

THE FRAME PROJECT—A COLLABORATIVE MODELING APPROACH TO NATURAL RESOURCE MANAGEMENT AT MESA VERDE NATIONAL PARK, COLORADO

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The rapid pace of social and environmental changes over the past few decades has presented significant challenges for the people who manage our public lands. Demographic shifts have placed large populations in close proximity to public lands and have resulted in increased public scrutiny of decision making on those lands. Natural resource managers are required to make informed decisions about multiple resources in complex natural systems in the face of competing and often conflicting objectives and values. The result is that natural resource managers are managing not only resources but also public expectations in the evolving nature of resource management (Tony Cheng, personal communication 2005). The challenge for today's natural resource manager is thus to optimize the management of multiple resources while minimizing the negative impacts of any given decision, and, at the same time, to engender trust and acceptance of the decision process. No small task.

In response to the increased expectations, two trends in natural resource management have emerged: a trend toward engaging stakeholders in participatory, collaborative processes, and a trend toward wider use of modeling to help manage the inherent complexity of natural systems. Collaborative engagement of stakeholders results in more inclusive and transparent decision making, which can engender greater acceptance of decisions and a wider sense of stewardship (Wondolleck and Yaffee 2000). The trend

toward the use of numerical modeling in resource management addresses the need to accommodate the numerous and complex interactions of natural systems (Jakeman et al. 2006).

To adequately represent the inherent complexities of natural systems we need a way to fully address the interactions and feedback among individual components of the system. Although a large number of individual models are available to address individual components of natural systems, the coupling of these models is missing. The USGS's Modular Modeling System (MMS; <http://www.brr.cr.usgs.gov/mms>) offers an ideal framework to facilitate the integration and linking of process models and the execution of them in a coupled manner. The framework also facilitates adaptive management approaches where alternative scenarios and model combinations can be applied and refined iteratively with new scientific understanding and observations from monitoring results.

The principles of collaboration are helpful in situations in which knowledge is distributed among different parties. Although collaborative approaches to natural resource management often involve participation by the public and stakeholder groups (Wondolleck and Yaffee 2000), our collaborative process centers on a smaller set of participants—namely, resource managers, scientists, and modelers. We wanted to evaluate the dynamics of collaborative modeling by combining an integrated modeling approach

(provided by MMS) with collaborative problem-solving approaches. We refer to this as a “collaborative modeling approach.” The two major assumptions in the approach are that collaborative identification and framing of the science issues effectively links science to decision-making needs, and that integrated modeling approaches such as MMS provide the necessary framework to link information across the natural sciences, resulting in more integrated planning strategies. We postulated that the collaborative modeling approach would allow us to more effectively identify and link the pertinent science to natural resource decision making. The value of collaborative modeling approaches is well recognized (Nicolson et al. 2002; van den Belt 2004). Now with MMS we can employ collaborative identification of the issue and selection of the appropriate models.

Our initial collaborative modeling efforts brought together resource managers, scientists, and modelers to address the management of pinyon-juniper (PJ) woodlands at Mesa Verde National Park. PJ woodlands are abundant on the Colorado Plateau (25 million ha), and PJ management involves a number of cross-cutting management issues, such as ecosystem restoration, fire management, grazing, off-highway vehicle use, and soil erosion. Moreover, a number of federal and university scientists and managers agreed to collaborate in this effort.

COLLABORATIVE MODELING APPROACH

Collaboration

The well-established principles of collaboration are articulated in a number of publications, most notably for natural resource management in Wondolleck and Yaffee (2000) and McVicker and Bryan (2002). It is useful to stress what collaboration is, as well as what it is not. This is often the case with words that rapidly gain currency only to find their meaning diluted in the process. The term collaboration is sometimes inappropriately used to describe interactions that do not meet the criteria for true collaboration. Key to true collaboration is a commitment to continuous engagement by all par-

ties, which helps to create an environment of collective learning so that each party recognizes the perspectives and knowledge base that others bring to the table. Collaboration is not the same as seeking input, cooperating, hosting listening sessions, or reaching out. As we shall see in the ensuing case study, a truly collaborative approach was key to success.

Our focus was on how to bring science into the collaborative problem-solving environment. An important premise of our approach is that the knowledge to model a complex natural system is distributed, in our case among the resource managers, scientific experts, and physical-process modelers. The distributed knowledge can be elicited through the collective learning that is characteristic of collaborative problem-solving environments because of the continuous and active engagement of all participants. The scientists bring their diverse expertise to the discussion. Modelers provide the means to capture this expertise in numerical models. The resource manager contributes his knowledge of the ecosystem and also helps maintain the focus on the decision context so that pertinent science, not just “sound” science, is brought to bear on the resource management issues. In addition, framing the science issues collaboratively promotes interdisciplinary science approaches necessary to address most resource management needs. The collaborative process described here helps to frame the science needs embedded in resource management issues.

Modeling

Physical or numerical modeling of natural processes provides a way to analyze and assess the likely effects of alternative management strategies on a variety of responses, such as hydrological and ecological responses (e.g. Starfield 1997). To those not familiar with models, this can seem like a “black box” approach, but in essence, modeling is a systematic way to capture what people are already thinking. Models allow people to conceptualize the way they think things work while providing a framework for collaboration in which resource mana-

gers, scientific experts, and modelers can jointly develop the scientific input for the modeling effort (Starfield 1990). By involving all participants at all stages of the modeling it is possible to ensure that the important questions critical to resource management are addressed, that the scientific research that forms the basis of the modeling effort is as accurate as possible, and that the appropriate interrelationships in the natural system are captured. The results of the modeling simulations based on different scenarios allow resource managers to evaluate the possible range of outcomes. Collective learning occurs during the iterations required to refine the models because of increased understanding of the natural systems and the capabilities of the models. As a result, the resource managers and scientific experts learn how to interact with the models and to modify them to more accurately reflect the current state of knowledge about ecosystem dynamics.

Constructing diagrammatic conceptual models—which visually depict interactions in ecosystems—provides the building blocks for quantitative numerical modeling. Conceptual models typically summarize existing knowledge and hypotheses about interrelationships among key system components and processes. These cause-and-effect relationships are illustrated diagrammatically with arrows that show how various parts of the system connect and interact. As a result, they can serve as important tools for communication among diverse audiences, aid in the identification of research needs, and inform the development of quantitative simulation models (Bestelmeyer et al. 2004). The communication function of conceptual models is often enhanced through their collaborative development (Heemskerk et al. 2003). Conceptual models provide abstractions of the ecosystems and the management issues that need to be quantified in order to provide the means to test, develop, and evaluate alternatives. Constructing diagrammatic conceptual models allows participating scientists and resource managers to identify the structures of relationships for which physical modeling later provides the founda-

tion. The conceptual models also help the modelers build a framework that can be flexible in testing knowledge.

THE ROLE OF MMS

Because natural systems are complex, the modeling approach used in ecosystem analysis must provide a means to express the interrelationships among components of the system. The models must therefore be able to accommodate integrated science approaches in order to accurately capture the feedback mechanisms in ecosystem dynamics. The USGS's Modular Modeling System (MMS) provides a modular framework in which to address these needs and is thus ideal for addressing cross-cutting resource management needs.

The MMS is an integrated system of computer software developed to provide the research and operational framework needed to enhance development, testing, and evaluation of physical-process modules and models; facilitate the coupling of models for application to complex, multidisciplinary problems; and provide a wide range of analysis and support tools for research and operational applications. MMS supports the integration of models and tools at a variety of levels of modular design. For process and single model applications, the MMS has a master library that contains compatible modules for simulating a variety of water, energy, and biogeochemical processes. A model for a specified application is created by coupling appropriate modules from the library. If existing modules cannot provide appropriate process algorithms, new modules can be developed and incorporated into the library. In addition to individual process models, the MMS also supports the development and application of tightly coupled models, loosely coupled models, and fully integrated decision support systems using both MMS and non-MMS modules, models, and analysis tools.

A geographic information system (GIS) interface is provided in MMS for applying GIS tools to delineate, characterize, and parameterize topographical, hydrological, and biological features for use in a variety of

lumped- and distributed-modeling approaches.

A set of tools is available for developing climate time series with which to run models. These include a climate generator, methods to downscale atmospheric model output, and methods to obtain and analyze historic climate data. Optimization and sensitivity analysis tools are also provided to analyze model parameters and evaluate the extent to which uncertainty in model parameters affects uncertainty in simulation results.

A major goal of the FRAME project (Framing Research in Support of Adaptive Management of Resources) is to link the vegetation dynamics model SIMPPLLE (Simulating Patterns and Processes at Landscape Scales) with a variety of watershed, erosion, hydraulic, and ecosystem models in MMS to enable the assessment of the effects of alternative resource-management options on a variety of hydrologic and ecosystem processes. Output from SIMPPLLE is an ensemble of potential vegetation conditions projected years to decades into the future. Key components of the linked MMS models and SIMPPLLE are tools to estimate new parameters in MMS process-based models using vegetation and ecosystem attribute data from SIMPPLLE output, and a climate generator to provide time series of meteorological variables, such as precipitation and temperature, for use as input to the process-based models.

MMS is a key component of collaborative modeling approaches because, in addition to its adaptability, it serves as a framework for collaboration. The resource managers and scientific experts can work jointly with the modelers to choose the appropriate types of models needed to bring the appropriate science to bear on the issues. The natural resource managers and scientific experts also have the opportunity to provide their knowledge and scientific insights to tailor the models to fit the natural setting. The modular toolbox design also enables the immediate integration of advances in physical and biological sciences, GIS technology, computer technology, and data resources

into the toolbox. Resource-management decision making thus benefits from the ability to constantly refine the models with state-of-the-art scientific information and technology.

MMS deals with complexity and the integrated science needed to address it because it allows the linkage of science information across the natural sciences. With the degree of integration that is permitted by the MMS, it is possible to evaluate the effects of potential management actions as they play out in the ecosystem. As a result, MMS is applicable to multi-objective resource management, allowing resource managers to develop more integrated planning strategies.

A FRAME PROJECT CASE STUDY

After designing the collaborative modeling approach to linking integrated science to natural resource management concerns, we needed an appropriate place and resource management issue to evaluate the approach. Project FRAME was proposed to test and refine the collaborative modeling approach by coupling collaborative approaches to framing science questions with modeling tools applicable to multi-objective resource management. Development of the strategy across a wide range of ecosystems will require a multi-year effort; however, we began with an initial focus on selected management issues in a single geographic area. We selected the Colorado Plateau region because it is an area dominated by federal lands, and because DOI and USDA agencies are currently reevaluating land management strategies because they face fundamental changes in ecosystems in this region (<http://www.mpcer.nau.edu/direnet/>). Drought provides the current focus for resource managers because many resource management plans were developed in the period 1978–1995, which were wet years in the region. Even in the absence of drought, however, resource management issues require a systems approach because choices made for each management objective have implications for other resources.

In partnership with the Colorado Plateau Cooperative Ecosystem Study Unit and the

Merriam-Powell Center for Environmental Research, we selected the management of PJ woodlands at Mesa Verde National Park (MVNP) as our initial focus. PJ management involves a number of cross-cutting management issues—such as fire management, invasive species, insect infestation, and soil and sediment erosion—that relate to ecosystem health, visitor safety, and cultural-site preservation. The natural resource manager at MVNP was enthusiastic about bringing science to bear on resource-management issues. MVNP was also an ideal location for the case study because of the numerous scientific datasets available for the modeling effort (e.g. Floyd et al. 2000 and 2004). Moreover, much of the park's remaining PJ woodlands lack the level of human disturbance that most other areas have experienced. A number of federal and university scientists, managers, and modelers agreed to participate in the effort (see <http://www.mpcer.nau.edu/frame/> for more information).

A key resource-management objective in MVNP is to protect and maintain structurally and biologically the park's diverse old-growth PJ stands. Will it be possible to maintain some of the oldest stands as refugia, while at the same time allowing for the occurrence of natural disturbance and successional processes that may impinge on these valued stands? Fire and fire-management strategies have been dominant concerns in the park in recent decades. About 50 percent of PJ has burned since 1934, and two-thirds of the park has burned in less than a decade even with a policy of total fire suppression. The remaining old-growth PJ stands are 300–500 years old. Extensive tree-ring dating and mapping of past fires indicate a 400-year fire rotation (i.e., the time required for the cumulative area burned to equal the entire area of pinyon-juniper vegetation in the park). During the long time intervals between stand-replacing fires, small-scale disturbances (black stain, "normal" beetle kills, and lightning-ignited fires of small extent) have led to development of dense old-growth stands that are susceptible to stand-replacing crown fires under extreme drought. The current drought and fire cycle

has thus caused heightened concern among park management. Is continued fire suppression to protect PJ appropriate for a national park that is supposed to let nature take its course? Is nature even able to really take its course under current conditions (air pollution, exotic weeds, climate change)? The resource manager wanted to be able to evaluate the effects of various management choices in the park and to engage fire management in the process so that resource management and fire management plans could be complementary, resulting in more comprehensive planning and management strategies.

Framing the Question in the Decision Context

We established a collaborative modeling environment for the FRAME project at Mesa Verde National Park by convening a series of interactive workshops and field trips in the park, with all project participants present as often as possible. Workshop participants included the park natural resource manager, quantitative modelers, and other scientists with expertise in the dynamics and management of pinyon-juniper ecosystems. In a workshop setting, we began by framing the science issues for modeling. First, the natural resource manager of MVNP provided background information about the state of old-growth PJ in the park. With this focus we could begin to frame the science needs for ecosystem modeling in light of the resource manager's decision context. The natural resource manager established that his desired future condition (Table 1) was maintenance of healthy PJ woodland with preservation of the remaining old-growth PJ stands. Our strategy was to accomplish this goal in the context of integrated management of fire and of natural and cultural resources; in this early stage of the project, fire management, cultural resource management, and representatives from adjoining lands were not yet involved.

Conceptualizing Ecosystem Dynamics

With the desired future condition determined, the scientists, modelers, and resource

Table 1. Desired future conditions for pinyon-juniper ecosystems in Mesa Verde National Park described at the vegetative-patch level, the landscape level, and in terms of key maintenance processes (George San Miguel, personal communication).

Patch Level: All pinyon-juniper community patches in the park collectively consist of and are dominated by their entire range of structural and functional groups of native plant species as well as the full functioning of succession and other key ecological processes that are naturally characteristic of Mesa Verde pinyon-juniper landscapes, soil-geomorphic settings, climatic conditions, and successional stages.

Landscape Level: The Mesa Verde landscape is composed of a mosaic of native plant communities with a dynamic range of compositions and configurations (i.e. landscape structure) determined jointly by characteristic disturbance processes (e.g. fire, flood, drought, insect outbreak) and environmental constraints such as soil, topography, and climate. As a whole, the community patches in the landscape represent the full range of natural variability determined by the natural disturbance regime, including old-growth pinyon-juniper woodlands. For the NPS to retain the full range of successional stages and natural variability, spatial scales extending well beyond park boundaries and encompassing the minimum dynamic area may need to be considered.

Key Maintenance Processes: Natural disturbance processes (e.g. fire, climate), successional processes, and management treatments (e.g. efforts to control invasive exotic species) are tools to facilitate the maintenance of desired ecosystem conditions at patch and landscape scales.

manager worked together to determine ecological factors and attributes related to PJ ecosystems that were pertinent to an integrated modeling effort. We engaged in collaborative dialogue to address the issue of ecological complexity. The process involved the challenge of not only identifying the complexity of interactions in the PJ ecosystem, but also reducing that complexity to facilitate the modeling task and the relevance of the model outputs for managers while also ensuring the scientific validity of outputs as well as user confidence. The goal is to maximize the utility of modeling for resource management. With the assistance of a facilitator and a recorder, participants reviewed and discussed (1) drivers of eco-

system change and variability (natural disturbances, anthropogenic stressors, and management actions); and (2) ecosystem attributes that are affected by these drivers, amenable to quantitative modeling, and suitable for evaluating ecosystem conditions in relation to management objectives. In relation to this latter point, the desired future condition concept played a central role by focusing the dialogue among resource managers, scientists, and modelers. The workshop facilitator led the discussion while the recorder captured information in a table projected on a screen in front of the meeting room. Throughout the discussion, an explicit effort was made to identify modeling attributes that were directly related to NPS "vital signs"—environmental attributes selected for long-term monitoring by NPS staff for purposes of tracking status and trends in the condition or "health" of park ecosystems (Thomas et al. 2006).

Once the drivers of ecosystem change and variability (and the attendant response variables) were determined (Table 2), it was possible to use diagrammatic conceptual models that visually depict interactions among key components and processes of pinyon-juniper ecosystems (Figure 1). If a conceptual model had not already existed, we would have used the information in Table 2 to construct one. In this case, FRAME relied upon models previously developed by scientists and resource managers to support the identification of long-term monitoring needs in NPS units of the Colorado Plateau (Miller 2005; Vankat unpublished data). The key components and critical pathways identified in Table 2 as essential to modeling pinyon-juniper woodlands are captured in Vankat's conceptual characterization of the pinyon-juniper ecosystem (Figure 1).

During the course of the case study, ongoing field studies by FRAME project participants revealed that the rapid spread of cheatgrass (*Bromus tectorum*) in the park posed an increasing threat with respect to fire frequency and spread. In collaboration with the natural resource manager, a group consensus emerged: We decided that the

Table 2. Drivers and measurable response variables included in the quantitative modeling effort as the result of collaborative dialogue between resource managers and scientists.

Drivers of Ecosystem Change and Variability			Response Variables: Ecosystem Condition Evaluation Criteria			
Natural Disturbances	Anthropogenic Stressors	Management Actions	→	Vegetative-Patch Attributes	Landscape Attributes	Watershed Attributes
Insect outbreaks	Landscape fragmentation	Fuel breaks; thinning	→	Fractional cover of native plant functional types (grasses, shrubs, trees)	Fire frequency and extent	Sediment production
Disease	Invasive exotic plants	Fire suppression	→	Fractional cover of invasive exotic plants	Total area and patch-size distributions of different types of vegetation	Runoff volume
Wildfire	Soil-surface disturbances	Management-ignited fire	→			Probability and magnitude of debris-flow events
Climatic episodes		Prescribed natural fire				

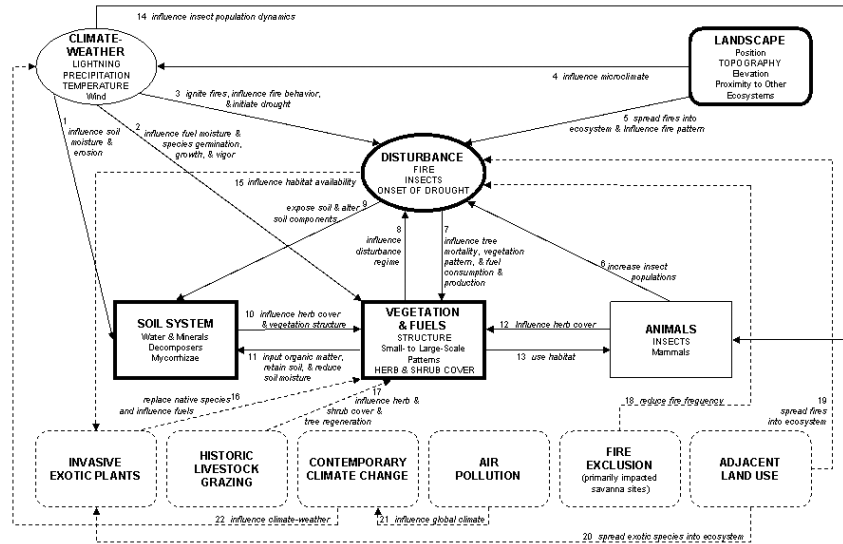


Figure 1. Pinyon-juniper ecosystem characterization model for the southern Colorado Plateau (Vankat, unpublished).

spread of cheatgrass—and its implications for the PJ ecosystem—had become a priority. Vankat's diagram (Figure 1) identifies exotic species (including cheatgrass) and fire as two major components of the PJ ecosystem, shown schematically as two boxes. Another diagrammatic conceptual model (Figure 2), previously developed by one of the FRAME project members (Miller 2005), describes detailed interactions within the two boxes represented on Vankat's figure, and thus provided the necessary conceptual model for us to focus our efforts on the cheatgrass component of the PJ ecosystem (Figure 2). The decision of the group to focus our modeling efforts on the potential threat of cheatgrass to the ecosystem dynamics at MVNP illustrates the adaptive nature of a collaborative modeling approach. In resource management, it is often the case that priorities shift with time, and modeling efforts designed to meet the needs of resource management ideally should be able to accommodate these shifts. In our case study, the long-range management concern—preserving old-growth PJ—necessitated first addressing the role of cheatgrass as it pertained to fire regimes in the park, because

cheatgrass posed the greatest immediate threat to the PJ ecosystem.

Cheatgrass is a non-native winter annual that germinates in the fall, grows slowly during the winter, and then grows rapidly in the early spring. By early summer it has set seed and died, creating a continuous fuel bed of quick-drying, flashy fine fuel that can readily carry fire, even without wind. In parts of the Great Basin and Colorado Plateau, cheatgrass has profoundly altered local fire regimes, from historically infrequent high-severity fires to frequent low-severity fires (Whisenant 1990; D'Antonio 2000); there is concern that this will happen in MVNP as well. The park's native flora exhibits a fascinating variety of adaptations for surviving fires that occur at long intervals, such as resprouting from roots and rhizomes or requiring a combination of heat and smoke to stimulate seed germination. However, some of these adaptations might be ineffective in the face of frequent fires. Indeed, in other areas where cheatgrass has altered the historical fire regime, some native plant species have been locally extirpated. In addition, an increase in the frequency of fast-spreading fires would pose a

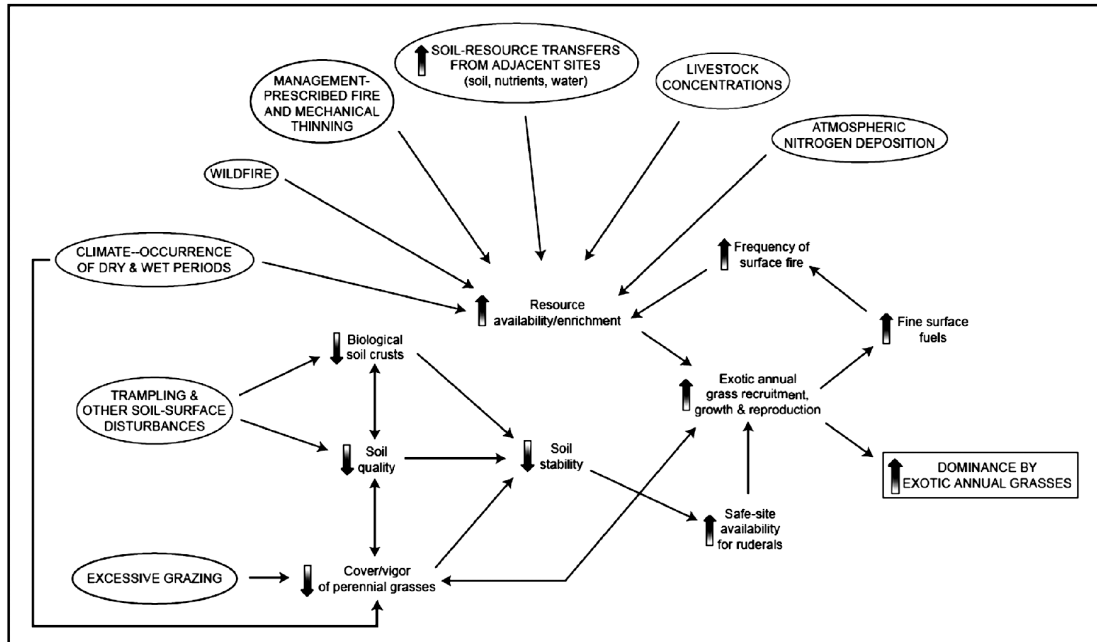


Figure 2. Ecological factors and processes that can interactively lead to increasing dominance of exotic annual grasses in pinyon-juniper ecosystems (from Miller 2005).

serious threat to MVNP's world-renowned cultural resources, last stands of old-growth woodlands, and visitor safety.

Cheatgrass has been present in MVNP for many years, especially in the deep canyon bottoms of the park's southern portion. However, it was never widespread until the last 5 years, when it began to expand its range across the mesa tops and into the highest elevations of the park. Apparently cheatgrass was previously limited by the relatively cool, moist conditions on the mesa tops, and was restricted therefore to the warmer, drier southern canyon bottoms. The unusually warm summers and winters of the past 5 years, coupled with heavy fall rains in all but one of those years—which is optimal timing of precipitation for cheatgrass germination—have allowed cheatgrass to rapidly expand its range, especially in places where fire or other disturbances have created bare ground. Cheatgrass is now a dominant species in much of the area that burned in the 2000 Bircher fire and elsewhere in MVNP.

Numerical Modeling

The construction and use of conceptual models comprise important first steps in ecosystem modeling efforts because they define the key relationships that capture ecosystem dynamics. In order to quantitatively evaluate the probability of interactions or consequences of decisions or events for resource management purposes, the relationships and interactions need to be modeled numerically, using the conceptual models as templates for selecting and constructing the numerical models. An underlying premise of the FRAME project is that quantitative simulation modeling can inform the decision-making process by enhancing managers' abilities to explore potential ecological consequences of different management alternatives (Starfield et al. 1995; van den Belt 2004).

The integration of all available modeling components using MMS is a long-term goal, whereas the results of our collaborative modeling process at MVNP identified cheatgrass invasion and the resulting fire

regimes as urgent initial priorities for our numerical modeling efforts. A major concern of post-fire disturbances is the effect of erosion and debris flows on the park's cultural resources and visitor safety. The initial numerical modeling effort was therefore aimed at evaluating the potential impacts of cheat-grass invasion on fire frequency and fire-related processes (erosion and sedimentation). The case study was thus limited to the coupling of the landscape model SIMPPLLE with a debris-flow-generation model related to post-fire runoff and erosion.

Landscape Modeling

The SIMPPLLE model has a generic, object-oriented design that allows quantitative modeling of the interactions captured in the conceptual models. The model has been developed and used in a wide range of ecosystems (Chew et al. 2004; <http://www.fs.fed.us/rm/missoula/4151/SIMPPLLE/>). In our FRAME case study, SIMPPLLE was populated using the components and critical pathways represented by Figures 1 and 2. Selection and quantification of the numerical model parameters was made by the participants using scientific knowledge from the literature, field studies, and expert opinion. The existing SIMPPLLE design was compared to the diagrammatic conceptual models for the Colorado Plateau ecosystems to identify modifications (additions or changes) that had to be made to capture the specific knowledge within SIMPPLLE necessary to model the Colorado Plateau ecosystems for specific management issues. For example, the design of the categories in SIMPPLLE used to describe wildfire disturbance and species had to have additions made to capture the interaction between an invasive species' percent ground cover response to moisture conditions and a species-specific interaction with fire spread logic. Changes also had to be made in the category that represents land units to account for the level of soil information needed to predict the probability of the invasive species (Floyd et al. 2006).

SIMPPLLE computes a probability for the occurrence of a disturbance process for each

plant community. These probabilities are determined by a combination of research results and expert opinion expressed as logic rules. These probabilities are determined not just by a plant community's attributes, but also by what exists around it, what processes are occurring around it, and what has occurred in the past. SIMPPLLE uses these process probabilities in a stochastic fashion, rather than using a transition matrix approach. There is no fixed transition rate of changes in the acres of vegetation states as a result of a disturbance process. Changes expressed for an entire landscape are the summation of changes at the plant community level. The range of possible combinations of outcomes for each plant community, as influenced by the interaction of the factors influencing disturbance probabilities in a simulation, results in a stochastic output.

Populating the model's structure with both numerical values and logic relationships, and validating its performance, involved a process of iterative interaction with the scientists and the resource managers. Selection and quantification of the modeling parameters were made by the participants using scientific knowledge from the literature, field studies, and expert opinion. Populating the structure is often the result of a consensus reached between scientists and resource managers. For example, decisions about how to identify vegetation species, size class, and density levels, and what level of soil survey information to use to describe land units, depends on what is available from inventories, what is needed to capture the dynamics, what is needed to predict probabilities of disturbance processes, and what is needed to address management issues. The system is designed with user-interface screens that facilitate the interaction with scientists and managers in making these choices. The model's behavior was validated at levels from individual plant communities to the entire landscape through a number of workshops with continuous and collaborative interaction among the modelers, scientists, and resource managers. The model had to display changes at an individual plant community level that were

consistent with other research and experience. The disturbance processes at the landscape scale had to be consistent with past process history.

RESULTS

For the first modeling effort, which involved evaluating the potential impact of cheatgrass on the fuel conditions and fire potential in MVNP, we simulated fire and vegetative response to fire under two contrasting scenarios: (1) without any impact of cheatgrass on fire frequency or spread in the park and (2) with cheatgrass expanding at what we believe to be a maximum likely rate over the next 20 years and affecting fire frequency and fire spread. We recognize that neither of these scenarios might be exactly what will happen over the next 20 years in the real MVNP. However, our intent was not to forecast the future with precision, but rather to describe a range of potential futures within which the real future is likely to fall. In that sense, these two scenarios represent the best and worst outcomes likely to occur in the real park, if current trends continue. These scenarios do not include any management actions. The intent of this analysis is to help identify the potential need for scenarios that would include management actions. Both scenarios were quantified by making a set of 20 stochastic simulations for each one.

For both scenarios, we assumed a 20-year sequence that mimicked the weather patterns of the 1950s drought—that is, most years with below-average or average precipitation, but occasional years of above-average precipitation. We assumed a general drought condition in our simulations because atmospheric scientists predict that the current drought in the western United States will continue for at least another decade, and because we wanted to develop a worst-case scenario for the fire situation in MVNP. Because a single set of simulations cannot incorporate all of the many variables that could be of potential interest without becoming overwhelmingly complicated, neither of our scenarios included direct effects on fire behavior of the recent pinyon

mortality in the park that has resulted from drought, bark beetles, and black stain fungus. We also chose not to incorporate any effects of fire suppression. It would be possible to incorporate these effects in future simulations, if desired.

Once cheatgrass establishes in a plant community, the rate of change in canopy cover is identified through logic rules that include the level of moisture for the year and other disturbance processes. The change in a fire process, spreading from one plant community to another, was modified to identify what level of canopy cover of cheatgrass made a difference in the spread. The values used in these relationships were the result of an iterative process of making simulations with a range of values and evaluations by managers and scientists.

Adding cheatgrass changed the simulations by including logic that provided for the probability of cheatgrass occurring, its change in canopy cover once it is introduced, and its impact on the fire spread process. These logic rules depend on past disturbance processes, the other plant species present, the soil type, and the moisture for the yearly time step (Floyd et al. 2006). Combinations of these factors result in a specific probability of occurrence and a canopy cover level at which cheatgrass occurs. The highest probability of cheatgrass invasion and increase was in recently burned areas. In both burned and unburned areas the probability was higher in plant communities with a low number of species capable of prolific resprouting after fire (e.g. PJ woodlands), and on certain soil types known to be vulnerable to weed invasion (such as Mikim loam and Arabrab-Longburn soils). Probabilities of cheatgrass invasion and increase also were higher during wet years than during normal or dry years, in both burned and unburned areas.

The impact on fire spread across plant communities is simulated by adding a layer of fine fuels that is capable of spreading fire without being driven by a wind event. In SIMPPLLE, the fire spread logic was expanded to include the presence of cheatgrass and its canopy cover level. There was no

change in the spread logic until it reached 45 percent cover. Above 45 percent cover the logic of fire spread was changed to be comparable to what is observed under conditions of dry fuels and high winds. We chose this 45 percent threshold along with the initial probability of occurrence and the change rates based on an iterative process of managers and scientists evaluating SIMPPLLE output across a range of input values. Professional judgment had to be used in selecting the final set of values because research has not yet clearly identified at what level cheatgrass initially occurs, changes on a yearly basis, or increases fire spread. In this second scenario, which incorporated an increase in cheatgrass distribution and abundance, at the end of each simulated year there was a probability of cheatgrass invading new portions of the landscape and of increasing in cover where it was already present.

20 Years of Simulated Fire Without Increasing Cheatgrass

We first ran SIMPPLLE under the assumptions (1) that cheatgrass would not have any impact on fire frequency or spread, and (2) that generally dry conditions would continue for 20 years. The result was very little fire in any of the 20 replicate simulations. The cumulative area burned over the entire 20 years was less than 600 acres in any of the 20 runs. Because we produced so little fire activity, we do not include any maps or further details of our results for this scenario.

We do note, however, that this is exactly the result we would expect given the assumptions that went into the simulations. Indeed, this scenario strongly resembles the actual fire regime that characterized MVNP for most of the twentieth century prior to 1996, that is, no significant fire spread in the great majority of years. Large fires occurred only in a few key years (1934, 1959, 1972, and 1989) when dry fuels and warm temperatures were accompanied by high winds—severe fire conditions that we did not incorporate in this scenario.

20 Years of Simulated Fire With Increasing Cheatgrass

Our second scenario was based on the assumptions of (1) progressive increases in the distribution and cover of cheatgrass, according to the probabilistic rules outlined above, and (2) generally dry conditions. Adding cheatgrass to the simulations resulted in a dramatic increase in total area burned. The average total area burned in each year, averaged across all 20 runs, ranged from less than 100 acres to 2400 acres. Smaller amounts of burned acreage were seen primarily in the first 5 years of the simulations, while cheatgrass is still expanding from its 2005 distribution. Once cheatgrass occupies its full potential extent across the park, the average area burned is more than 1000 acres in almost every year. Because the simulations are stochastic, there was much variability among the 20 runs. Every simulated year included at least one run with almost no area burned. (Note that this was a different run for each year; none of the individual runs produced a near-zero area burned in all or even many of the simulated years.) On the other hand, the maximum area burned in any of the 20 years ranged from 4000 to 8000 acres per year from year 6 to the end of the simulation. And at the end of 20 years, the median cumulative area burned was 22,880 acres. This represents a fire rotation of approximately 45 years for the park as a whole—a dramatic change from the historical fire rotation, which was measured in centuries.

To further explore the implications of such an increase in annual burning, we identified the individual simulation that produced the median cumulative total area burned over 20 years (22,880 acres) and mapped the locations of each year's fires as simulated by that particular run. Our focus was on locating the places that were burned more than once during the 20-year simulation; see Figure 3. A substantial amount of area was simulated to burn twice and several areas were simulated to reburn as many as five times in 20 years. For comparison see

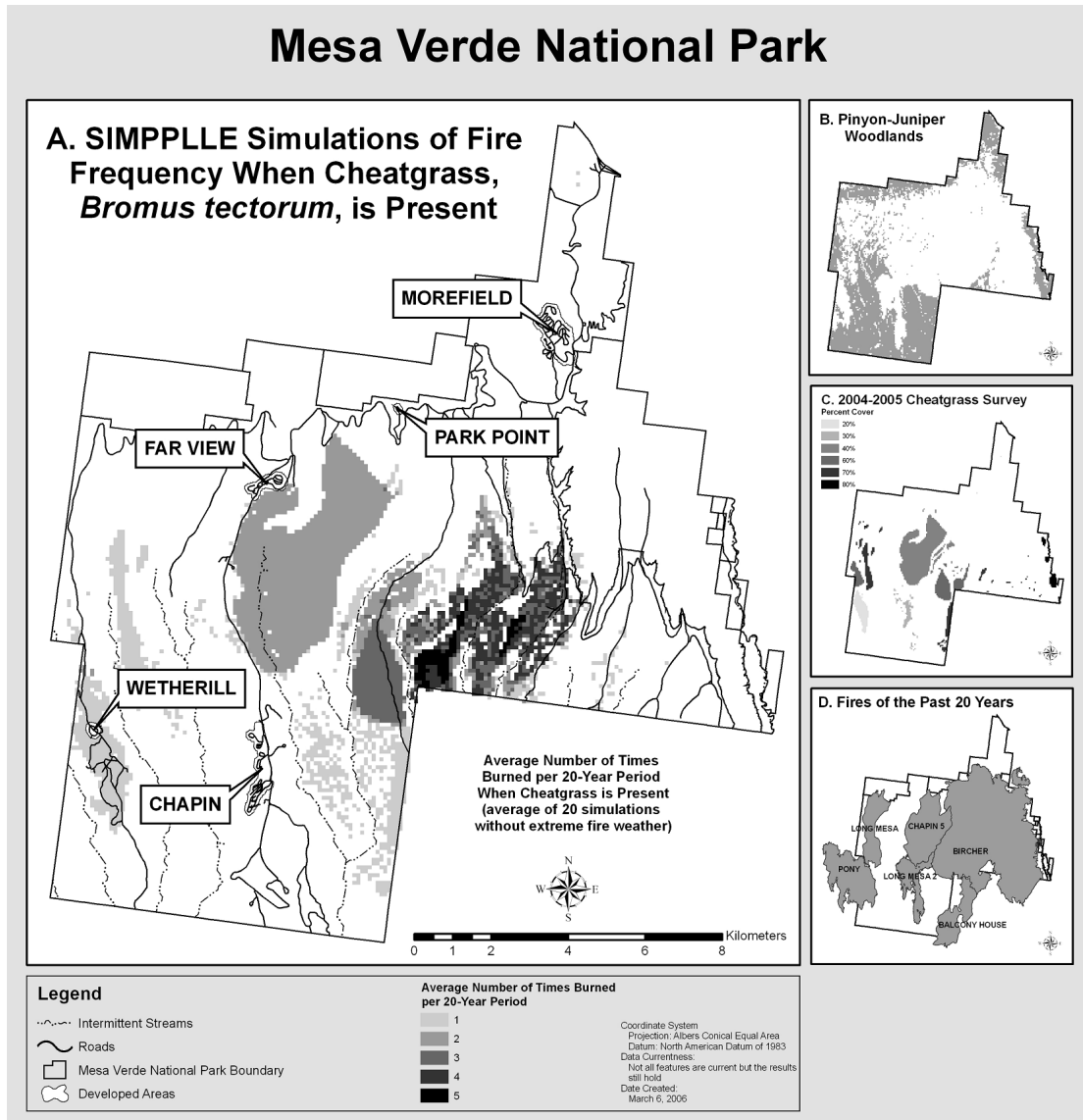


Figure 3. (a) Results of the SIMPPLLE simulations of fire frequency when cheatgrass, *Bromus tectorum*, is present at Mesa Verde National Park; (b) the remaining old-growth pinyon-juniper woodlands in the park; (c) mapped populations of cheatgrass during 2004 and 2005 surveys; (d) recent fires that have burned more than half of the park.

Figure 3b–d showing the PJ woodlands, the 2004–2005 cheatgrass survey, and fires of the past 20 years. The greatest concentration of the repeatedly burned areas in the simulations was in the south-central portion of the park, generally within the perimeter of the 2000 Bircher fire. Very little old-growth pinyon-juniper woodland was burned in the simulations.

Implications of Results for Cheatgrass and Fire

The results of these simulations raise serious concerns about cheatgrass invasion and its potential effect on fire frequency. Any substantial increase in the extent of annual burning might be of concern from the standpoint of conserving the park's native biota because most of the native fauna and flora are adapted to relatively infrequent fire. However, the most worrisome aspect of these projected changes in MVNP's fire regime is the demonstrated potential for frequent reburning, at intervals as short as a few years. Such a disturbance regime would be far outside the historical range of variability for this ecosystem, and would likely lead to substantial reductions and even local extirpation of many native plant species. For example, the park's pinyon and juniper need about 75 years after fire to become reestablished in burned areas. A 45-year fire rotation could thus prevent normal successional processes and adversely affect all of the native flora and fauna that depend on the woodland structure. At the same time, such a fire regime would create a nearly optimal environment for cheatgrass, musk thistle, and other non-native invasive species.

Debris-Flow-Potential Models

Debris flows are among the most hazardous consequences of rainfall on burned hill-slopes. Because recently burned areas are vulnerable to debris flows during heavy precipitation events, the potential soil and hydrologic impacts of more frequent fires pose a serious management concern. The risk is greatest when locally intense precipitation falls within 1–3 years of a fire. We selected an empirical debris-flow model

(Cannon 2001; Cannon et al. 2004; Gartner 2005) to evaluate the potential for debris flows for the basins within the park following a cheatgrass-altered fire regime. This model has been used extensively throughout the intermountain West. The debris-flow model was incorporated into MMS to facilitate its linking with the output from SIMPPLLE.

The debris-flow model relates the probability and volume of a debris flow to a combination of geologic, soil, basin morphology, burn severity, and rainfall conditions. Basin, geologic, and soil characteristics can be obtained from databases that include digital elevation models (DEMs) and the USDA STATSGO soils database. Total rainfall and average rainfall intensity can be estimated using NOAA's *Precipitation-Frequency Atlas of the Western United States*. Using these digital databases and the fire-affected areas defined by SIMPPLLE, the GIS-based tools in MMS can be used to delineate and parameterize the debris-flow model. However, a major concern of MVNP was the potential for floods, erosion, and debris flows anywhere in the park and their impacts on cultural resources and visitor safety. Therefore, all basins in MVNP were evaluated for post-fire debris-flow potential.

The debris-flow model is limited to basins 25 km² or less in size. To focus on headwater areas in and adjacent to the park, and to avoid the lower canyon regions where the equations may not be appropriate for the steep sandstone walls and narrow valley bottoms, drainage basin size was limited to basins ranging from 2 to 10 km². All basins evaluated were assumed to burn completely at a moderate or high severity in order to provide a common basis for comparison among basins. The rainfall events selected for this application were the 2-year 1-hour and 100-year 1-hour storms. Total rainfall and average rainfall intensity for each storm were estimated using NOAA's atlas.

Debris-Flow Potential With Increasing Cheatgrass and Fire

The result of the debris-flow model application was that all of the basins showed an

increase in the probability of a debris flow and in debris-flow volume when the 2-year and 100-year rainfall events were compared (Figures 4 and 5). Debris-flow probabilities and volumes were computed individually for each of 68 delineated basins. Results were then categorized into 10–20 percent probability classes and 20,000 m³ volume classes (Figures 4 and 5) for the 2-year and 100-year rainfall events. The magnitude of the changes varied among simulated basins, reflecting underlying variation in topographic and soil characteristics.

These maps provide information that can be used to prioritize mitigation efforts, to aid in the design of mitigation structures, and to guide decisions for evacuation, shelter, and escape routes in the event that storms of similar magnitude to those evaluated here are forecast for the area. The potential for debris-flow activity after a fire decreases with time and the concurrent revegetation and stabilization of hillslopes. One can conservatively expect that the maps presented here may be applicable for approximately 3 years after the fires for the storm conditions considered here. Projected changes in the MVNP fire regime indicate the potential for frequent reburning, at intervals as short as a few years. This would bring an increased risk of significant debris-flow events, with the potential for substantial damage to water resources and cultural resources.

FRAME and PJ Ecosystem Management

The potential of the collaborative modeling approach developed in our FRAME case study goes beyond the boundaries of any particular department within a park or any land management unit. When we initially focused on PJ management as a natural resource issue in MVNP, we recognized the cross-cutting nature of the issue and that PJ management could best be addressed in the context of integrated management of fire and natural and cultural resources both within the park and on adjacent lands. It was discussed early in the FRAME project that Mesa Verde National Park may be too small a subset of an ecosystem to manage optimally without cooperation from neigh-

boring lands. There are ecosystem drivers and stressors outside the park over which the NPS has no jurisdiction. For PJ management, for example, sufficient acreages of all PJ seral stages need to be maintained in a healthy state so that succession can lead back to a sound old-growth PJ community. To achieve that goal, we need to explore what size area (“minimum dynamic area”) it takes to optimize the management of natural resources and to manage fire. Complementary management strategies across neighboring lands would be the optimum way to manage any part of the PJ ecosystem. As the modeling effort at MVNP progressed, fire management personnel from MVNP and land managers from adjacent BLM and Ute Mountain Ute tribal lands joined us in the workshops. They saw that we were developing a methodology that would address the full range of natural resource issues that they collectively face. Having all the adjoining land managers in the discussions increased the geographic area in which to view preservation of old-growth PJ woodland. This raised the possibility of preserving old-growth PJ on adjacent lands rather than exclusively within MVNP boundaries.

Collaboration across agency boundaries and across neighboring parcels of land is an emerging trend in land management. The collaborative modeling approach developed in the FRAME project provides a framework for collaborative decision making across agency boundaries. As a result, ecosystem-level land management can become a reality.

The FRAME project at Mesa Verde is a “proof-of-concept” case study that can be extended to other regions with PJ woodlands, the dominant vegetation type on the Colorado Plateau and the third largest vegetation type in the contiguous United States. Moreover, the FRAME collaborative modeling approach goes beyond any specific vegetation type. The approach can be incorporated into synthetic work conducted by NEON Districts where comparisons of managed, wildland, and urban landscapes would be possible. FRAME can also be used to incorporate information from regional drought

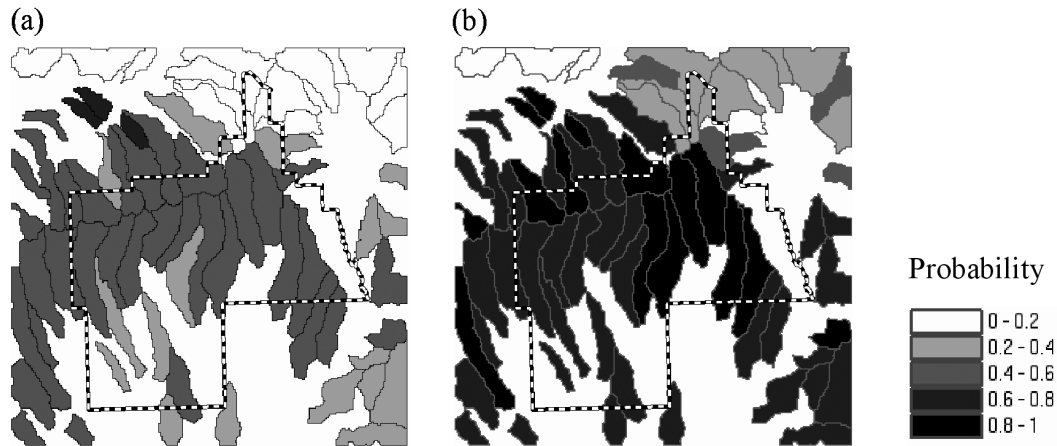


Figure 4. Probability of a debris flow for (a) 2-year 1-hour and (b) 100-year 1-hour rainfall events.

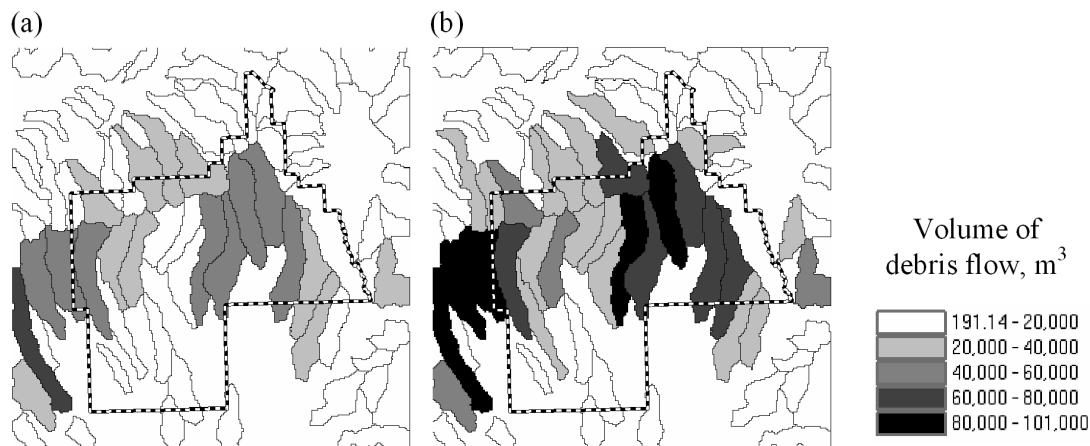


Figure 5. Volume of debris flow for (a) 2-year 1-hour and (b) 100-year 1-hour rainfall events.

studies, such as those promoted by the Drought Impacts on Regional Ecosystems Network (DIREnet) to prioritize management decisions.

Ecosystem management is also expanding to include evaluation of large-scale drivers of system dynamics, such as climate. At Northern Arizona University, the landscape modeling effort under the auspices of FRAME has expanded to include a study whose goal is to make available a version of SIMPPLLE that incorporates output from global climate models (general circulation models). Species-specific responses across

the landscape will be modeled through an interaction of changing susceptibility to disturbances, changing regeneration capabilities, and changing probabilities of disturbance processes. The expanded version of SIMPPLLE will therefore have the ability to track changes in species distribution as a response to climate change.

COLLABORATIVE MODELING AND THE FUTURE

The adaptive, collaborative modeling approach being developed in the FRAME project will provide land managers with the

ability to evaluate the effects of alternative scenarios on multiple resources; the approach and the modular modeling system (MMS) are flexible enough to allow adjustments to changing conditions. Feedback from monitoring and assessment efforts can be used to refine the numerical models, creating an ideal adaptive management environment. Modeling can directly meet the needs of resource managers of various land management agencies because each agency can select the appropriate components of the model to apply. For example, NPS may not need to include grazing in their models, whereas BLM would.

An adaptive collaborative modeling approach also addresses a frequent concern expressed by both land managers and research scientists—the disparity between the scientists' desire to decrease the uncertainty of their understanding of complex natural systems through further research, and the resource manager's need to make the best possible decision in the near term based on the current state of knowledge. In the past, the conflict between the long-term and short-term perspectives has interfered with the ability to use science effectively in resource management decision making. The adaptive nature of MMS easily accommodates new research findings in addition to feedback from monitoring and assessment efforts. MMS provides an excellent way to both support decisions with current understanding and adapt to new scientific insights over time.

In addition to the specific models implemented thus far in the FRAME project, the modular modeling system provides the ability to link a variety of models, which offers particular promise in dealing with the complex natural resource issues that require incorporating knowledge from a broad range of scientific disciplines. The ability to evaluate the effects of alternative scenarios on multiple resources allows resource managers to optimize the management of multiple resources while minimizing the negative impacts of any one decision.

Our FRAME case study at Mesa Verde National Park was focused specifically on

the collaborative modeling interactions of resource managers, scientists, and modelers. Engaging the public in collaborative modeling efforts, particularly those that are characterized by transparency and collective learning, can help build public trust in resource management decisions (Jakeman et al. 2006). The frameworks and models used in our study are open-source, allowing unrestricted use. In collaborative modeling efforts that include the public, facilitation of the process helps ensure that the principles of collaboration are honored, which is crucial to building and maintaining trust in the process. Key principles of collaboration that are crucial in these collaborative modeling settings include meaningful and continuous inclusion of interested parties, transparency, recognition of distributed knowledge, and fostering of a collective learning environment. The Citizens on the Uncompahgre Plateau Project (<http://www.upproject.org/>) in western Colorado have run their own simulations of ecosystem dynamics, illustrating that modeling can be made readily accessible to all interested parties.

CONCLUSIONS

The overall strategy of the FRAME project is to combine the principles of collaboration with the adaptive capabilities of the USGS modular modeling system to develop a transportable, collaborative modeling approach to adaptive, multi-objective natural resource management. Although this will be a multi-year effort, the focus of our initial case study was management of pinyon-juniper woodlands at MVNP. The case study involved collaborative modeling efforts among resource managers, scientists, and modelers. The group collaboratively identified key system components, critical pathways, and associated conceptual models of pinyon-juniper ecosystem dynamics. The recent invasion and rapid spread of cheatgrass in the park has the potential to significantly alter the fire regime at MVNP by increasing fire frequency and impacting long-term vegetation successional patterns. This concern led us to focus on cheatgrass for the

first modeling simulations. For the purposes of landscape modeling at MVNP, the SIMPPLLE landscape model, a physical process model, was modified to capture the key ecosystem components and dynamics of the conceptual models. The SIMPPLLE model was further refined through an iterative process in which project scientific experts helped define probabilities.

Model results indicate the potential for frequent reburning, at intervals as short as a few years. These simulations suggest a projected fire rotation of approximately 45 years for the park as a whole—a dramatic change from the historic fire rotation, which was measured in centuries. Such a disturbance regime would be far outside the historical range of variability for the PJ ecosystem, and would likely lead to substantial reductions and even local extirpation of many native plant species. To evaluate the effects of frequent reburning on post-fire erosion and sedimentation, a debris-flow-potential model was incorporated in MMS to facilitate its linking with the output from SIMPPLLE. The results showed that the projected changes in MVNP's fire regime would bring an increased risk of significant debris-flow events, with the potential for substantial damage to water resources and cultural resources.

The FRAME case study at MVNP gave us an ideal opportunity to implement and refine the principles and components of a collaborative modeling approach. By coupling the principles of collaboration with integrated modeling approaches we are developing a collaborative modeling framework to facilitate adaptive, multi-objective resource management that is applicable across a wide range of ecosystems. Recent trends in natural resource management—toward integrated science approaches, co-management of public lands, adaptive management in the face of uncertainty, and public engagement in land-use decision making—are trends that developed in response to a greater appreciation of the inherent complexity, feedback mechanisms, and uncertainty in natural systems, plus increased public scrutiny of decisions on public lands. The

FRAME collaborative modeling approach was developed to address the challenges faced by natural resource management, and provides a way to effectively link integrated science to natural resource management needs. The FRAME approach can also readily be adapted to engage the public in participatory natural resource management efforts.

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