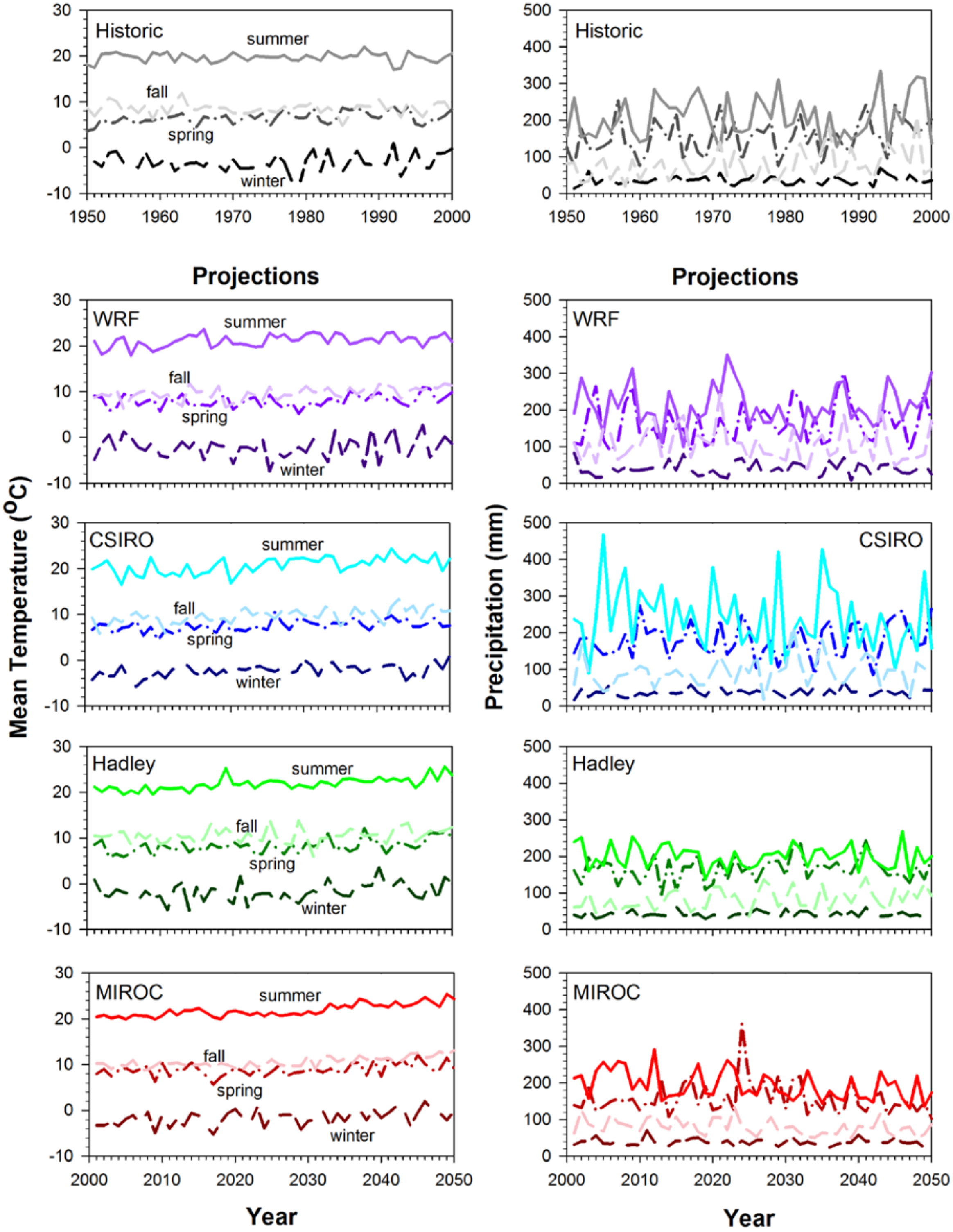

**Figure 3-8.** Representative climate input (A2 emissions) for the MC1 simulation of the WICA ecosystem.

Graphs show seasonal historical and projected mean air temperature and total precipitation for the MC1 grid cell in which the WICA headquarters lies. Metric units and English units are shown on the left and right axis, respectively, of each graph. Line texture and color in precipitation graphs as in temperature graphs.

A major conclusion of the previous report and subsequent work (King et al. 2013b, a) was that, although fire and climate interact to influence the distribution and biomass of trees across the WICA landscape, fire is a stronger force. This is illustrated by the generally greater difference among fire scenarios than among climates (rows and columns, respectively, of Figure 3-9). MC1 simulations using all climate projections yielded an overall decrease in tree biomass in the currently forested area of the park by the middle of this century regardless of the fire regime used, either because of increased fire frequency ("natural fire" and "controlled burn" modes) compared to historical times, or because of a few intense fires that kill more trees ("fire suppression" mode). Simulations using the fire suppression mode showed an increase in tree biomass in areas currently with very few trees, whereas simulations using the natural fire and controlled burn modes largely maintained the current spatial distribution of forest vs. grassland, with the controlled burn simulations having much more uniform tree biomass within the forested cells than the natural fire simulations.

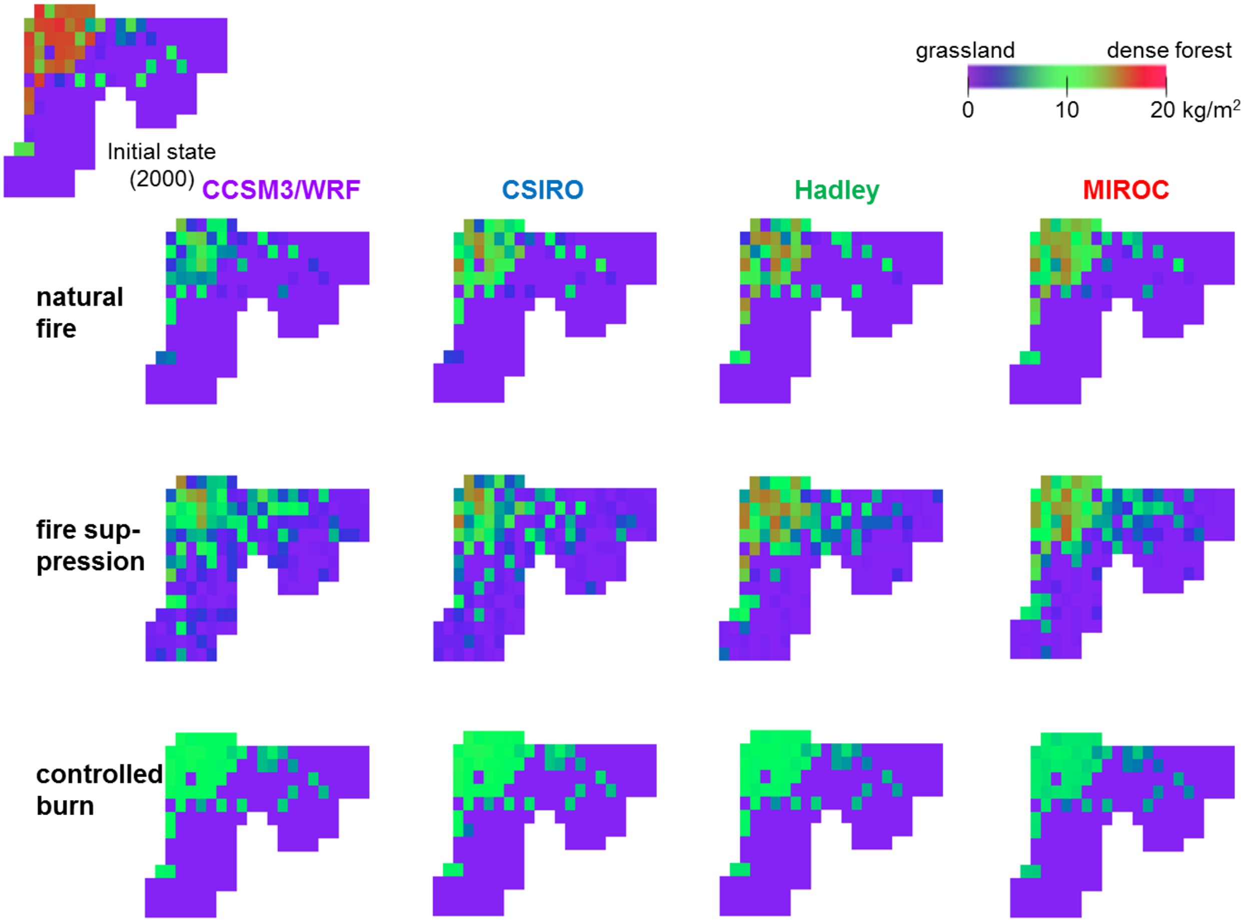

**Figure 3-9.** WICA tree biomass simulated with MC1 for historical conditions (year 2000, upper left) and the four projected climates represented in Figure 3-8 (year 2050) in three fire regimes.

Each shape represents the polygon encompassed by the 2010 WICA boundary. Fire regimes are described in section 3.2.3. 20 kg/m2 = 89 tons/acre. Alternative grayscale image in Appendix A.

The MC1 simulation using the natural fire scenario and based on the CCSM3/WRF projection reinforces the importance of the climate-fire interaction. Somewhat counterintuitively, tree biomass increased as projections' summer air temperatures increased (left to right in Figure 3-9), with the simulation based on CCSM3/WRF having the lowest tree biomass of the four. This is because the higher temperatures of the Hadley and MIROC projections caused consistently dry fuels and resulted in high fire frequency, particularly in the second half of the projected time period (Figure 3-10, left). High fire frequency maintained relatively low fuel loads and lowered tree mortality compared to the infrequent fire frequency of the MC1 simulation based on the CCSM3/WRF projection, which allowed time for fuel load buildup and therefore high intensity fires. The frequent fire years in the simulation based on the CSIRO projection generally corresponded with years of lower summer precipitation in this relatively wet, but highly variable, climate projection (Figure 3-10, right). Either fires of similar intensity or somewhat faster recovery of tree biomass after more severe fire in the simulation based on the CSIRO projection produced tree biomass similar to that in simulations based on the drier Hadley and MIROC projections (Figure 3-9).

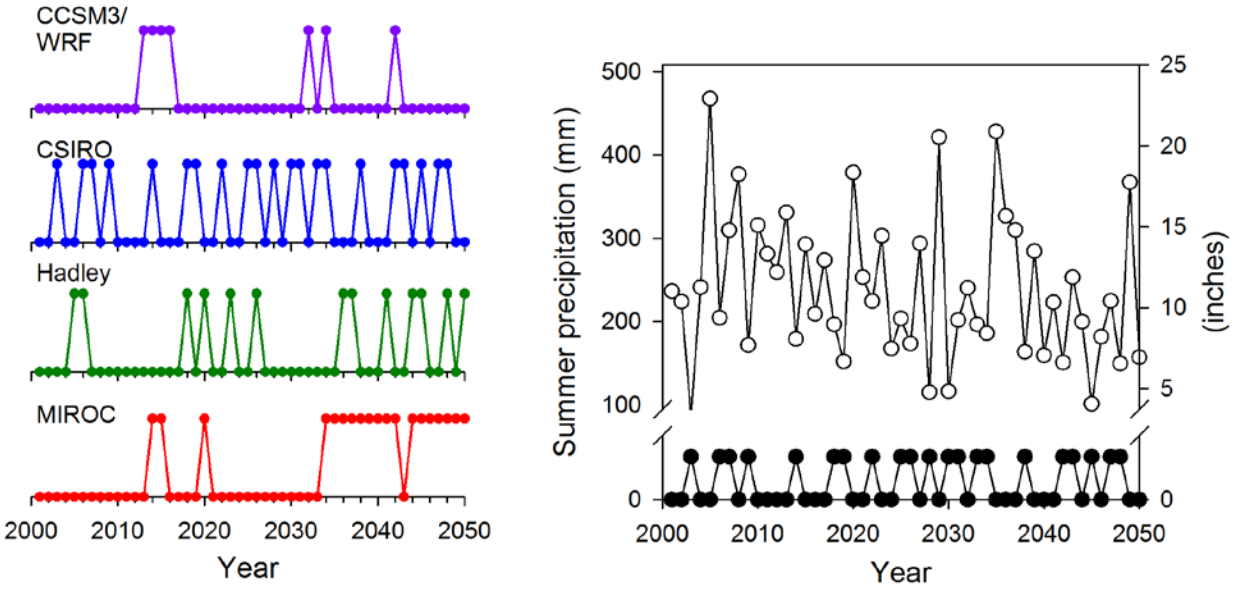

**Figure 3-10.** Years of MC1-simulated fire, in the "natural" fire regime, based on the four climate projections in Figure 3-8, for a forested cell (left), and correspondence between dry summers and fire years for the simulation based on the CSIRO projection (right).

Left panel: fire years are indicated by a dot above the horizontal axis. Right panel: fire years are indicated by a filled circle off the horizontal axis, summer precipitation for that year by an open circle.

Since trees compete with grasses for light, water, and nutrients, the effects of the fire-climate interaction on tree biomass are also seen in simulated park-wide grass production. Regardless of climate input, projected grass production was higher in the simulations using the controlled burn fire regime compared to the fire suppression fire regime (Figure 3-11). Fire suppression's damping effect on grass production was greatest for the MC1 simulation based on the MIROC climate (average of 35% reduction over the 2001-2050 period), least for the simulation based on the CSIRO climate (23%) and intermediate for the simulations based on the Hadley and CCSM3/WRF climates (30%).

This pattern was associated with the greater woody encroachment of grasslands for MIROC than for CSIRO (Figure 3.9, middle row).

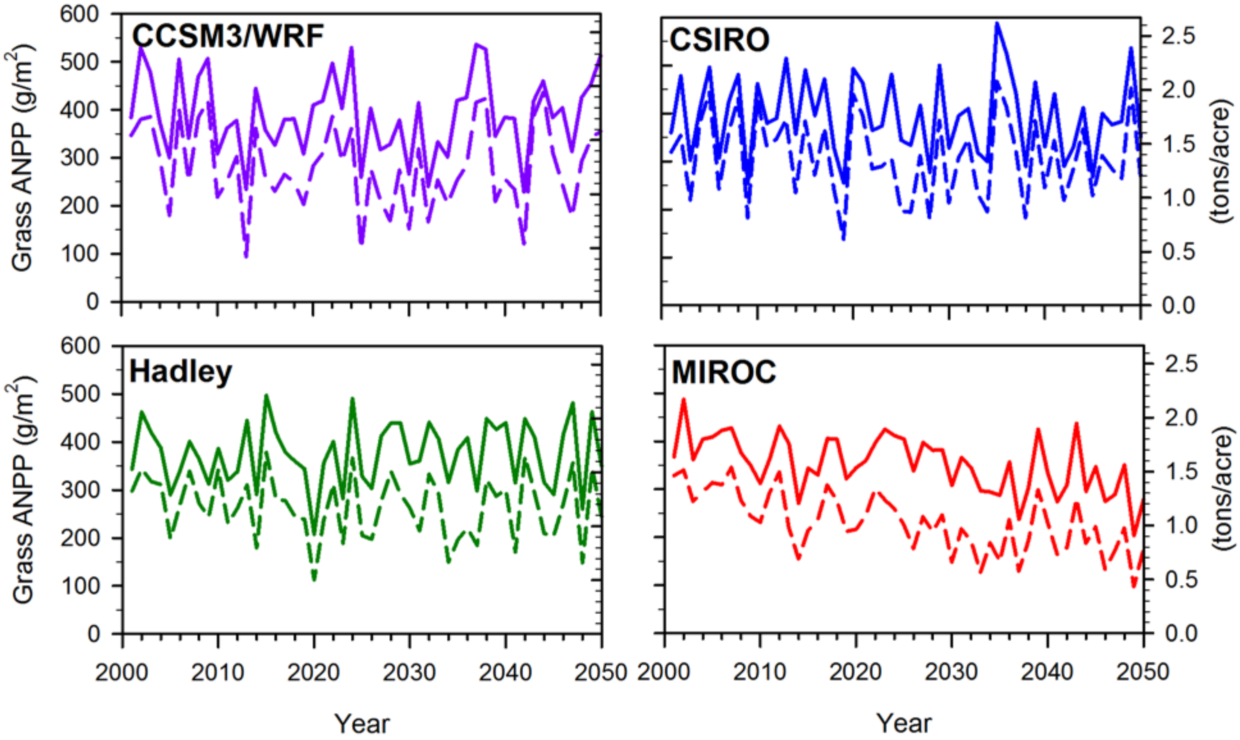

**Figure 3-11.** Park-wide grass annual net primary production (ANPP) for the four climate projections in Figure 3-8 as simulated by MC1 using an 11-year return interval controlled burn regime (solid lines) or suppression of less severe fires since 1941 (dashed lines) fire regime.

Differences in the patterns of tree encroachment into prairies among the MC1 simulations based on the four climate projections explained the differences in fire effects on grass production. However, greater grass production in the controlled burn fire regime simulations based on any climate projection was also influenced by MC1's assumption that grass production is stimulated by fire's removal of surface litter. Keeping these two fire effects essentially constant across climates, as was done in the controlled burn fire regime, reveals the more direct impact of the different climate projections on grass production. Although all were highly variable from year to year and largely followed precipitation patterns in that variability, the climate projections yielded quite different trends in grass production over the projected period in the controlled burn fire regime, from a 10% increase for the simulation based on the CSIRO climate, to no change for the simulation based on the CCSM3/WRF climate, and 7% and 19% decreases for the simulations based on the Hadley and MIROC climates, respectively (Figure 3-11, solid lines). These trends were driven by patterns in both precipitation and temperature. In contrast, the composition of grass production in MC1 simulations is controlled by temperature smoothed over multiple years; simulations based on all climate projections yielded downward trends in the proportion of grass produced by $C_3$ (cool-season) grasses, but the decline was least pronounced for the relatively cool CCSM3/WRF climate (Figure 3-12).

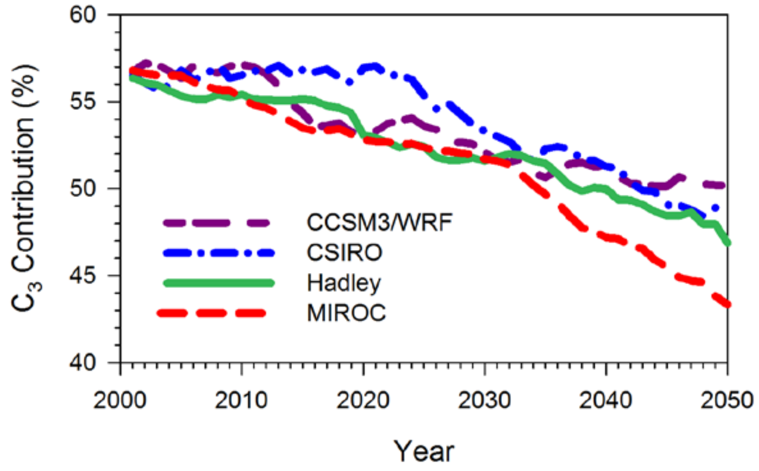

**Figure 3-12.** MC1-simulated percentage of grassland production by C3 (cool-season) grasses for the four climate projections in Figure 3-8, for the MC1 cell in which WICA's headquarters lies, in a "natural" fire regime.

These simulations vividly illustrate the importance of fire and its interactions with climate for the future of WICA's forests and prairies. However, simulations by MC1 or by any other global vegetation model do not capture fire's highly stochastic nature – when and where an ignition occurs, effects of wind speed and topography on fire spread and intensity, etc. Another way to understand potential changes in the prairie-forest dynamic at WICA is to compare the frequency of "high fire danger" days in the projected period compared to the past. We consider a "high fire danger" day to be one in which the buildup index (BUI) – an indicator of the dryness of coarse woody fuels – exceeds 80, one of the two thresholds for fire ignition used in the MC1 simulations.

The MC1 simulation based on the CCSM3/WRF climate projection yielded a pattern of fire danger of relatively high decadal variability compared to simulations based on the other climate projections (Figure 3-13). The simulation based on the CSIRO projection produced mostly low-fire-danger years (like the 1990s) punctuated by single moderately high-danger years (26-60 days of high fire danger); the simulation based on the Hadley projection yielded low (0-10 days) or moderate-danger years (11-25 days) punctuated by high fire-danger years similar to those in the drought periods of the 1930s and 1950s (60-90 days); and the simulation based on the MIROC projection produced a steadily increasing frequency of high fire danger days. In contrast, the simulation based on the CCSM3/WRF projection yielded 5-10 year periods of relatively low (2000-2010, 2015-2025), moderate (2025-2035), and moderately high (2010-2015, 2035-2045) fire danger. This decadal variability resembles that of the historical period but makes it difficult to determine whether or not the tendency for more years with at least some high fire danger days in the second half of the CCSM3/WRF projection compared to the first is a trend. In addition, it is also important to remember that the four climate projections used here are just one time sequence projected by each model. The patterns of temperature and precipitation variability shown by each climate projection used here do not necessarily represent patterns characteristic of those climate models or of future climates with similar temperature and precipitation characteristics. Instead, they illustrate the potential effects of different patterns of interannual and decadal climate variations. Regardless of these complexities, all four climate projections suggest that park managers should be prepared for years in the future that have greater potential for fire – and the impacts it could have on the park's forest – than most years in the institutional memory of the agency (~1970-present).

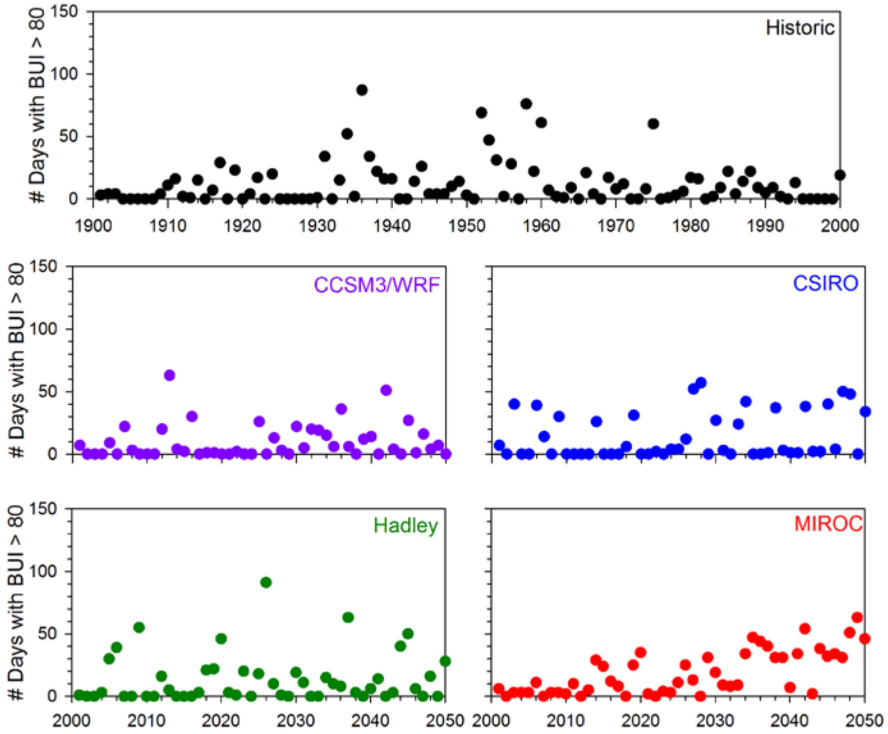

**Figure 3-13.** MC1-simulated number of days per year that the buildup index (BUI) exceeds 80 in the historic period (top) and in the projected period for the four climate projections in Figure 3-8 (middle and bottom).

### 3.4 Summary and Management Implications

Our climate, hydrologic, and ecological simulations for WICA through the middle of the 21st century provide quantitative understanding of potential impacts of climate change on key natural resources in the park. All six climate projections used in this evaluation had significantly higher temperatures in the first half of the 21st century compared to the recent past and the longer historical record, and they showed significant positive trends in temperature over the 2011-2050 projected period – from 1.4 to 2.1 °C (2.5 to 3.8 °F) for mean annual air temperature. Changes in precipitation between historical and future periods varied greatly among climate projections and season, not only in magnitude and degree of variability, but even in overall direction. This range of precipitation conditions reflects the universal pattern of greater uncertainty about the effects of global change on precipitation than on temperature (Meehl et al. 2007; Collins et al. 2013; Kirtman et al. 2013), although for the northern Great Plains the mean and median change in precipitation over many models is slightly positive (Collins et al. 2013; Kirtman et al. 2013; Kunkle et al. 2013).

However, even with a 14% increase in precipitation in the CCSM3 climate projection (a relatively large increase; see Section 4.3.3), simulated streamflow of Beaver Creek decreased significantly in the same time period. This, in combination with the periods of very low flow simulated by RRAWFLOW based on either the CCSM3 or CCSM3/WRF climate projection, suggests that **developing additional surface water sources for high-priority wildlife**, both to ensure adequate water for the wildlife and to ease their pressure on streamside vegetation, should be considered a potential priority management action. This is further reinforced by the fact that our work does not address indirect effects of climate change, such as increased surface water diversion or groundwater pumping, on Beaver Creek or other surface water sources in the park. **Consistent, quantitative monitoring of surface water (streams, springs, seeps, water developments) and associated vegetation** will be necessary to assess the availability of water to wildlife, their impacts on streamside vegetation, and whether management actions are achieving the desired results. Ecosystem simulations suggest that, regardless of fire regime and even in relatively wet future climates like the CCSM3/WRF projection produced specifically for WICA, fire-induced mortality is expected to lead to lower tree biomass in currently forested areas. This stems from the importance of temperature on fire danger indices. Thus, **depending on park goals, management actions aimed to reduce the rate of fire-induced tree mortality in currently forested areas may be warranted.** Furthermore, the simulations also suggest that encroachment of ponderosa pine into current grasslands in a fire suppression scenario is expected regardless of future climate. Consequently, the quantitative simulations suggest that, in the absence of a natural fire regime, **maintaining the current grassland areas as grassland will require an active prescribed fire program regardless of future climate.** Although not simulated by MC1 because of its lack of cell-to-cell communication, it is likely that woody encroachment into grasslands would occur in areas with nearby trees that could serve as seed sources. In addition, the frequency of years with fire danger like that of historical drought periods even in the relatively mild CCSM3/WRF climate projection suggests that **park managers should be prepared for more wildfires in the future.** King et al. (2013b) note some caveats about MC1's simulation of fire effects, including its interpolation of monthly climate data into daily values for the fire module. A dynamic ecosystem model using daily climate input, like that used in RRAWFLOW, would better simulate fire regime changes and their ecological effects in response to climate change.

When prescribed fire maintained WICA's current extent of grassland, MC1 simulated a consistent, severe decrease in grass (forage) production by 2050 only with the hottest, driest climate projection that we evaluated. However, even in the two wettest climate projections, simulated grass production during dry years reached levels as low as in the hot, dry climate. Such interannual variability is a well-known characteristic of the northern Great Plains region in which WICA lies (Borchert 1950; Knapp and Smith 2001; Smart et al. 2007) and is unlikely to decrease in the future (Collins et al. 2013; Kunkle et al. 2013; Polade et al. 2014), suggesting that **resource managers should be prepared for the impacts of drought years on vegetation and wildlife.** Furthermore, MC1 also simulated a substantial decrease in the relative contribution of cool-season grasses to forage production for all four climate projections. Due to the paucity of field data on which to base the algorithms that represent the effect of elevated $CO_2$ on warm- and cool-season grasses' behavior in future climates, considerable uncertainty about the composition and seasonality of grassland plant production in the future remains. **Consistent monitoring of grassland vegetation composition, seasonal forage production, and wildlife health, as well as flexibility in grazing management, will be necessary to ensure long-term vegetation and wildlife health in the uncertain future.** Further details – including important discussion about the limitations of MC1 and other quantitative ecosystem models – and management implications are discussed by King et al. (2013b, a).

# 4. Our Climate Projections and Scenarios in the Broader Context

## 4.1 Background

The Intergovernmental Panel on Climate Change (IPCC) has produced two recent assessment reports, the fourth assessment, or “AR4”, in 2007 (IPCC 2007) and the fifth assessment (AR5) in 2013 (Stocker et al. 2013). AR4 included six GHG emissions scenarios and 21 GCMs, and AR5 used four representative concentration pathways (RCPs) of GHG through time. In both of these assessments, a given model was run up to five times using the same external forcing factors (emissions scenario or RCP) and model configuration, but with slightly different initial conditions for the start of simulations of contemporary climate, which generally began in the late 1800s. Since naturally occurring processes and interactions within the climate system produce internally generated climate variability on many time scales, each of these runs produces a unique result (Cubasch et al. 2013). These multiple runs with the same model are referred to as members of an ensemble. Furthermore, there are multiple methods for downscaling global climate model output to the higher spatial resolution necessary for natural resource management planning. Thus, given the multiple emissions scenarios and RCPs, climate model ensembles, members within each ensemble, and downscaling methods, there are a large number of unique climate projections available on which to base natural resource planning in a changing climate.

No climate projection provides a definitive forecast for the specific time period for which land managers assess alternatives for future planning, and methods for assessing the credibility of individual projections and their downscaled incarnations for a specific location are just now being developed (Barsugli et al. 2013). Consequently, different approaches to climate change planning use the plethora of climate projections in different ways. Some approaches use essentially qualitative descriptions of future climates, as was done for WICA’s scenario planning exercise using the full range of projections in the 2007 IPCC report (Section 2.2.2). Some quantitative response approaches use averaged results from a large number of models. For example, Galatowitsch et al. (2009) averaged annual and summer temperature and precipitation for 2030-2039 and 2060-2069 from data statistically downscaled from 16 climate models using the A2 emissions scenario. The multiple model approach tends to more closely match the central tendencies of observed changes in climate than does any single projection (Gleckler et al. 2008), but multi-model ensemble mean climates are not physically coherent through time.

Process-based response models like we used in Section 3 require this coherence, since the models require full time series of climate input to adequately represent the dynamic nature of the processes they simulate. Thus, when using process-based response models, it is important to first, choose the unique climate projections carefully and, second, understand how those projections fit into the broader context of available climate projections and potential future climates (Barsugli et al. 2013). Sections 3.2.1 and 3.2.3 describe how we chose the projections used in Section 3. Here we quantitatively illustrate, for a variety of climate statistics, where these projections fit along a spectrum of projections using the A2 GHG concentration pathway in the AR4, since our work began before results from AR5 were widely available. We refer to these projections from the AR4 as

"CMIP3" projections, where CMIP3 refers to the Coupled Model Intercomparison Project Phase 3, the set of climate models used in the AR4. We also briefly discuss our projections with respect to projections using the RCP4.5 (low-moderate) and RCP8.5 (high) pathways used in the AR5; we refer to these as "CMIP5" (for Coupled Model Intercomparison Project Phase 5) projections. Finally, where appropriate, we also discuss the qualitative scenarios used in the scenario planning exercise (Section 2) in both of these contexts.

## 4.2 Methods

Comparing climate projections and historical climate for a study's specific location using the same bias-correction and downscaling methods provides the cleanest method for putting climate projections used in a climate change study into a broader future climate context. Unfortunately, available data often do not meet the climate input requirements of response models being used, making it necessary for project- or model-specific downscaling and bias-correction of global or regional climate model output. These efforts require substantial amounts of time and computing resources, often making it unrealistic to produce a large number of uniformly downscaled/bias-corrected climate projections in the form needed for the response modelling.

This was the case in the present project. To meet the climate input needs of the RRAWFLOW and MC1 models, we downscaled and bias-corrected global climate model output using methods appropriate for and specific to each model (Section 3.2.1). Doing this for a large number of climate models and ensemble members was beyond the scope of this project, however. Instead, to put our projections in a broader context, we obtained a publicly available dataset of bias-corrected and statistically downscaled climate data for a large number of climate projections.

We downloaded data for monthly mean surface air temperature and total precipitation for 38 A2 emissions scenario, CMIP3 ensemble members from "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/, accessed July 15-16, 2013) for the 1/8 degree grid cell encompassing the location of WICA's headquarters building (latitude bounds 43.5-43.625°N, longitude bounds 103.375-103.5° E) for the time period 2000-2050. These data were downscaled from GCM output using the bias-corrected spatial disaggregation (BCSD) method described by Maurer et al. (2007). We also downloaded, from the same database, "observed" gridded data for monthly mean surface air temperature and total precipitation for the same location for 1950-1999. Maurer et al.'s (2007) statistical downscaling method interpolates weather station data to a gridded database, including locations without weather stations; this method was used for both the historical and projected data that we downloaded. Thus, the "observed" gridded data for the historical record may differ slightly from actual records collected at the WICA weather station. All data downloaded from this site are hereafter referred to as "BCSD data".

For each of the BCSD datasets (projections or historical observations), we calculated the average annual and seasonal mean air temperature and total precipitation, as well as the ratio of winter to summer precipitation, for each year. As in Section 3, we defined the winter season as December-February, spring as March-May, summer as June-August, and fall as September-November. We calculated the mean and standard deviation of those values for 2031-2050 (projections) or for 1951-1970, 1980-1999, and 1950-1999 (historical observations). The 1951-1970 period was chosen to represent a relatively dry historical period and the 1980-1999 period to represent a relatively wet historical period (see Figure 4-2). We calculated the same statistics for the projections used as climate input for RRAWFLOW and MC1 ("climate input"). For RRAWFLOW's climate input, values shown here are for the WICA headquarters weather station; because of its short historical record, the only historical period represented for these data is 1985-1999 (truncated because of unreliable data before 1984). For the historical PRISM data and four projections used as MC1's climate input, values shown here were calculated for the 30 arc-second grid cell in which the WICA headquarters building lies. Table 4-1 summarizes the data used in quantitative comparisons.

**Table 4-1.** Combinations of climate models, downscaling/bias-correction methods, and time periods used in quantitative comparisons of AR4 climate projections.

Symbols and colors in time period x climate model combinations match those used in figures in Section 4 of this report.

| | **RRAWFLOW Climate Input** | | **MC1 Climate Input** | | | | **BCSD Comparison Datasets** | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Location | WICA weather station | | 30-arc-second PRISM grid cell containing WICA headquarters | | | | 1/8-degree grid cell containing WICA headquarters | | | |
| Downscaling and bias-correction | Based on annual (temperature) and monthly (precipitation) means from WICA weather station (this report, Section 3.2.1) | | Based on monthly means from PRISM gridded dataset (this report, Section 3.2.1) | | | | Maurer et al. (2007) | | | |
| Time period | 1985-1999 | 2031-2050 | 1951-1970 | 1980-1999 | 1950-1999 | 2031-2050 | 1951-1970 | 1980-1999 | 1950-1999 | 2031-2050 |
| Historical | O | | x | x | x | | + | + | + | |
| Climate model | | | | | | | | | | |
| CCSM3 | | O | | | | | | | | + |
| CCSM3/WRF | | O | | | | x | | | | |
| CSIRO | | | | | | x | | | | + |
| Hadley | | | | | | x | | | | + |
| MIROC | | | | | | x | | | | + |
| Other climate model/member combinations | | | | | | | | | | + |

Our comparisons to CMIP5 projections are only semi-quantitative, since the GHG forcing pathways for these AR5-generation projections differ from the one used in the AR4-generation climate projections used in this study. For these comparisons we calculated the change in mean air temperature (annual, winter, and summer) and precipitation (annual, October-March, and April-September) between 1986-2005, the reference period used in the AR5, and 2031-2050 for each of the climate inputs used in Section 3. We compare these to the range of changes defined by the 25th and

75th percentiles of the distribution of CMIP5 ensemble members, for the low-moderate (RCP4.5) and high (RCP8.5) RCPs, as depicted for the WICA area in Annex I Supplementary material of the AR5 (IPCC 2013b, a).

## 4.3 Results and Discussion

### *4.3.1 Important Caveats*

It is essential to note some important caveats before presenting and discussing the results of our comparisons. First, ensembles of climate model outputs, even those including a broad range of models and assumptions about future GHG emissions, do not necessarily represent the full range of plausible future climates (Collins et al. 2013). Second, no single agreed-on and robust methodology to describe the uncertainty about the future climate currently exists (Kirtman et al. 2013). Thus, although the CMIP3 and CMIP5 projections to which we compare our climate input do represent a broad range of plausible futures, the probability that any of these futures will occur, or that they encompass the actual future climate, cannot be stated. In lieu of this quantification of uncertainty or probability, managers can instead use a future climate's position along a spectrum of projections to interpret qualitatively envisioned (Section 2) or quantitatively simulated (Section 3) future hydrology or vegetation in a broader context of plausible futures. More plainly, have the important possibilities been considered?

Finally, quantitative comparison of specific climate inputs to a broader spectrum of projections is complicated. Although members of a given model tend to cluster together along the spectrum of annual and seasonal mean temperature and precipitation, there can be substantial differences among members of the same model (Fischer et al. 2013). Consequently, it is important to note that, when we refer to a climate model, we are referring to the specific member used for the simulations in Section 3. Moreover, as our results illustrate, different methods for statistical downscaling, spatial interpolation, and bias correction of climate projections yield somewhat different future climates and even historical reference climates for a specific location. For example, average annual and seasonal mean temperatures for the 1980-1999 historical period show the differences between the two spatially interpolated datasets (PRISM and BCSD) and between those datasets and WICA weather station observations (Figure 4-1a). In addition, MC1 requires climate input at a monthly time step, which allows for easy estimation of a monthly bias correction for MC1. We found that a monthly bias correction yields more realistic (relative to historical records) seasonal distribution of precipitation than an annual bias correction (data not shown). However, RRAWFLOW requires climate input at a daily time step, and this raises complications in applying a monthly bias correction to air temperature, in that it can result in steps in daily air temperature at month transitions. Therefore, a comparison of an annual versus monthly bias methodology is implicit in our comparison of air temperature projections. Differences among projections with different downscaling (i.e., CCSM3/WRF is the only dynamical model that resolves the Black Hills), interpolation, and bias-correction methods are expected, and each dataset could be considered a different estimate of the true climate of a given area. Despite these complications, the illustrations in this section are useful for understanding the characteristics of the climate input used in Section 3 relative to each other, to the historical periods, and to a broader range of climate projections.

### *4.3.2 Air Temperature*

Hereafter “air temperature” signifies daily mean air temperature. All CMIP3 projections simulate mean annual and mean seasonal air temperatures greater than any of the three historical periods, with the greatest projected vs. historical discrepancies for the model input being in summer (Figure 4-1a). For the RRAWFLOW climate input, mean annual and seasonal air temperature for CCSM3 is in the upper third of the CMIP3 projections except for mean winter air temperature; CCSM3/WRF is similar to CCSM3 for mean annual air temperature but varies in its placement among the projections among the four seasons. For the MC1 climate input, the MIROC input is – as intended – near the high extreme for mean annual air temperature; it also tends to be one of the hottest CMIP3 projections for mean seasonal air temperatures. The CSIRO and CCSM3/WRF climate inputs are generally similar for air temperature – in the lowest third of CMIP3 projections for mean annual, winter, and summer air temperatures, but in the middle of these projections for mean spring and fall air temperatures. The Hadley input is in the top quartile of the CMIP3 projections for mean annual air temperature but varies, albeit always within the top half, in its placement for mean seasonal air temperatures.

Thus, the climate input for the RRAWFLOW and MC1 simulations are consistent with the broad array of BCSD climate products in that their mid-21st-century temperatures for the WICA area are warmer than any of the three historical reference periods represented here. The goal of including a broad range of air temperature increases, compared to the CMIP3 projections available, for this location for the vegetation simulations (MC1 climate input) was mostly met, although more so for the high end of the temperature range than the low end (Figure 4-1a). This conclusion also applies when the climate inputs are compared to CMIP5 projections. Mean annual air temperatures for the 2031-2050 period of MC1 climate inputs closely resemble that of the low-moderate GHG pathway (RCP4.5) for 2046-65 – warmer than projections for the earlier 2016-35 period but not as warm as for the high GHG pathway (RCP8.5). However, the climate input projections tend to be on the cool end for winter mean air temperature and the warm end for summer mean air temperature (Figure 4-1b).

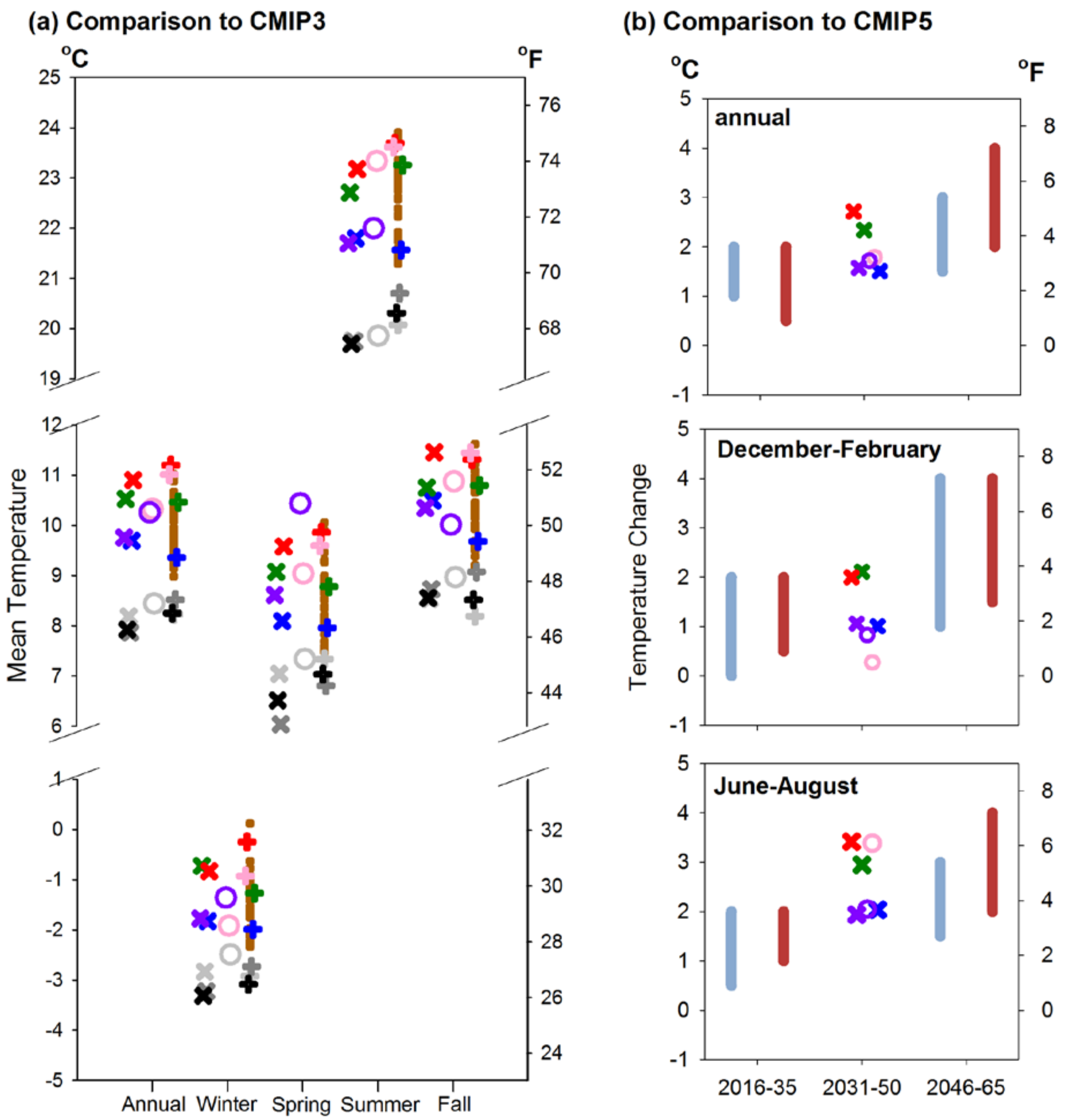

**Figure 4-1.** (a) Mean annual and seasonal air temperature for historical periods and bias-corrected CMIP3 climate projections, A2 emissions scenario, described in Table 4-1. (b) Air temperature anomalies for climate projections used as input for MC1 and RRAWFLOW compared to distribution of anomalies from the CMIP5 ensemble.

**(a)** Each symbol is for an individual historical period (1951-1970, 1980-1999, 1951-1999) or downscaled climate projection (2031-2050). Symbols defined in Table 4-1. **(b)** Symbols (defined in Table 4-1) are absolute difference in mean annual or seasonal air temperature between the AR5 reference period (1985-2006) and a future period (shown on x-axis). Light blue and dark red bars represent 25th-75th percentile ranges of CMIP5 ensembles for low-moderate (RCP4.5) and high (RCP8.5) GHG concentration pathways, respectively. Alternative grayscale image in Appendix A.

### *4.3.3 Precipitation*

In contrast to the results for temperature, there is overlap between the historical and projected means for mean annual and seasonal precipitation (Figure 4-2a), indicating greater uncertainty, compared to air temperature, as to whether precipitation will increase or decrease by the middle of this century. The CCSM3 climate input for RRAWFLOW represents a wet future compared to the other CMIP3 projections, particularly for spring and summer. The CCSM3/WRF climate input for RRAWFLOW also represents a wet future except for summer. Although the MIROC MC1 climate input is the driest of all the MC1 climate inputs for the year and most seasons, it is wetter than most CMIP3 projections for winter and at least 18% of these projections for the other seasons. On the other hand, the CSIRO and CCSM3/WRF MC1 climate inputs are at least the third wettest projection for mean annual, spring, and fall precipitation and in the top half for mean summer and winter precipitation. The Hadley climate input for MC1 is also in the top 20% of projections for the year and all seasons but summer.

Thus, compared to the BCSD climate products, most climate input used for the hydrologic and vegetation response simulations represent the higher end of the precipitation spectrum. When compared to the CMIP5 precipitation spectrum, all of the MC1 and RRAWFLOW climate inputs except MIROC are similar to or greater than the median for the annual and growing-season (April-September) timeframes, but they span a wider range for the October-March dormant season (Figure 4-2b).

Although climate projections are often chosen for or discussed in terms of their mean values for air temperature or precipitation, the variability in these two climate components may also be important for hydrologic and ecosystem response to climate change, as well as natural resource management. For example, the same moderate increase in mean annual air temperature compared to a reference period may result from a moderate increase in air temperature in all years (i.e., with interannual variability similar to the historical reference period) or from a large increase of air temperature in hot years but no increase in air temperature in cool years (interannual variability greater than in the past). This variability occurs at a variety of time scales. The importance of intra-annual precipitation variability – the dispersion of total rainfall across days within a year – was illustrated in the contrasting effects of the CCSM3 and CCSM3/WRF projections on streamflow and cave lake level (Section 3.3.1). Another scale is interannual variability, which we measured as the standard deviation over a 20-year period. The Hadley projection used as climate input for MC1 was near the high end of interannual variability for mean annual temperature and near the low end for variability of annual precipitation, but still within the range of the BCSD projections and our various representations of historical periods. In contrast, the CCSM3/WRF projections used for MC1 and RRAWFLOW input had higher interannual variability in annual precipitation than almost all other representations of the future or past, but moderate variability in temperature. Thus, although the climate inputs used in our hydrologic and vegetation simulations do not span the range of projected interannual variation, they do cover at least a majority of it. The effect of this variation on the results of MC1 simulations has not been explored, but it is reasonable to expect it to be reflected in interannual fluctuations in grass production and fire danger.

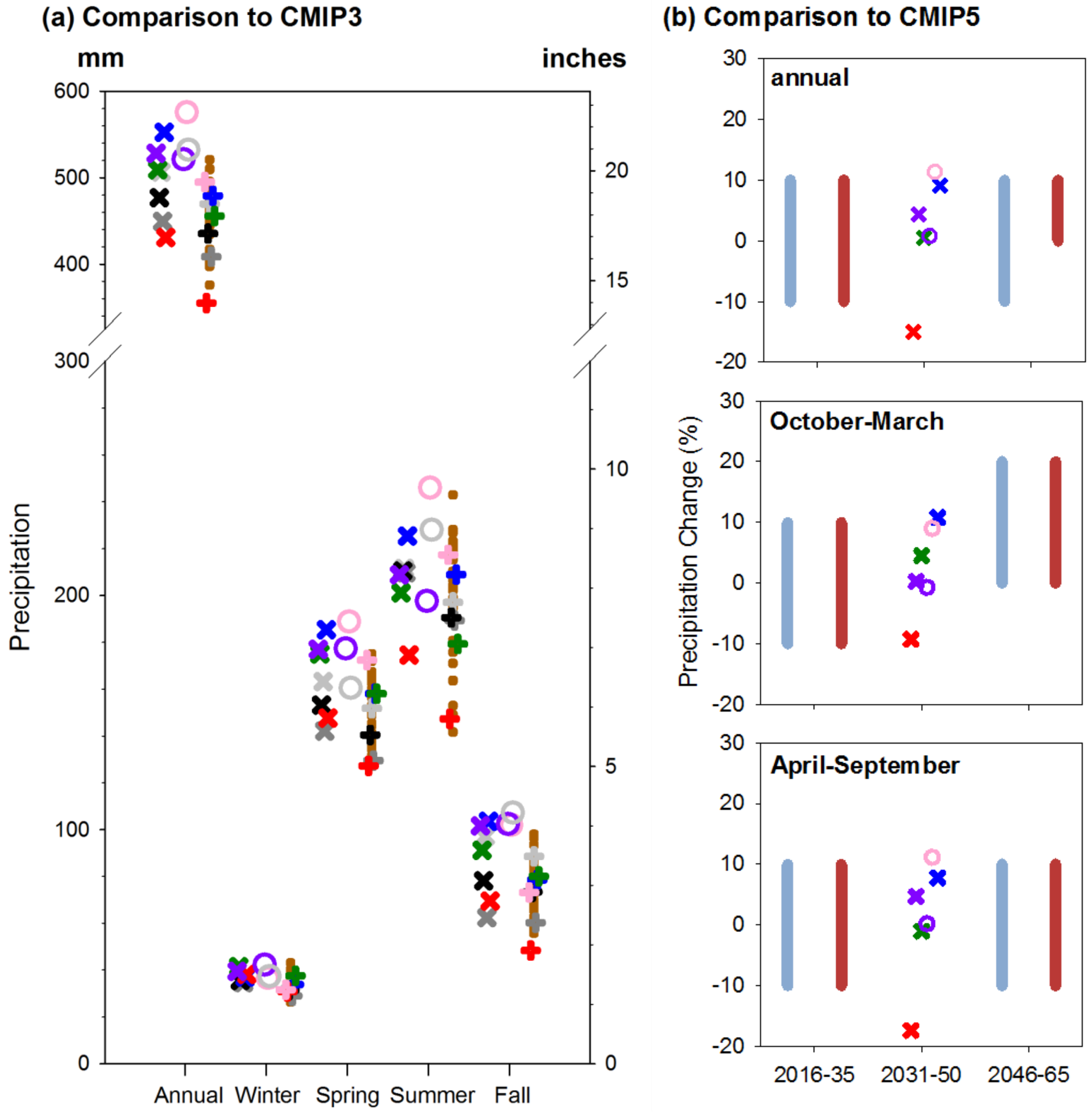

**Figure 4-2.** (a) Mean annual and seasonal precipitation for historical periods and bias-corrected CMIP3 climate projections, A2 emissions scenario, described in Table 4-1. (b) Precipitation anomalies for climate projections used as input for MC1 and RRAWFLOW compared to distribution of anomalies from the CMIP5 ensemble.

**(a)** Each symbol is for an individual historical period (1951-1970, 1980-1999, 1951-1999) or downscaled climate projection (2031-2050). Symbols defined in Table 4-1. **(b)** Symbols (defined in Table 4-1) are relative difference in mean annual or seasonal precipitation between the AR5 reference period (1985-2006) and a future period (shown on x-axis). Light blue and dark red bars represent 25th-75th percentile ranges of CMIP5 ensembles for low-moderate (RCP4.5) and high (RCP8.5) GHG concentration pathways, respectively. Alternative grayscale image in Appendix A.

Specific values of air temperature or precipitation played little role in the scenario planning exercise. However, the ratio of winter to summer precipitation played a large role in shaping the scenarios for this exercise, since the "Shrubland" and "Novel Ecosystem" scenarios were based on the assumption that this ratio would change to resemble that of central or southwestern Wyoming and the vegetation would follow suit (Section 2.2.3). Despite substantial differences in total precipitation among the three historical periods (Figure 4-2a), their winter:summer precipitation ratio generally varied little (0.16-0.18; 0.20 for the WICA weather station's 1985-1999 period). The CSIRO climate input for MC1 has a ratio similar to that of the historical periods, and the CCSM3/WRF and Hadley climate inputs for MC1 slightly higher values (Figure 4-3). Although the average winter:summer precipitation ratio for the 2031-2050 period in the MIROC MC1 climate input is higher (0.22) than the observed average values, a shift to a shrubland vegetation type did not occur in the MC1 simulation using this climate input (Section 3.3.2.2).

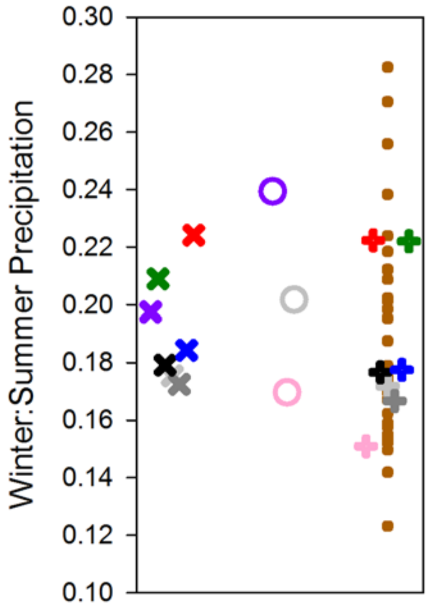

**Figure 4-3.** Mean ratio of winter to summer precipitation for three historical periods and bias-corrected CMIP3 climate projections, A2 emissions scenario, described in Table 4-1.

Symbols defined in Table 4-1. Values are averages for 2031-2050 (climate projections) and 1950-1999, 1951-1970, 1980-1999 (historical periods). Alternative grayscale image in Appendix A.

We acknowledge that MC1 is not optimal for simulating shrubland vegetation types because it contains no distinct shrub life form. In addition, its monthly climate input does not capture probable increases in daily to weekly precipitation variability. This greater variability could favor increased woody plant growth in grassland-forest transition zones (Kulmatiski and Beard 2013). However, we suspect that the lack of a shift to shrubland is not solely due to MC1's shortcomings. Specifically, the winter:summer precipitation ratios of all climate inputs and CMIP3 projections lie well below that of the same ratio for recent climate in the regions on which the Shrubland and Novel Ecosystem scenarios were based: 0.79 and 1.14 for south-central and southwestern Wyoming, respectively[5].

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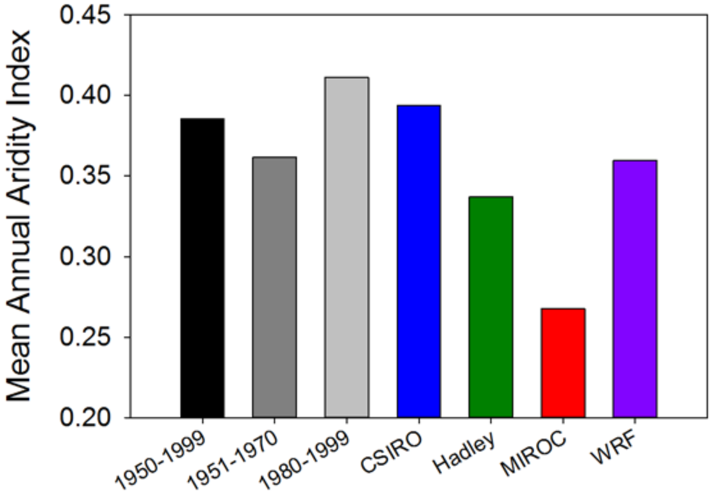
[5] Ratios calculated from 1950-199 monthly precipitation data for Wyoming climate divisions 10 (south-central), 3 (southwest), and 8 (southeast). Data downloaded from http://www.ncdc.noaa.gov/cag/ on 16 April 2014.

Even in southeastern Wyoming, where shrubs are slightly more prominent than in the WICA area, this ratio is still higher (0.34) than all climate projections for WICA. CMIP5 projections for winter:summer precipitation appear to be similar to the range expressed in the BCSD climate products (IPCC 2013b, a). Although we acknowledge, as cautioned above (Section 4.3.1), that the range of future winter:summer precipitation ratios in Figure 4-3 or by the CMIP5 ensemble does not represent all plausible futures, the large difference between even the highest of those and the precipitation regimes understood to result in shrub-dominated landscapes (Paruelo and Lauenroth 1996; Epstein *et al.* 2002) suggests that the Shrubland and Novel Ecosystem scenarios envisioned in the scenario planning exercise are unlikely, at least for the mid-21st century timeframe of that exercise and the quantitative projections in this report.

Another important assumption made during the scenario planning exercise was that, even if precipitation does increase significantly, those increases would not be enough to compensate for the drying effects of increased temperatures on evapotranspiration and, consequently, soil moisture, plant growth, fire behavior, and streamflow. Therefore, a climate less arid than that of the present or recent past was not considered in the scenario planning exercise (Section 2.3.3, Table 2-2). Our quantitative simulations did include one projection that probably contradicts this assumption. We calculated an aridity index as the ratio of annual precipitation to annual potential evapotranspiration (PET) (UNEP 1992) and estimated PET using MC1's standard formulation (King et al. in revision) for climate projections used as input for MC1. The 2031-2050 mean annual aridity index for these four projections varied between 70 and 102% of the 1950-1999 mean annual aridity index. The CSIRO projection was the least arid of these, but it was still more arid than that of the wet 1980-1999 period (Figure 4-4). Similarly, when calculated with MC1's simple streamflow algorithm, which collects the water that has not been used for transpiration at the bottom of the soil profile, mean streamflow for 2031-2050 is greatest for the CSIRO climate projection (142% of the 1950-1999 mean) and least for the MIROC input (15% of the 1950-1999 mean). IPCC reports provide different measures of aridity and emphasize great uncertainty, but their general message for the WICA region is one tending towards greater aridity. Specifically, the short-term (2016-2035) CMIP5 multi-model mean change for soil moisture is negative but not greater than internal variability (Kirtman et al. 2013). In the longer term, soil moisture is projected to significantly decrease for all but the lowest (and least realistic) RCP by the end of the century (Collins et al. 2013). Thus, the assumption of a more arid future used in the scenario planning exercise is entirely reasonable, but the CSIRO quantitative simulation provides an example of ecosystem response in a slightly less arid future.

**Figure 4-4.** Mean annual aridity index for historical periods and four projected climates used in ecosystem simulations with MC1.

Aridity index is the ratio of annual precipitation to annual potential evapotranspiration (PET), calculated for the MC1 grid cell in which WICA headquarters lies. Historic period values were calculated with PRISM climate output. PET was calculated by MC1. Index values for projections are averages for 2031-2050. A lower value indicates a more arid climate.



## 4.4 Summary and Implications

Given the lack of a standard methodology for describing the uncertainty about future climate, one method for understanding how the specific climate input used in quantitative response modeling compares to plausible futures is to relate that input to the range of climate projections available based on a number of statistics. Although different methods of bias correction and downscaling from global to local scales complicate these comparisons, the climate projections used as input for our quantitative simulations of ecosystem response to climate change with MC1 appear to represent a major portion of the range of projections available. This provides some confidence that the management implications drawn from these simulations will be robust to the uncertainties inherent in incorporating climate change into future planning. The climate inputs used for hydrologic response modeling with RRAWFLOW represent a narrower range of the spectrum, in that they both have mean annual precipitation comparable to a wet portion of the historical period and higher than most other projections using the same emissions scenario. Thus, the results of the hydrologic response modelling do not provide a quantitative picture of streamflow and cave lake level in a drier climate compounded by warmer temperatures. However, they do vividly illustrate the importance of precipitation variability.

It is important to remember that even the full ensemble of climate projections from models using a range of future GHG emissions do not necessarily represent the full range of plausible future climates (Collins et al. 2013). Scenario planning exercises like those described in Section 2 are designed to account for this possibility, but the quantitative examination of climate projections in this section suggests that two of the scenarios used in the WICA scenario planning exercise are unlikely to occur, at least for the exercise's stated time frame. Exploration with different ecosystem response models could be used to further evaluate this conclusion.

# 5. Conclusions

To conclude this report, we compare the results, as related to natural resource management planning, of the scenario planning exercise described in Section 2 and the quantitative simulations described in Section 3. We focus on two components of the results, (1) the actual management implications and (2) the confidence in and defensibility of those implications. We close by discussing how the two approaches as used for WICA vary from current NPS climate change response planning practices and suggest how the results from WICA might be used to strengthen those practices.

## 5.1 Comparison of Results from Scenario Planning and Quantitative Simulations

Not surprisingly, there are many commonalities between the management implications derived via the scenario planning exercise and the quantitative simulations of hydrologic and ecosystem response to climate change (Table 5-1). However, quantitative simulations suggested some refinements or additions to these implications, in part because of responses not anticipated in the scenario planning exercise.

**Table 5-1.** Management implications and suggested management actions derived from the WICA scenario planning exercise (Section 2) and quantitative hydrologic and ecosystem response modeling (Section 3 and King et al. 2013b).

| Scenario Planning Exercise | Quantitative Simulations |
|---|---|
| Develop additional surface water sources for wildlife | Develop additional surface water sources for wildlife |
| Achieve current target population sizes for managed herbivores | Avoid long-term, heavy grazing |
| 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 |
| 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 |
| Emphasize more drought-tolerant species in seed mixes | Anticipate impacts of decline in cool-season grasses while warm-season grasses become more dominant |
| Reduce ponderosa pine forest density to reduce chances of widespread crown fire | Determine management goals for tree density in currently forested areas; manage for appropriate prescribed- or wildfire-induced tree and seedling mortality according to these goals |
|  | Maintain an active prescribed fire program to maintain current grassland areas as grassland (burn grasslands every 10-20 years) |
| 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 |
| 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 |
| Monitor mountain pine beetle impacts, invasive plants, and surface and cave water quantity and quality | Monitor surface water and associated vegetation; wildlife health; grassland vegetation composition, production, and phenology; mountain pine beetle impacts; and ponderosa pine recruitment |

All scenarios used in the scenario planning exercise envisioned at least some decline in forage production in the future due to warming temperatures. Quantitative simulations suggest that this is not inevitable for the middle of this century; the opposite could happen in a future climate with moderate temperature and precipitation increases like that of the CSIRO projection, and even in a relatively hot climate like that of the Hadley climate input the reduction could be moderate because of the ameliorating effects of higher $CO_2$ concentrations and earlier spring green-up. However, the simulations also emphasized the fact that moderate changes in averages may mask large interannual variability (CSIRO climate input, Figure 3-11), and that the timing of peak production could change. Increasing major herbivore management flexibility and ability to respond quickly to current conditions would be a sound action in any future climate, but it would be especially helpful in a more variable climate.

Although quantitative simulations presented less dire futures for forage production than envisioned in the scenario planning exercise, they confirmed the vulnerability of surface water sources to climate change. Thus, especially when considered with results of recent evaluations of the vegetation associated with these water sources and of grassland forage production in the park (Burkhart and Kovacs 2013, 2014), climate change planning by either approach points to the importance of developing surface water management practices that will ensure water availability adequate for wildlife health and prevent further degradation of riparian vegetation.

In the Shrubland and Novel Ecosystem scenarios of the scenario planning exercise, decreased forage production for grazers was envisioned due to an increase in hardwood shrubs at the expense of perennial grasses. In contrast, quantitative simulations suggested that forage production could be negatively impacted by the continuing encroachment of ponderosa pine into park grasslands in the absence of fire. Concerns during the scenario planning exercise that WICA's current prescribed fire program of burning grassland areas to prevent such encroachment could work against climate-change-driven vegetation shifts to something like sagebrush shrubland were not supported either by the quantitative vegetation simulations or by quantitative comparisons of a broad range of climate projections to the winter:summer precipitation regime needed to support those changes. Thus, the quantitative simulations support the continuation of a prescribed fire program in grasslands.

Scenarios in the scenario planning exercise admitted much uncertainty about the future of ponderosa pine in the currently forested areas at WICA, although three of the four described its decline. This decline was attributed to increased moisture stress and its effects on pine recruitment and susceptibility to mountain pine beetle, but also to increased tree mortality caused by more intense fires. Quantitative simulations could not account for mountain pine beetle, but they did suggest that indirect effects through fire will have a greater influence on the future of pine forests and woodlands than will direct effects of climate, and that these indirect effects would indeed reduce pine biomass in the currently forested areas regardless of the future climate. Both approaches yielded a management implication of using prescribed fire or other means to thin currently forested areas to reduce the potential for high tree mortality in a wildfire. This would serve the dual purpose of hopefully increasing forest resistance to high mountain pine beetle mortality. However, the quantitative simulations did not alleviate concern about pine recruitment in a warmer future. MC1 does not account for different life stages having different climate requirements, but the drastic retraction of ponderosa pine from the WICA area projected by climate envelope studies (Shafer *et al.* 2001; Rehfeldt *et al*. 2006) suggested to management staff that a precautionary approach to pine forest management is warranted. Thus, a further management recommendation from the quantitative simulation was to closely monitor pine recruitment and adjust prescribed fire timing to ensure adequate recruitment (King et al. 2013b).

The scenario planning exercise anticipated greater fire danger (frequency and intensity) and the quantitative simulations supported this. The latter illustrated that the nature of this increase is very dependent on the climate projection, in that one (MIROC) showed a gradual but fairly steady increase in the number of high-fire-danger days each year while the others showed various patterns of switching between years of very low fire danger and years with many more high-fire-danger days than in the past. Managers might consider how funding might react in these different situations, or conversely, how a fire program funding structure could be designed to be robust to all of these situations.

WICA's scenario planning workshop identified a need for more information on the impacts of climate change on cave resources. Accomplishing quantitative simulations of the geologic processes that form and erode Wind Cave's speleothems is hindered by a lack of historical data on which to base them. In the scenario planning exercise, only the Shrubland scenario mentioned the Madison aquifer, which is manifested in Wind Cave as various subterranean lakes, and it was assumed that lake levels would drop due to greater evapotranspiration. Quantitative observations and simulations suggest that the current lake level is high due to the historically wet period of the 1990s, and that this wet period will continue to influence cave lake level through the middle of the century, but that cave lake level could rise or fall depending on the degree of air temperature increases and whether intra- and inter-annual variability in precipitation change. Increased groundwater pumping – anticipated even in the absence of climate change – and surface water diversions were not considered in either climate change planning approach but could have much stronger impacts on cave water than would climate change.

Finally, both approaches suggested that resource monitoring will be critical for adjusting management actions to fit the climate as it unfolds. Such feedback monitoring is an assumed component of the scenario planning approach taught at the workshop in which WICA staff participated, but it would also provide valuable feedback for improving both hydrologic and ecosystem response models. Even in the unlikely event that global GHG emissions are drastically reduced in the very near future, the long-lived effects of the GHG already emitted will necessitate incorporating climate change into management planning for a long time to come (Collins et al. 2013). Thus, such monitoring would provide the information necessary to improve confidence in future climate change management planning exercises.

### 5.2 Defensibility of Management Implications Derived Via the Two Approaches

As described in Section 2.4, one recommendation stemming from WICA's scenario planning exercise was to better develop, test, and validate the scenarios. This was deemed necessary to ensure that the scenario planning approach had the credibility necessary to defend management plans derived from it when scrutinized by the public, such as through the NEPA process. Direct testing or validation of the scenarios used in the 2009 exercise is not possible for two reasons. First and foremost, the climates assumed to produce the ecosystem scenarios were not quantified. In addition, manipulating climate projections to produce specified ecological outcomes (i.e., to assess the climatic conditions required to create a specific vegetation type) violates the physical connectivity of climatic processes that produce the physically consistent, continuous time-series projections needed in models like MC1 and RRAWFLOW.

Nonetheless, even though our quantitative simulations of hydrology used a narrow range of climate futures, the fact that the wet but hot climate projections used did not produce increased streamflow partially supports the assumption in all the scenario planning scenarios that streamflow would decrease. Moreover, our quantitative simulations of fire danger supported the assumption that fire danger would increase. On the other hand, our quantitative simulations of vegetation covered a wide range of climate futures but failed to produce vegetation futures envisioned in the Shrubland and Novel Ecosystem scenarios in the mid-century timeframe targeted by both approaches, and declines in forage production assumed in all scenarios were not as strong as envisioned. Thus, the WICA team's lack of confidence in the ecosystem scenarios used in the scenario planning exercise was warranted.

Although the quantitative simulations did not support some of the scenarios, the management implications derived from the two approaches did not differ strongly (Table 5-1). The greatest discrepancy was for fire management of the grassland areas of the parks; the quantitative simulation approach suggested that ponderosa pine encroachment, not retraction, will be an important management issue. The quantitative simulations' greatest contributions were (1) quantitative illustration that climate change effects of WICA vegetation are more likely to be indirect – through fire – than direct; (2) quantitative understanding of the magnitude of changes in forage production under various climate projections; (3) the realization that the long system memory of Calcite Lake (WCL) will provide some buffer against direct climate change effects on its level in Wind Cave; (4) counter-intuitive results stemming from the importance of intra- and interannual climatic variability on quick- (streamflow) and slow- (aquifer level) response hydrological systems; and (5) a more complete list of items that should be monitored.

The high agreement between the management implications derived from the two approaches can be attributed to two factors. First, despite a lack of literature on climate change impacts specific to the WICA region, the collective expertise in the WICA scenario planning team allowed the team to mostly anticipate the direction of hydrologic and ecosystem changes caused by both direct and indirect effects of climate change, even if they weren't sure of the magnitude of those changes in the target time frame. In fact, some uncertainties expressed during the scenario planning regarding details of ecosystem response (such as the future ratio of warm- to cool-season grasses) remained uncertain with the quantitative simulations; data to reduce these uncertainties do not exist. Second, the management implications derived from the scenario planning exercise were "no-regrets" actions – those that would be applicable in any of the scenarios, and these scenarios encompassed those produced by the quantitative simulations. Management actions derived to address just the more drastic scenarios – ceasing prescribed fire in grasslands to allow development of a shrub community, for example – would not be as defensible as those applicable in all considered scenarios, especially when, as was the case here, those scenarios are not supported by quantitative modeling.

## 5.3 Putting It All Together

Scenario planning for incorporating climate change into natural resource management in the NPS has evolved since WICA's scenario planning exercise in 2009 (National Park Service 2013). For example, instead of nesting climate-driven scenarios into a society-driven scenario matrix as in the WICA exercise, both types of drivers are used in a single matrix. In the WICA exercise, the requirement to create distinct ecosystem scenarios based only on climate uncertainties resulted in the two scenarios that quantitative simulations suggest are unlikely. If WICA were to do another scenario planning exercise, the results of the quantitative simulations suggest that uncertainties about future funding for prescribed fire and fire suppression would be an important driver to consider. This illustrates the utility in combining the two approaches to produce robust, defensible management plans that account for climate change.

The 2009 WICA scenario planning exercise also predated the release of the NPS Climate Change Response Strategy (National Park Service 2010). This document provides a conceptual approach for collaborative climate change adaptation planning. This approach begins by framing the issue – determining relevant temporal and spatial scales, resources and required decisions – and establishing a core interdisciplinary team. The second step is assessing science and knowledge – summarizing literature, compiling climate projections, and conducting vulnerability assessments. The Response Strategy states that NPS does not have an established procedure for conducting a climate change vulnerability assessment (CCVA), and the procedure will inevitably vary depending on the resources and decisions highlighted in first step (Glick et al. 2011). The third step develops scenarios, assesses the risks of each of those scenarios, and evaluates management options. Results of this step naturally lead into the final step of producing an action plan that prioritizes actions and implements them following compliance requirements.

As a prototype park, WICA did not follow this order of procedures. The 2009 scenario planning exercise did provide an opportunity for framing the issue and to identify science partners, the latter being critical for science-based climate change response (Peterson et al. 2011). The exercise involved some science and knowledge assessment, but not to the point of compiling a formal literature summary, quantitatively downscaled climate projections for the area, or a CCVA. Those are largely provided in this document and other products of the climate, hydrologic, and vegetation simulation modeling (King *et al.* 2013b; climate, hydrology and vegetation databases described in Appendix D; 2013a), though formal vulnerability assessment of all factors identified in the scenario planning exercise was not possible to complete. Although WICA completed the first three steps of the approach in an order different than that recommended, the high consistency in management implications between the park's scenario planning exercise and this quantitative assessment of hydrologic and ecosystem responses indicates that WICA has the rigorous information needed to incorporate climate change into future action plans.

Finally, the process of WICA's two approaches for incorporating climate change into natural resource management planning yielded important lessons that could be incorporated into other NPS climate change planning work. We highlight two of these. First, as a prototype park for a scenario planning training workshop, WICA may not have had as much time or personnel support for compiling information before the workshop that presently occurs. Adequate amounts for both of these are critical, however, for higher confidence in the results of a scenario planning exercise, and the two-workshop approach described in the NPS scenario planning handbook (National Park Service 2013) would be better than the one-workshop approach used for the prototype parks. Second, the NPS Climate Change Response Strategy (National Park Service 2010) advocates the development and use of models that can be used by managers to plan for and adapt to climate change impacts, but the NPS climate change scenario planning handbook does not. Quantitative simulations provide a more defensible base for management decisions, but we suggest that an equally important role of such simulations is in providing tangible values for the degree of change that might be expected in important factors; at WICA, these include the number of high-fire-danger days and grass production. Although these values come from models, and all models are wrong (but some are useful), they provide a better understanding of the degree of change in management, funding, policy, or goals that might be required in the future than do simple statements of "higher fire danger" or "lower forage production". Thus, we see value in incorporating quantitative climate scenarios and simulations into climate change planning exercises. Developing widely applicable, affordable means for doing this would provide an efficient mechanism for translating climate change science into management actions.

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# Appendix A: Alternative Figures

Color-blind friendly alternatives of select figures in the main text are provided in this appendix.

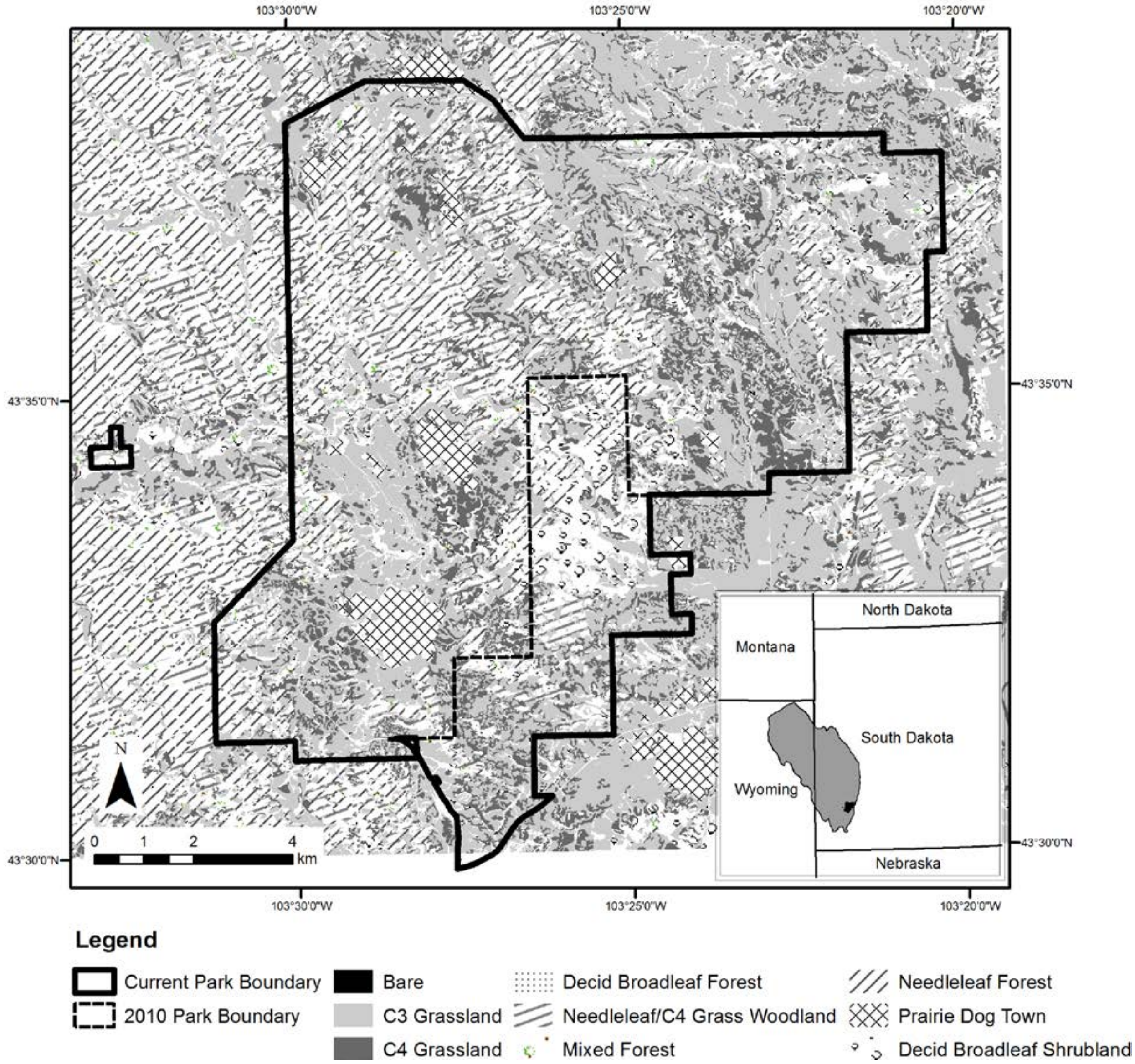

**Figure A1-1.** General vegetation types at Wind Cave National Park based on vegetation mapping from 1997 aerial imagery (Cogan et al. 1999).

Inset shows location of park (black) within the Black Hills (gray). Coordinate System: NAD 1983 UTM Zone 13N.

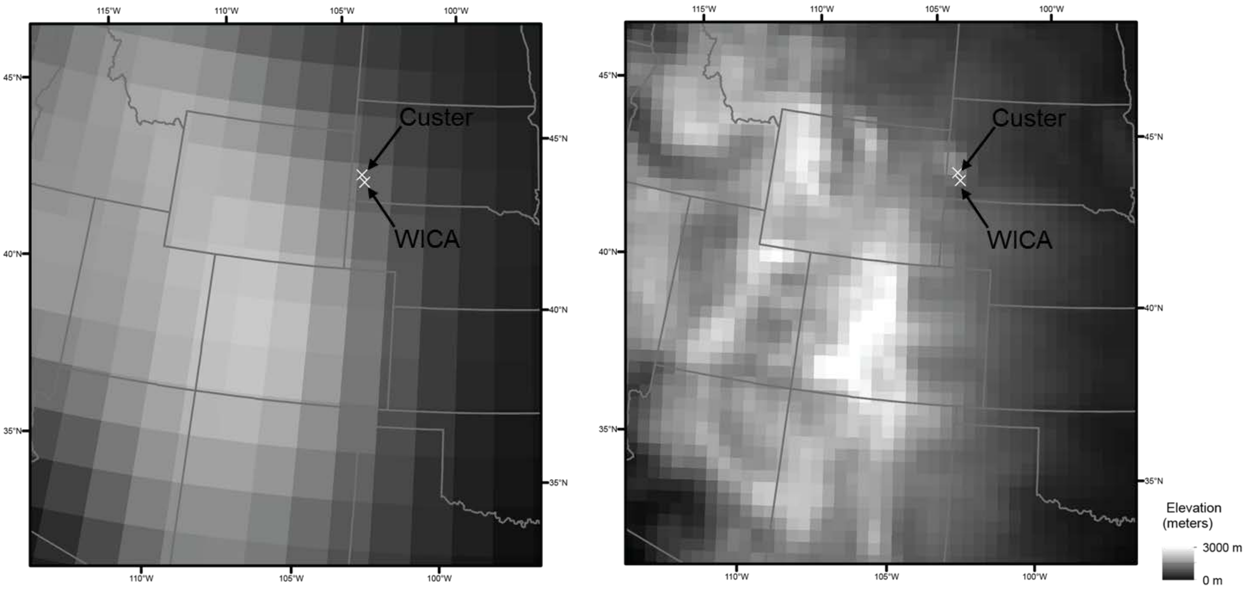

**Figure A3-5.** Elevation of the west-central United States as represented by (left) the Community Climate System Model, version 3 (CCSM3) and (right) the Weather Research and Forecasting (WRF) model as implemented in this project.

Locations of Custer and WICA weather stations are indicated on each map. Coordinate System: World Geodetic System, 1984. 3000 m elevation is 9,850 feet.

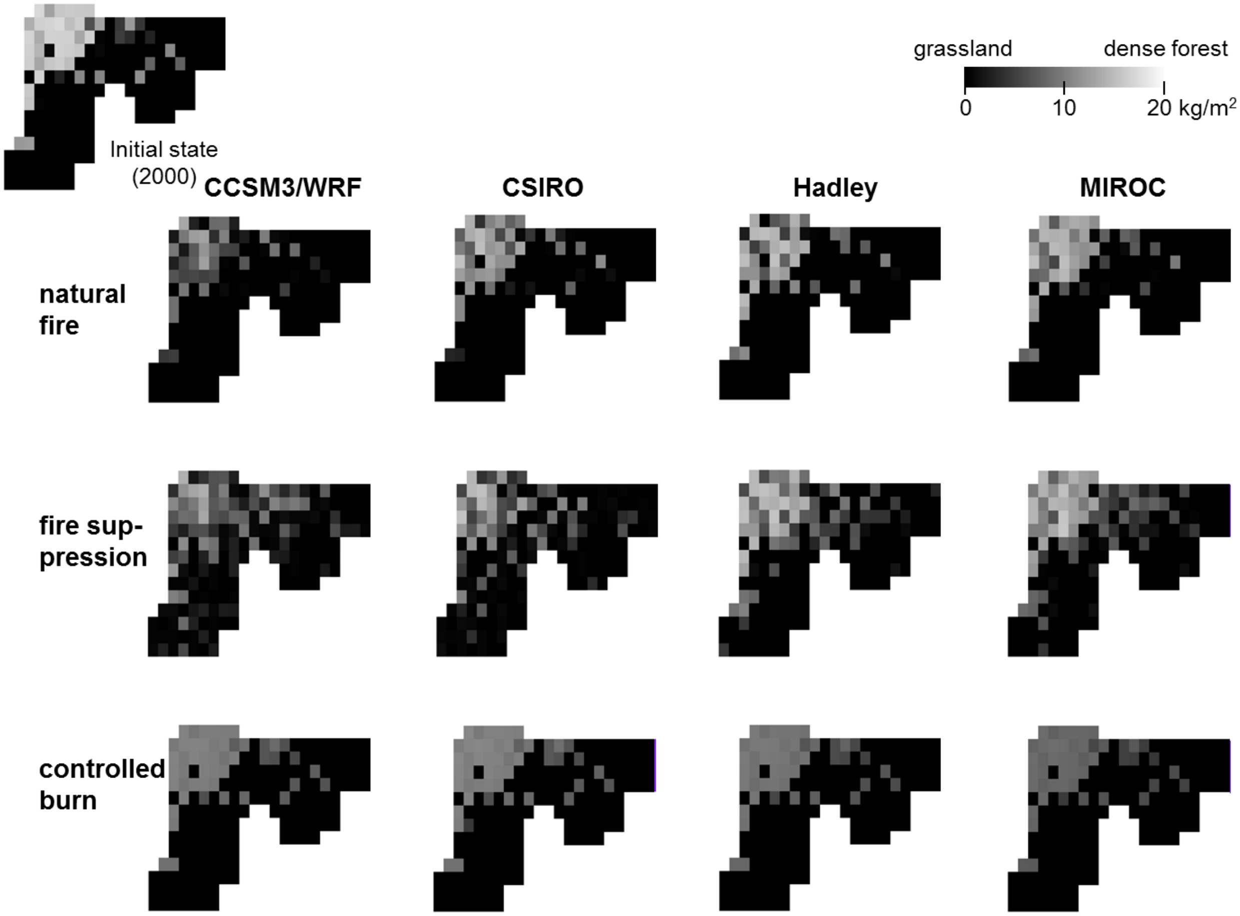

**Figure A3-9.** WICA tree biomass simulated with MC1 for historical conditions (year 2000, upper left) and the four projected climates represented in Figure 3-8 (year 2050) in three fire regimes.

Each shape represents the polygon encompassed by the 2010 WICA boundary. Fire regimes are described in section 3.2.3. 20 kg/m2 = 89 tons/acre.

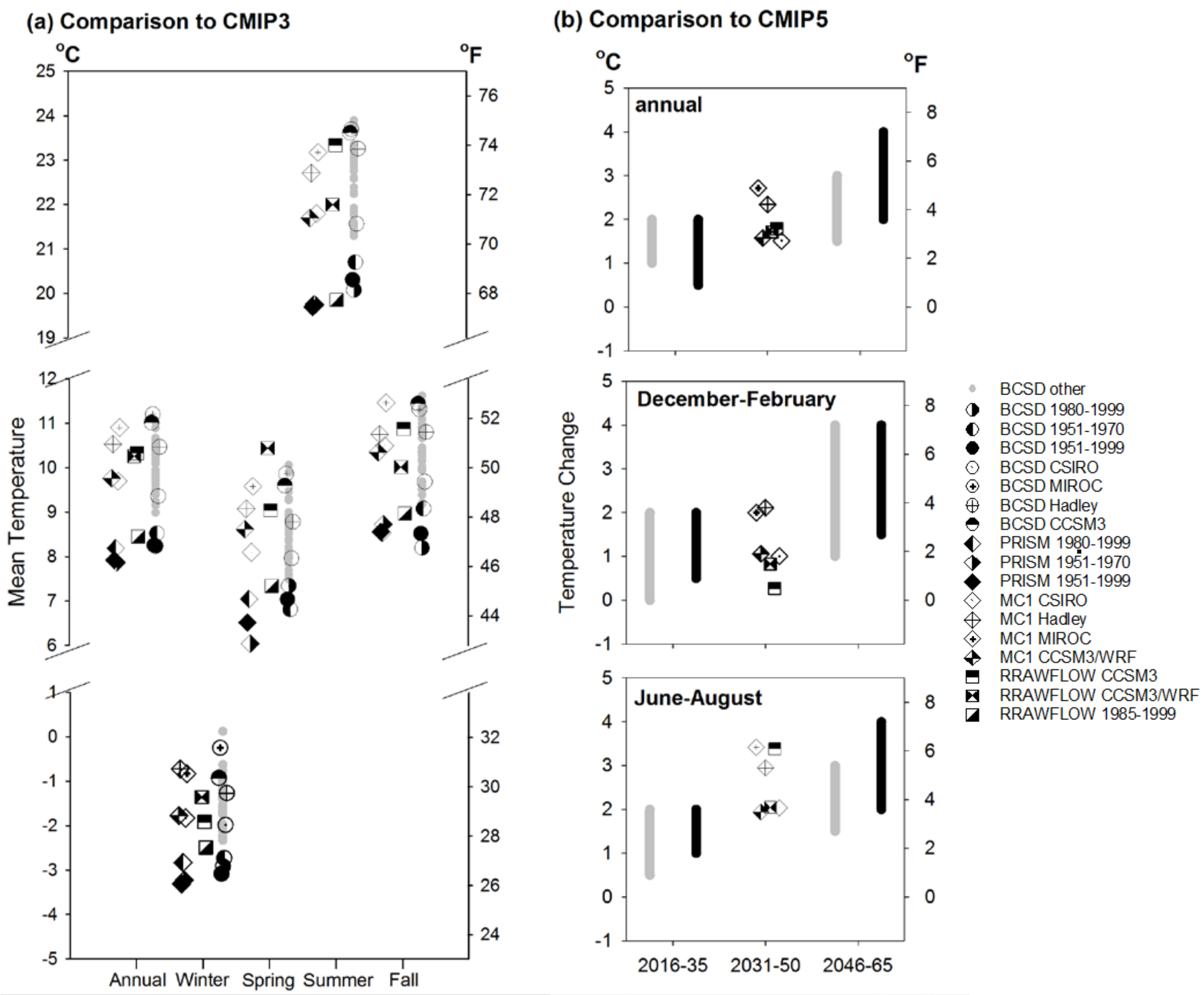

**Figure A4-1.** (a) Mean annual and seasonal air temperature for historical periods and bias-corrected CMIP3 climate projections, A2 emissions scenario, described in Table 4-1. (b) Air temperature anomalies for climate projections used as input for MC1 and RRAWFLOW compared to distribution of anomalies from the CMIP5 ensemble.

**(a)** Each symbol is for an individual historical period (1951-1970, 1980-1999, 1951-1999) or downscaled climate projection (2031-2050). **(b)** Symbols are absolute difference in mean annual or seasonal air temperature between the AR5 reference period (1985-2006) and a future period (shown on x-axis). Gray and dark black bars represent 25th-75th percentile ranges of CMIP5 ensembles for low-moderate (RCP4.5) and high (RCP8.5) GHG concentration pathways, respectively.

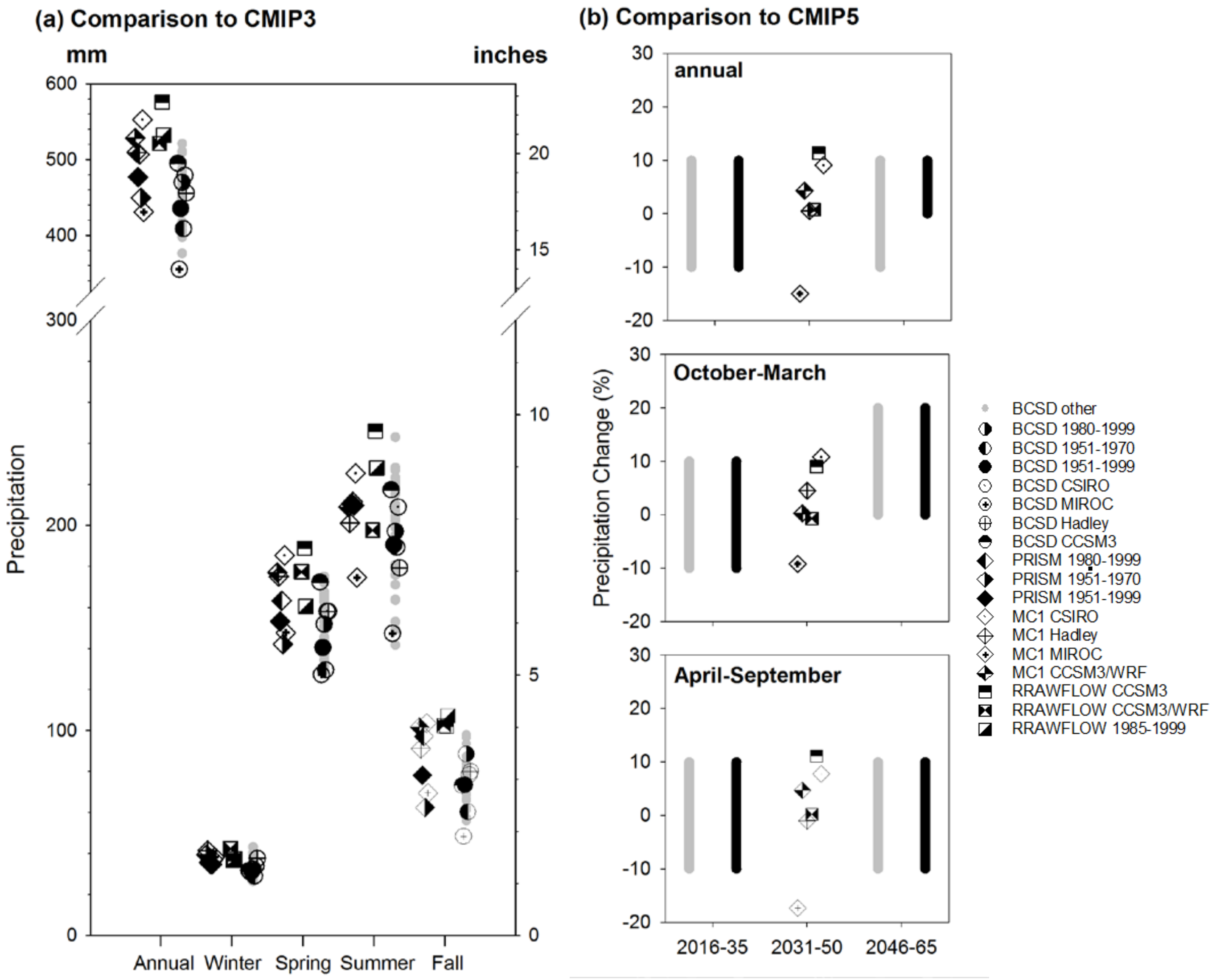

**Figure A4-2.** (a) Mean annual and seasonal precipitation for historical periods and bias-corrected CMIP3 climate projections, A2 emissions scenario, described in Table 4-1. (b) Precipitation anomalies for climate projections used as input for MC1 and RRAWFLOW compared to distribution of anomalies from the CMIP5 ensemble.

**(a)** Each symbol is for an individual historical period (1951-1970, 1980-1999, 1951-1999) or downscaled climate projection (2031-2050). **(b)** Symbols are relative difference in mean annual or seasonal precipitation between the AR5 reference period (1985-2006) and a future period (shown on x-axis). Gray and black bars represent 25th-75th percentile ranges of CMIP5 ensembles for low-moderate (RCP4.5) and high (RCP8.5) GHG concentration pathways, respectively.

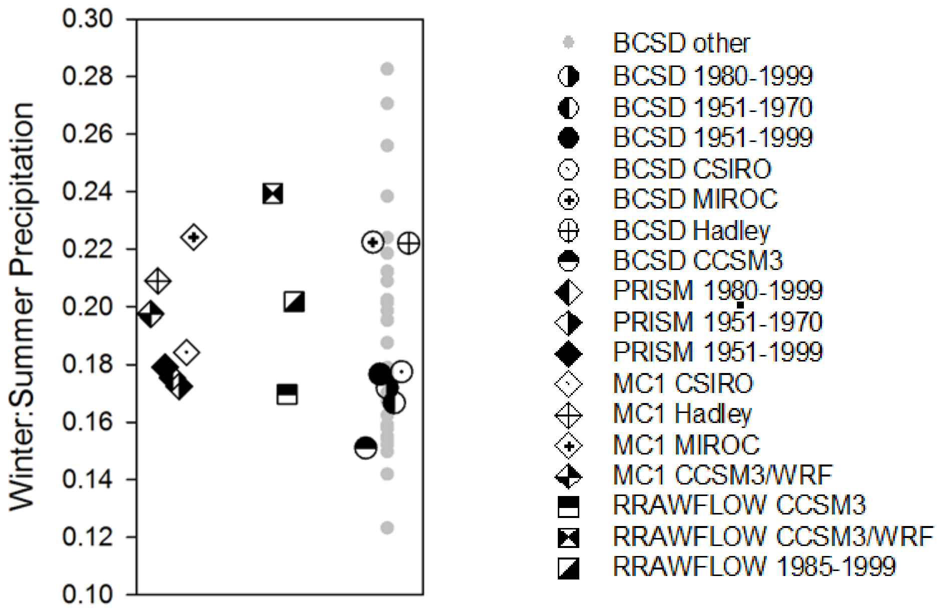

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**Figure A4-3.** Mean ratio of winter to summer precipitation for three historical periods and bias-corrected CMIP3 climate projections, A2 emissions scenario, described in Table 4-1.

Symbols defined in Table 4-1. Values are averages for 2031-2050 (climate projections) and 1950-1999, 1951-1970, 1980-1999 (historical periods).

# Appendix B: Climate Change-Sensitive Items at Wind Cave National Park

WICA ecosystem response team members assembled a list of items they expected to be affected by climate change, either directly or indirectly. This table, organized by areas of responsibility (sector), is probably incomplete, but it provided the background for determining which aspects of the changing climate were most important in determining how these items would be affected.

Items at Wind Cave National Park sensitive to climate change.

| Sector | Sub-Sector | Item |
|---|---|---|
| Natural Resources | Hydrology & Water Resources | • Drinking water (human and animal)<br>• Stream, seep, and spring flow (amount and timing of peak and dry periods)<br>• Floods and associated erosion and sedimentation<br>• Snow cover<br>• Cave lake/Madison aquifer levels<br>• Drip rates in cave<br>• Stream temperatures<br>• Southern Black Hills water mining |
| | Cave | • Internal climate<br>• Formation/dissolution of features<br>• Volume of water loss/gain through cave breathing<br>• Cave wind events affected by frequency and amplitude of pressure changes |
| | Air Resources | • Dust/particulate matter/visibility<br>• Pollution (nutrient and acid deposition) |
| | Paleontological Resources | • White River sites (exposure and effects of exposure affected by erosion rates, freeze-thaw cycles)<br>• Illegal visitor collections if more exposed |
| | Vegetation | • Dominant species/community composition<br>• Species richness<br>• Species range and abundance (loss/gain of those on edge; rare species)<br>• Riparian, wetland and aquatic plant species and communities<br>• Phenology, including synchrony with pollinators/herbivores/granivores/dispersers (affecting reproduction timing and success)<br>• Resilience to disturbance and restoration potential<br>• Invasive species<br>• Wildlife forage availability<br>• Wildlife patterns of vegetation use<br>• Habitat for structure-sensitive species<br>• Forest/prairie interface<br>• Forest structure |

Items at Wind Cave National Park sensitive to climate change (continued)

| Sector | Sub-Sector | Item |
|---|---|---|
| Natural Resources | Wildlife | • New, or altered resistance to existing, wildlife diseases<br>• Dominant species/community composition<br>• Species richness<br>• Resilience to disturbance and restoration potential<br>• Invasive species<br>• Phenology, including synchrony with food/host species (e.g., butterflies)<br>• Migration patterns<br>• Reproduction timing and success rates<br>• Activity patterns in space and time<br>• Species range and abundance (loss/gain of those on edge; rare species)<br>• Aquatic and riparian animal species and communities<br>• Carrying capacity<br>• Endangered species (ferret) |
| | Disturbance | • Fire (wild and prescribed)<br>  • frequency, intensity, extent<br>  • impact on forage availability<br>  • heavy metal release from burnt trees<br>• Mountain Pine Beetle and other insects<br>• Diseases/pathogens<br>• Flood<br>• Early/late freezes<br>• Ice storms<br>• Wind events<br>• Hail<br>• Heavy rain<br>• Human disturbances |
| | Soil | • Wind and water erosion/soil structure<br>• Carbon & nutrient cycling<br>• Soil flora & fauna |
| Cultural Resources | Historic Structures | • Pest infestations<br>• Damage from climate events (ice, hail)<br>• Maintenance requirements, effect on compliance workload |
| | Museum Collection | • Need to collect more voucher specimens<br>• Pest infestation rates |
| | Archeological Resources | • Exposure and effects of exposure affected by erosion rates, freeze-thaw cycles<br>• Illegal visitor collections if more exposed |
| | Ethnographic Resources | • Use patterns for sun dances and other ceremonies<br>• Collection of ethnographic resources (plants, animals)<br>• Related to natural resources |
| | Cultural Landscapes | • Changes to/maintenance of cultivated vegetation<br>• Ice storms and wind events affecting look of cultural landscape<br>• Viewshed of whole park (especially vegetation communities) |

Items at Wind Cave National Park sensitive to climate change (continued)

| **Sector** | **Sub-Sector** | **Item** |
|---|---|---|
| Facilities | Roads & Trails | • Maintenance rates affected by summer temperatures, freeze/thaw cycles, erosion, fire<br>• Hazard tree reduction |
| | Structures | • Same as historic structures |
| | Utilities | • Costs for temperature/humidity control<br>• Sewage lagoon maintenance<br>• Availability of water for public drinking water system |
| | Fleet Management | • Needs for snow plowing and grass mowing<br>• Tire wear/replacement |
| | Boundary Fence | • Changes in wildlife migration patterns<br>• Pressure from outside wildlife and livestock |
| Visitor & Resource Protection | Recreation | • Visitor use -- patterns in time and space |
| | Fire | • Human and structure protection<br>• Human-caused (intentional and unintentional) fire rates |
| | Emergency Response | • Heat-related illnesses and injuries<br>• EMS response for poisonous/swarming animal injuries (Africanized bees, fire ants, rattlesnakes) |
| Interpretation & Education | Outreach: Media & Educational | • More offsite outreach to educate local populations on changes<br>• Themes of park messages<br>• Management changes to programs due to climate changes |
| | Visitor Services & VC Operations | • New exhibits<br>• Visitor expectations of visitor center (safety, expertise, etc.) |
| | Visitor Programs | • Visitation levels to different sectors (above- vs. below-ground; parts of above-ground)<br>• Length of main visitation season and patterns of visitation throughout year<br>• Whole or partial park closures due to pandemics or wildlife disease outbreaks<br>• Availability of cave tours<br>• Changes in demographics |
| Administration | Funding | |
| | Staffing needs | |

# Appendix C: Wind Cave National Park Climate Drivers Table Used for Scenario Planning

The table below is the summary of projected climate changes for Wind Cave National Park used during the 2009 scenario planning exercise. Steve Gray, Wyoming State Climatologist, adapted it from the IPCC Fourth Assessment report (IPCC 2007). It is based on output from 21 climate models run under the A1B greenhouse gas emission scenario. Ranges for temperature and precipitation represent the 25th and 75th percentiles from the model runs. Wind Cave National Park (WICA) is on the border of two broad climate zones summarized in the regional IPCC estimates: western North America and central North America. Western North America estimates are used to represent winter conditions and central North America estimates are used for summer.

Summary of projected climate changes for Wind Cave National Park based on the IPCC Fourth Assessment Report (IPCC 2007).

| **Climate Variable** | **General Change Expected** | **Range of Change Expected & Reference Period*** | **Size of Expected Change Compared to Recent Changes** | **Seasonal Patterns of Change** | **Confidence** |
|---|---|---|---|---|---|
| Temperature | Increase | 1.7 to 2.2 °C<br>(3.1 to 3.9 °F) increase by 2050 | Large | Forecast increases are slightly higher in summer | Virtually certain that temperature will increase; predictions for rate and magnitude of change vary, but forecasts consistently call for an ecologically significant rise in temperature |
| Precipitation | No change to small increase in total annual precipitation | 2-5% increase in winter by 2050; -7 to -3.5% decrease in summer by 2050 | Small to Moderate; most changes within the bounds of the observed record | Increase in winter, decrease in summer | The majority of projections suggest modest increases in winter precipitation, though some predictions disagree; forecasts are generally inconsistent in their portrayal of summer precipitation |
| Evaporation | Increase | Primarily dependent upon temperature change (magnitude, seasonality and diurnal change) | Large | Primary impacts in late spring, summer and early fall | Changes in evaporation are tied to increasing temperatures; therefore it is very likely that increased evaporation will occur |
| Drought | Increased frequency and severity; possible increase in duration | Varies with magnitude of temperature change and evaporation change; decreasing precipitation would exacerbate this drying | Moderate to large | Greatest impacts in summer; also potential for hydrologic drought related to changes in snow pack | Changes in regional drought are primarily a function of increasing temperatures; large increases in precipitation would be needed to offset these impacts. Therefore it is very likely that drought severity and frequency will increase; multiple forecasts also suggest that drought duration will increase. |

Summary of projected climate changes for Wind Cave National Park (continued).

| Climate Variable | General Change Expected | Range of Change Expected & Reference Period* | Size of Expected Change Compared to Recent Changes | Seasonal Patterns of Change | Confidence |
|---|---|---|---|---|---|
| Snow cover | Increase in snow-free days; decreased snow accumulations | Could see >50% reduction in average March snow depths by 2050 | Varies with potential snow cover | Greatest potential impacts in late fall, late winter and early spring | Changes in snow cover are tied to increasing temperature. Therefore it is very likely that snow cover will decline, though increased winter precipitation may offset the overall impact of this change |
| Length of growing season | Increase | Varies with magnitude of temperature change, but likely to be several weeks longer by 2050 | Moderate to large | Spring-like temperatures arrive earlier; date of last frost becomes earlier; fall-like temperatures and frost arrive later | Very likely |
| Extreme Events: Temperature | Warm Events Increase / Cold Events Decrease | Varies with magnitude of temperature change | Moderate to large | Increase in frequency and length of extreme hot events (summer); decrease in extreme cold events (winter) | Very Likely |
| Extreme Events: Precipitation | Decreased frequency of precipitation events coupled with increased intensity | Uncertain | Moderate | Potential for more intense spring floods and flash floods during summer | Model projections are inconsistent, but summer warming may lead to more intense thunderstorms. Response in spring depends on the impact of increasing temperatures on moisture delivery from the Gulf of Mexico |
| Extreme Events: Storms | Increased intensity; possible decrease in frequency | Uncertain | Moderate | Potential for more intense thunderstorms and storm-related impacts | Same as above |

# Appendix D: Project-Related Datasets Provided to WICA

Two datasets summarizing the input for and results of the quantitative simulations in this report are provided to the park for their use, including in the development of interpretive materials.

- “Hydro_data.xls” includes the daily climate input for, and hydrologic output from, RRAWFLOW simulations. Each of four worksheets in this single file contains the data for a single simulation; the four simulations result from the factorial combination of two climate projections (CCSM3/WRF and CCSM3) and two response sites [Beaver Creek and Calcite Lake (WCL)].

- “MC1” contains two folders. The first (MC57) is the directory structure used to compile MC1 and run the MC1 executable file, as used for this project. The second (WindCaveFinal) contains archived inputs and outputs used in writing this report and the earlier vegetation report (King et al. 2013b). The climate input and primary output are in the form of netCDF files, which can be viewed in ArcGIS. Documentation included in each folder and subfolder describes their content.

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