Session Two.
The Sage-grouse Dilemma: A Case Study of Long-term Landscape Use and Abuse

Chair
Rollin D. Sparrowe
Daniel, Wyoming

Cochair
Len H. Carpenter
Wildlife Management Institute
Fort Collins, Colorado

Climate Change Implications for Sagebrush Ecosystems

Ronald P. Neilson
U.S. Department of Agriculture, Forest Service
Corvallis, Oregon

James M. Lenihan
U.S. Department of Agriculture, Forest Service
Corvallis, Oregon

Dominique Bachelet
Oregon State University, Department of Bioengineering
Corvallis, Oregon

Raymond J. Drapek
U.S. Department of Agriculture, Forest Service
Corvallis, Oregon

Introduction

The sagebrush biome in the Great Basin of the western United States is among the three largest in the country (approximately 243,000 square miles [630,000 km^2]), comparable to the Great Plains and the eastern deciduous forest (Barbour and Billings 1988). However, the area has recently been reevaluated to 66,000 square miles (430,000 km^2)(Miller and Eddleman 2000, Wisdom et al. 2005). There are several defining climatic features of the sagebrush ecosystem that are vulnerable to change under rapid climate change. The system is continental, being very hot in the summer and subject to recurrent hard frost every winter. It is “Mediterranean,” being wet in the winter and dry in the summer but remains a generally semiarid ecosystem. One of the more fascinating features of the Great Basin is its relative flatness, being around 4,000 feet (ca. 1,200 m) in elevation, punctuated by numerous north-south mountain ranges. As a consequence of the cold, Mediterranean climate, the plants tend to be very frost tolerant and dependent on deep soil water, recharged from winter precipitation, to supply their summer transpiration demands. The natural perennial grasses flourish in the spring but struggle through the long, dry summer and support a relatively meager fire regime. Frequent fires take out the vulnerable shrubs, as is apparent under the rapidly invading annual cheatgrass, which increases the fire frequency.

The cold-temperate sagebrush ecosystem is immediately bounded on the south by the hot, southwest deserts. There is about a 2,000-foot (600-m) scarp separating the higher Great Basin from the much warmer southwest deserts. Thus, much of the vegetation in the Southwest is extremely frost sensitive and supports a high diversity of cacti, as well as frost-sensitive evergreen broadleaf trees and shrubs and many other plant groups. The frost line separating these two broad biomes, hot and cold semideserts, is currently locked on the steep elevational scarp separating the two biomes. Two of the three southwest deserts, the Chihuahuan and Sonoran, also differ from the Great Basin by virtue of a well-defined midsummer rainfall regime, the Arizona monsoon, which can supply as much as 40 percent of the annual precipitation. During the middle Holocene thermal maximum, perhaps 4,000 to 6,000 years ago, much of this hot-desert diversity must have penetrated into the Great Basin, as indicated by the 250- mile (400-km) northward advance of at least one frost-sensitive species, shrub live oak (*Quercus turbinella*), implying a northward march of both the frost line and the summer rainfall regime (Cottam et al. 1959, Neilson and Wullstein 1983). This suggests things to come.

Another prominent feature in the sagebrush ecosystem is the widespread range expansion and in-filling of woody species, primarily pinion-juniper and ponderosa pine over the past several decades. It is widely accepted that this woody expansion is largely due to both fire suppression and fire exclusion via grazing of fine fuels. We hope to demonstrate that climate variability has also contributed to this woody expansion and that it may well continue into the future, regardless of the best intentions to reduce inland fuel loads. So, the sagebrush ecosystem is currently under threat of reduction in size from two immediate sources, invasion of nonnative annual grasses (possibly as much as 25% of its area, [West 2000]), altering the fire cycle, and expansion of native woody species. We will suggest that climate change could add a third dimension to the risk of a waning sagebrush ecosystem and that it could occur rapidly. We will also suggest, through process-based modeling, that there are synergistic interactions among these various stressors.

There is also a certain irony with respect to two large-scale policy concerns within the United States. On the one hand, we wish to reduce fuel loads in the West in order to reduce the risk of catastrophic fire and to restore natural ecosystems. On the other hand, we wish to foster the sequestration (storage) of large amounts of carbon in natural ecosystems as an offset to carbon dioxide emissions from fossil fuel combustion. It has been estimated that the United States is currently sequestering about 0.3 petagram of carbon per year in ecosystems and that fully a third to a half of that is going into the expansion of woody vegetation in the western United States (Hurtt et al. 2002). How can these two policy streams be reconciled, reducing fuels (and hence carbon) while increasing carbon storage in general?

Most of the following discussion regarding the ecological impacts of climate change on the sagebrush ecosystem is based on simulations, which were published in Bachelet et al. (2001) and which were produced for the recent U.S. national assessment of the impacts of global warming (National Assessment Synthesis Team 2000). However, for ease of presentation, the discussion in Bachelet et al. was simplified to a small number of highly aggregated ecosystem classes, even though the ecosystem models actually simulate a larger number of vegetation types. For the current purpose, we have gone back to the original simulations and reanalyzed some of the output using the full suite of vegetation types that were simulated. Since the many vegetation maps do not readily translate to a noncolor gray-scale, the reader is referred to Bachelet et al. for a visual presentation of all the future climate vegetation simulations (aggregated classification), as well as a listing of the various vegetation types simulated by the models.

Simulating Vegetation Change under Climate Change

Vegetation Models

The Mapped Atmospheric-Plant-Soil System (MAPSS) Team uses two different process-based models to forecast possible changes to ecosystems under rapid climate change: MAPSS, a steady-state vegetation distribution model (biogeography) and MC1, a dynamic general vegetation model (DGVM).

MAPSS is a model that was developed to simulate the potential natural vegetation that could exist on any upland site in the world under present, past or future climate (Neilson 1995). It is an equilibrium, or steady-state biogeography model. That is, it simulates the distribution of vegetation under any average climate but does not simulate the dynamics of change from one average climate to another. MAPSS operates on the fundamental principle that ecosystems will tend to maximize the leaf area that can be supported at a site by available soil moisture or energy. MAPSS is fully integrated with a continentally-calibrated hydrologic model, linking hydrologic and vegetation processes, and it has been validated over the globe (Neilson et al. 1998). The model calculates the leaf area index (LAI) of both woody and grass life forms (trees or shrubs, but not both) in competition for both light and water while maintaining a site water balance consistent with observed runoff. Water in the surface soil layer is apportioned to the two life forms in relation to their relative LAIs and stomatal conductance, i.e. canopy conductance, while woody vegetation alone has access to deeper soil water. Biomes are not explicitly simulated in MAPSS; rather, the model simulates the distribution of vegetation lifeforms (trees, shrubs, grass), the dominant leaf form (broadleaf, needleleaf), leaf phenology (evergreen, deciduous), thermal tolerances and vegetation density (LAI). These characteristics are then combined into a vegetation classification consistent with the biome level. MAPSS currently simulates 45 unique vegetation types in the conterminous United States, weighted more toward the semiarid, savanna, shrubland, grassland and desert ecosystems. The MAPSS simulation of the sagebrush biome area (approximately 290,000 miles [760,000 km^2]) is closer to the Barbour and Billings (1988) estimate, but the model does not distinguish sagebrush from the widespread salt desert vegetation that populates much of the low-lying areas within the Great Basin.

The DGVM, MC1 (MAPSS-CENTURY, Version 1), is the integration of the MAPSS biogeography model and the CENTURY biogeochemistry model into a new dynamic vegetation model (Daly et al. 2000). Significant changes resulted from this model integration, such as new biogeography rules, changes in the parameterization of CENTURY, use of the simplified CENTURY hydrology (as opposed to the MAPSS hydrology) and a new dynamic fire module developed to simulate the occurrence and impacts of fire events that are relatively infrequent but extreme. The model simulates dynamic vegetation distribution, structure and functional change over continental scales at a monthly time step using climate time series from decades to centuries in length (Daly et al. 2000).

The main functions of the biogeography module are: (1) to predict the composition of deciduous/evergreen trees or shrubs and of C3/C4 grass life form mixtures and (2) to classify the predicted biomass from the biogeochemistry module into different vegetation classes. MC1 currently simulates 22 unique vegetation types.

The biogeochemistry module simulates monthly carbon and nutrient dynamics for a given ecosystem. Above- and below-ground processes are modeled in detail and include plant production, soil organic matter decomposition, and water and nutrient cycling. Parameterization of this module is based on the lifeform composition of the ecosystems, which is updated annually by the biogeography module.

The fire module simulates the occurrence, behavior and effects of severe fire. Allometric equations, keyed to the lifeform composition supplied by the biogeography module, are used to convert above-ground biomass to fuel classes. Fire effects (i.e., plant mortality and live and dead biomass consumption) are estimated as functions of simulated fire behavior (i.e., fire spread and fire line intensity) and vegetation structure. Fire effects feed back to the biogeochemistry module to adjust levels of various carbon and nutrient pools.

Future Climate Scenarios

Seven future climate scenarios generated by general circulation models (GCMs) were used by MAPSS at 10-by-10-kilometer resolution (hereafter 10 km) over the conterminous United States (Kittel et al. 1995, Bachelet et al. 2001), and two of them were used by MC1 and MAPSS at a 0.5-degree latitude/longitude (approximately 50-by-50-kilometer) resolution. Fine scale features of the climate, related to topographic effects, are better represented in the higher resolution (10 km) datasets and the larger number of equilibrium scenarios provides a greater context to assess possible future changes. However, there are currently no 10-kilometer transient climate datasets.

The scenarios span a range of about 5 to 12 degrees Fahrenheit (2.8-6.6°C) in projected average annual temperature increase over the conterminous United States near the end of the 21st century. Four are equilibrium scenarios (GFDL-R30, GISS, UKMO, OSU) which were included in the first assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Cubasch and Cess 1990). They include a single layered ocean and assume an instantaneous doubling of carbon dioxide. Three scenarios are transient and were included in the second assessment report of the IPCC (Gates et al. 1996). Two transient scenarios come from the Hadley Climate Center (HADCM2GHG and HADCM2SUL, the latter of which includes effects of sulfate aerosols), and one comes from the Canadian Climate Center (CGCM1, also including aerosols). Transient GCMs include a fully dynamic, three-dimensional ocean, and they are run from the 1800s to the present, using observed carbon dioxide increases, and into the future, using IPCC projections of future greenhouse gas concentrations (IS92a, Kattenberg et al. 1996). The last 30 years of the three transient scenarios were averaged to be treated as equilibrium scenarios by the biogeography model, MAPSS. However, the transient scenarios were clearly not at equilibrium, having attained only about half to two-thirds of their eventual temperature change, due to thermal inertia of the oceans (Gates et al. 1996). Only HADCM2SUL and CGCM1 were used to run MC1.

Mechanisms of Change in the Great Basin under Climate Change

The future climate scenarios show two prominent features in the West: increases in temperature, hence a decrease in frosts, as well as increases in precipitation (Bachelet et al. 2001). The increases in precipitation produce a dramatic increase in woody expansion, at the expense of shrubland, throughout much of the interior West, and a corresponding increase in fire, due to the increased fuel load. Apart from the increases in fire, woody expansion still occurs in the future scenarios, because fire does not occur everywhere or all the time and because sufficient fire-free intervals would exist for new woody establishment. The expanded woody vegetation would enhance carbon sequestration but would also challenge our management community to structure ecosystems so as to diminish the risk of fire in the wildland-urban interface (itself expanding rapidly).

However, the West is currently in a massive drought, so how does one reconcile the future scenarios of increased precipitation with the current drought? The answer lies in interannual and interdecadal climate variability. The well-known El Niño-La Niña cycles produce much of the interannual climate variability, but there are also oceanic interdecadal oscillations, such as the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) (Hurrell 1995, Thompson and Wallace 1998, Mantua and Hare 2002). These interannual and interdecadal patterns of climate variability can produce droughts or floods in the near term, even though the longer-term climate may produce a wetter trend. For example, the Canadian model future climate scenario (CGCM1) produces a 22-percent increase in precipitation over the conterminous United States by the end of the 21st century but ironically produces a 4-percent decline in precipitation by mid-21st century via three decadal-length droughts. Thus, while changes in greenhouse gas forcing may drive a long-term trend, internal ocean-atmosphere oscillations provide a large degree of variability about that trend.

The importance of interdecadal climate variability to Great Basin ecosystem dynamics is quite apparent in a simulation of fire and vegetation dynamics using the MC1 model over the past 100 years. A simulation of leaf mass, a very sensitive indicator of ecosystem processes, averaged over all of Nevada (Figure 1), shows a modest amount of variability until the mid-1970s. However, beginning then, leaf mass is simulated to go through two massive wet-dry cycles. The wet periods are associated with the 1983 and 1998 El Niños with intervening droughts. The leaf mass oscillations increase during these latter cycles. This shift in ecosystem dynamics in the mid-1970s has been related to interdecadal climate variability, specifically a shift in the PDO (Swetnam and Betancourt 1998). Another PDO ocean-climate regime shift had profound effects on interior ecosystems. Notably a shift in the 1940s ended the 1930s drought, produced a favorable climate for expansion of woody vegetation in the West and corresponded with a large increase in the effectiveness of fire suppression. The extreme amplitude in wet-dry cycles since the PDO shift in the 1970s followed a period between the 1940s and 1970s of very low amplitude climate variability, further assisting the expansion of woody vegetation. Grazing reduced competition from grass, thus enhancing the expansion of woody vegetation.

The MC1 model has also been used with fire suppression, whereby only one-eighth of the area that would be simulated to burn is actually allowed to burn. The amount of reduction is based on comparisons of empirical observations to the MC1 simulations where fire is not excluded or reduced. In the absence of fire suppression, the MC1 model accurately simulates fire area over the United States. in the 1920s, 1930s and 1940s. But, after World War II, increases in manpower and equipment vastly improved the effectiveness of fire suppression, resulting in the model-data comparison that suggests we are effective in suppressing about seven-eighths of potential fire area (J. M. Lenihan, unpublished simulation results 2005).

The effect of fire suppression on the Nevada ecosystems is that biomass, notably leaf mass, is then allowed to grow to its water-limited carrying capacity (Figure 1). A fundamental premise used in all large-scale, process-based, biogeographic modeling is that ecosystems will continue to grow until they reach a limiting factor, usually water in temperate regions. Fire naturally keeps the biomass below that water-based carrying capacity, conferring some protection from interannual wet-dry variability. However, in the absence of fire, in the Nevada simulation, the ecosystems (and leaves) grow to larger than normal amounts during the wet periods, rendering them more vulnerable to dieback or decline during the following dry periods because so many leaves transpire too much water (Washington-Allen et al. 2004). The increased amplitude of the leaf mass variation with fire suppression is quite evident in the simulation. Notably, there is currently a massive dieback of woody vegetation occurring throughout much of the Great Basin today (Whitham 2005). Apparently much of the dieback of pinion pines in the pinion-juniper ecosystem in Arizona is due to a beetle infestation, enhanced by the drought (ibid.).

If, as hypothesized by many climate scientists, climate variability increases under rapid global warming, then such wet-dry cycles could interact synergistically with fire, insects, diseases and possibly invasive species to further stress the sagebrush ecosystem.

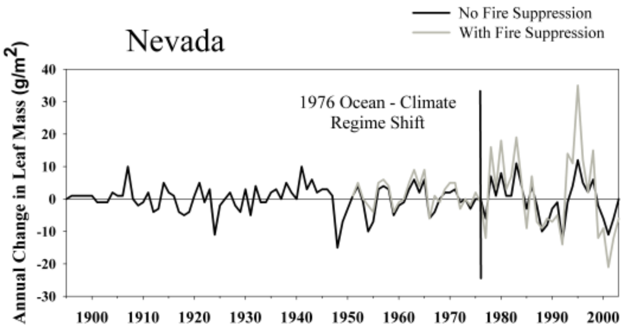

Figure 1. The temporal variability of leaf mass, averaged over all of Nevada, was simulated by the MC1 dynamic general vegetation model. Simulated leaf mass variability is relatively low from 1895 to about 1976, when there was a major ocean-climate regime shift in the Pacific Decadal Oscillation (see discussion in text). After 1976 the region experienced two major wet-dry cycles, noted as large increases and losses in leaf mass. The MC1 simulations demonstrate the synergistic effects of fire suppression and climate variability on leaf mass. In the absence of fire, the ecosystems rapidly seek their water-limited carrying capacity of leaves. In the wet years, leaf mass increases, which withdraws more soil water than would be transpired if fire had been present and had kept leaf mass in check. The high leaf mass increases the sensitivity of the ecosystem to interannual variability of moisture, resulting in a much larger loss or dieback of leaves (and whole plants) during the following dry years. Thus, the presence of a natural fire regime enhances the resilience of the ecosystem to natural climate variability.

Nevertheless, the uncertainties inherent in future precipitation forecasts must be emphasized. Although the seven future climate scenarios previously examined produced increased precipitation in the 21st century over the western United States, newer scenarios are always being created using improved global climate models and the regional precipitation patterns can vary among these scenarios.

Future Invasion of the Great Basin by Other North American Species

Temperature increases in the Great Basin over the next century carry much more certainty than do precipitation increases. The primary uncertainties regarding temperature are the magnitude and timing of the increases and the effects such increases will have on frequency and intensity of annual frosts.

The MAPSS simulations show a large migration of frost-sensitive vegetation into the Great Basin under all future warming scenarios. Much of the advance is in the form of woody vegetation types, such as xeromorphic subtropical shrubland, a physiognomic depiction of the same kind of vegetation typified by the sclerophyllous shrub live oak that migrated 250 miles (400 km) north during the middle-Holocene thermal maximum (Cottam et al. 1959). As these different kinds of vegetation move into the Great Basin, they displace large areas of sagebrush. We have plotted the area of sagebrush in the West, as simulated by MAPSS under current and all seven future climate scenarios as a function of the GCM's simulated increase in temperature over the conterminous United States (Figure 2). The area of sagebrush simulated at zero temperature change represents the current climate. There is a statistically significant loss of sagebrush area forecast as a function of increasing temperature at a loss rate of about 18,700 square miles per degree Fahrenheit (87,000 km^2/^{o}C), or about 12 percent of the present area per degree of temperature increase ($P < 0.01$, where P equals significance level). Under the worst-case scenario (hottest), the area of sagebrush would be reduced to about 20 percent of its current area.

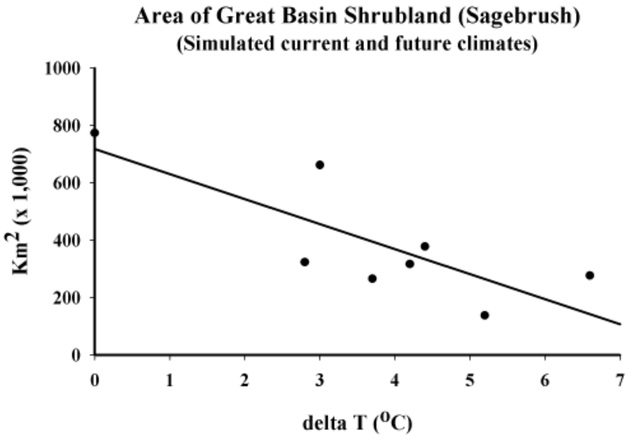

Figure 2. The area of the sagebrush ecosystem is simulated by the MAPSS vegetation distribution model under current climate and seven future climate scenarios, as a function of the temperature change produced by those scenarios over the entire conterminous United States. The area simulated under zero temperature change is the current climate simulation. There is a statistically significant decline in the area of the sagebrush biome due to encroachment of vegetation from southern ecosystems ($r^2 = 0.62$ [where r represents correlation], $P < 0.001$). The sagebrush biome is very frost tolerant and is separated from the southern frost-intolerant ecosystems by a frost line that is currently positioned on the 2,000-foot (600-m) scarp that separates the Great Basin from the southwest deserts. Under global warming, the frost line shifts over the scarp and moves rapidly to the north, opening a window for invasion by southern frost-intolerant vegetation.

The cause of the reduced sagebrush area under increasing temperature is clearly the shift of the frost line over the topographic scarp and its rapid march north through the relatively flat Great Basin terrain. None of the scenarios agree on the precise location or type of vegetation that would displace the sagebrush, largely due to differences in the simulated future precipitation regimes. However, the tendency of displacement from south to north is readily apparent by overlaying all seven of the simulated future distributions of the sagebrush biome, along with the current climate, and by displaying for each location (10 km gridcell) the number of simulations that agree on the occurrence of sagebrush (Figure 3). For

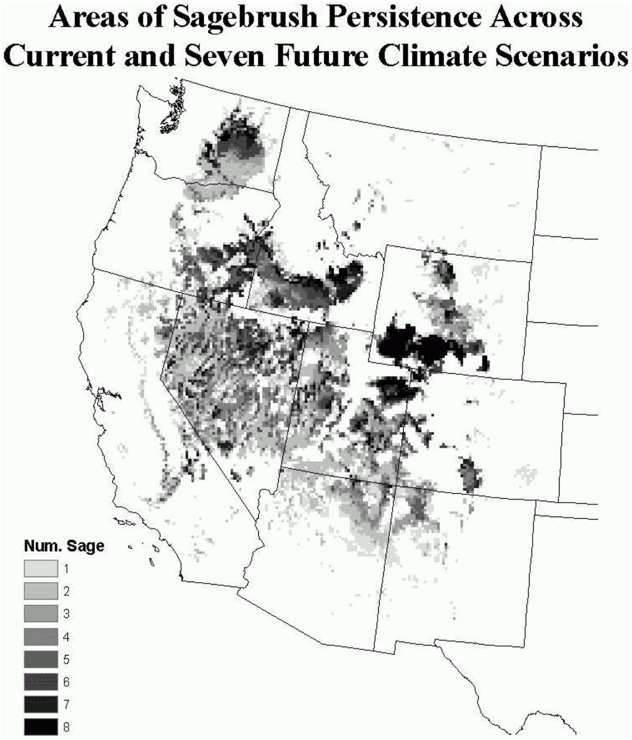

Figure 3. The locations that are simulated to remain sagebrush under each of the seven future scenarios and the current climate are tallied for each site. Those sites which show only one simulation with sagebrush are generally in the southern reaches of the distribution and represent simulations of sagebrush under the current climate that do not remain sagebrush under any future climate simulation. Those sites that show eight simulations with sagebrush are generally in the northern parts of the range and are essentially refuge areas that are simulated to hold sagebrush under the current climate and all seven future scenarios.

example, the areas showing only one simulation are generally the areas simulated to contain sagebrush under the current climate, but they do not support sagebrush under any of the future climates and these tend to be along the southern edges. At the other extreme, those areas showing agreement among eight simulations are where sagebrush is simulated to occur under the current climate and all seven of the possible future climates, and these areas tend to occur along the northern edges. Thus, there are only a few small areas in the Great Basin where sagebrush is simulated to persist under both current and all future climate simulations. The largest is in southern Wyoming in the gap between the northern and central Rocky Mountains, followed by areas along the northern edge of the Snake River Plateau and small areas in Washington, Oregon and Nevada. The model does not differentiate sagebrush from salt-desert vegetation that occupies some of the core basin areas and thus simulates a bit too much sagebrush. The area south of the Uinta Mountains in Utah, which is favored for continued support of sagebrush, may be one such area.

There is some uncertainty about future precipitation changes in the Great Basin. Most of the scenarios show an increase; however, some do show decreases. If there is an increase in precipitation, along with an increase in temperature, then woodland lower elevational boundaries may move down the mountains and out into the sagebrush, displacing the shrubland. A variety of frost-sensitive woodland species from the warmer Southwest will also likely invade but with migrational lags. However, if precipitation decreases along with warming, then elevational woodland ecotones may go up the mountainsides, but frost-sensitive desert shrubs and other southwest species will still likely move into the sagebrush, again displacing the existing shrubland but also with migrational lags. So, the southern reaches of sagebrush appear to be at some risk under most circumstances.

The rate of change or displacement of sagebrush would likely follow three different stages, each with longer time lags. The first change would be physiognomic within the existing community. For example, if moisture conditions were to dramatically improve, sagebrush has the capability to grow to heights of at least two meters, as it currently does in areas on the eastern toe-slope of the Steens Mountain in southeastern Oregon. Secondly, nearby, but perhaps subdominant species might become more dominant and might begin displacing the existing species. The current encroachment of woodlands into the sagebrush may be an example of that. Lastly, the migration of new species from other areas, such as the southwest deserts would require seed dispersal over long distances, establishment and growth in order to displace the sagebrush. This last process could require decades to centuries.

It should also be mentioned that increases in carbon dioxide are the most certain effects of the industrial revolution and that elevated carbon dioxide will directly affect the ability of different plants to invade and to alter sagebrush ecosystems. Most notably, invasive grasses, such as brome (*Bromus* spp.), are favored under elevated carbon dioxide concentrations (Smith et al. 2000).

Conclusions

Sagebrush vegetation in the Great Basin is already at risk of decline in area due to invasive species, notably cheatgrass, and the encroachment of other woody vegetation. Some of the encroachment may be the result of synergistic interactions between fire suppression and climate variability, whereby the suppression allowed a favorable period of climate to be expressed in woody expansion. Future climate scenarios tend to show continued woody expansion due to increased precipitation, given that there may be decadal-length periods of drought intervening. The greater amount of vegetation forecast for the Great Basin also portends more fire, which could augment the shift from shrubland to grassland. Interestingly, the greater vegetation amount would support a U.S. policy of carbon sequestration in ecosystems, even given the greater risk of fires.

The almost certain increases in temperature could have a long-term impact on the species composition and would further displace the sagebrush. The temperature increase is likely to move a frost line over the elevational scarp separating the Southwest and Great Basin regions and move the line rapidly north. The frost line separates the frost-sensitive vegetation in the southwest deserts from the frost-tolerant vegetation in the Great Basin. There would be lags in the response, but many southwest species could move hundreds of miles into the Great Basin, displacing the sagebrush. Thus, there could be major changes ahead for the Great Basin. On the one hand, they may cause reductions or extinctions of many extant species. On the other hand, these changes may also result in a much higher species diversity of a very different character within the Great Basin.

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