Conceptual Ecological Models to Guide Integrated Landscape Monitoring of the Great Basin

By D.M. Miller, S.P. Finn, Andrea Woodward, Alicia Torregrosa, M.E. Miller, D.R. Bedford, and A.M. Brasher

Chapter 1. Conceptual Models for Landscape Monitoring

By D.M. Miller, S.P. Finn, Andrea Woodward, and Alicia Torregrosa

Introduction

The Integrated Landscape Monitoring Pilot Project (ILM) was developed by the U.S. Geological Survey (USGS) in response to the need of its partner agencies for a monitoring and predictive capability that addresses changes in broad landscapes and waterscapes. Human communities and needs are nested within landscapes formed by interactions among the hydrosphere, geosphere, and biosphere. Understanding the complex processes that shape landscapes and deriving ways to manage them sustainably while meeting human needs require sophisticated modeling and monitoring. The long-term goals of the ILM are to

1. Identify, evaluate, and validate system components that are indicators of landscape change;
2. Provide feedback to land managers on the results of management actions in the context of ecosystem change through synthesis of data, models, and other decision support tools;
3. Define the unique ability of USGS to respond to customer needs in the area of landscape monitoring; and
4. Lay out a vision for the future that will make use of USGS' capabilities to design and implement monitoring networks, understand and model ecosystem change, and forecast landscape change.

The Great Basin was selected as one of four national pilot landscape areas for integrated landscape monitoring effort because (1) there is a well-defined need by Federal, State, and local community groups for monitoring and ecosystem understanding at the landscape scale; and (2) USGS has significant capability, ongoing work, robust partnerships, and regional datasets in place. In response to the national directive, the Great Basin Integrated Landscape Monitoring Project (GBILM) was formed with participation from the five USGS disciplines and several Department of Interior partner agencies.

In this document, we summarize and organize current understanding of ecosystem structure and function in the Great Basin using conceptual models. Communicating this understanding is fundamental to developing monitoring programs and can be done with clarity using the pictorial format of conceptual models. Conceptual models are not ends in themselves but are helpful organizers of thought, information, and ideas, and represent tools for communication and inquiry among scientists, managers, and the interested public. Consequently, the conceptual models in this report can be thought of as maps or flowcharts that help navigate a progression of scientific thought that starts with determining key ecological components and ends with a summary of mechanisms for the causal influences and relations among them. Eventually, conceptual models can provide a structure for designing monitoring programs, interpreting monitoring and other data, and assessing the accuracy of our understanding of ecosystem functions and processes. Additionally, the models can guide the identification of a few important attributes that provide information about multiple aspects of ecosystem status (Noon, 2003) and are efficient indicators to monitor.

In summary, conceptual models inform monitoring programs in the following ways (Maddox and others, 1999):

1. Models summarize the most important ecosystem descriptors, spatial and temporal scales of major biological processes, and current and potential threats to the system. They provide feedback to, and help formulate, goals, objectives, indicators, management strategies, results, and research needs. A model should not be expected to be complete and all-encompassing; rather, it should illuminate components of the ecosystem that relate to management and its impacts. Models facilitate discussion and debate about the nature of the system and important management issues and questions.

2. Ecological models play an important role in determining indicators for monitoring. The model is a statement of important biological and physical components and processes. It therefore identifies aspects of the ecosystem that should be measured.
3. Ecological models can provide useful tools to help interpret monitoring results and explore alternative courses of management. Monitoring results should be used to update and improve the ecological model, which is the summary statement or framework of the system. Monitoring results may support or conflict with current understanding, thereby contributing to evolution of knowledge and understanding. Models are expected to evolve over time as they are developed, tested, and informed by new data and knowledge.

There is no single model that adequately describes an entire system or even a part of a system, because it is impossible to achieve both model generality and model realism. Model generality is needed to characterize broad-scale influences and relationships among resources. In contrast, model realism is needed to identify specific potential expressions of change that could be effective monitoring indicators, which requires considerable detail. Consequently, integrative general models and more detailed specific models are needed to represent systems of the spatial extent and ecologic complexity of the Great Basin. Models that have the generality to describe an entire region will include few details about individual ecosystem components and will instead provide a broad overview of how those components interact. Achieving model realism necessary for understanding local-scale processes can be likened to moving a magnifying glass around to focus on individual ecological systems or management issues. With each change in position, some elements are brought into sharp focus while others become less distinct.

Recognizing that a group of related models is needed to describe the complexity of the Great Basin at different levels of detail, the GBILM project developed a set of conceptual ecosystem models to: identify key ecological functions and services; develop an overarching model of landscape function; inform regional monitoring strategy development that integrates existing capabilities; and identify critical gaps in our knowledge of ecosystem function. This report is a first step in the process; it:

- Describes the process that the Conceptual Modeling Team used to develop the conceptual models,
- Develops the framework for ecosystem models,
- Identifies the most important ecosystem drivers,
- Presents and describes our set of conceptual models, and
- Illustrates our approach of scaling from a framework model to system-specific models and integrating the component pieces.

This document provides a conceptual framework for many of the unique ecosystems within the Great Basin and includes conceptual models of 'reference-states' and the drivers and stressors particular to each biophysical system. The document develops models at different levels of specificity to illustrate our approach. A conceptual model also has been developed to address landscape integration, such as interactions among ecosystems and cumulative impacts of multiple drivers, and approaches for scaling from local to landscape-level understandings. Fine-scale models for several biophysical subsystems are not developed, but will be developed pending future focus of project staff on these subsystems. This document is presented to help develop a broad-scope monitoring strategy that, when implemented, will provide data to help answer the resource management questions that catalyzed the creation of the GBILM. The indicators developed through this effort function as measurement points that can be used to test the validity of the models and refine research paths needed to better understand change within the Great Basin.

The GBILM models are intended to help identify the natural and anthropogenic drivers/stressors of a system, serve as a structure to interpret data and assess the accuracy of our understanding of ecosystem functions and processes, and facilitate communication with partners about how decisions for indicators, priorities, and protocols in monitoring programs are determined. In response to Department of the Interior agency and partner needs, the GBILM models will place strong emphasis on management relevance and societal values.

Our Approach

Models in this document were developed using a systematic process that defined our goals and limitations; identified key systems, subsystems, and system drivers; and characterized primary linkages among systems in the Great Basin. We loosely followed a set of tasks for developing conceptual models described by Gross (2003). These tasks are:

1. Determine the goals of the conceptual models.
2. Identify bounds of the system of interest.
3. Define a common language.
4. Identify key model components, subsystems, and interactions.
5. Develop control models of key systems and subsystems.
6. Identify natural and anthropogenic stressors.
7. Describe relationships of stressors, ecological factors, and responses.
8. Articulate key questions or alternative approaches.
9. Identify inclusive list of indicators.
10. Prioritize indicators.
11. Review, revise, and refine models.

The process was initiated through a series of conference calls leading to a 2-day workshop held in June 2006, during which team members provided expert knowledge on systems and linkages and identified knowledge gaps amongst the team members. The workshop was followed by regular communication among several subteams, each focused on ecosystem-specific models. Subteams continued to communicate when using and refining the models with the intention of keeping the models relevant and updated. In this conceptual modeling phase, the group did not stress the systematic identification and prioritization of indicators, although many are identified in the model narratives. The Conceptual Modeling Team articulated the following goal:

> We will develop conceptual ecosystem models that describe ecosystem components, external drivers, and interactions of the components, drivers, and processes in such a way that components and processes can be prioritized with regard to importance for monitoring.

We identified the relevant spatial, systemic, and temporal bounds of the Great Basin by iterative review and discussion within the interdisciplinary team in consultation with agency partners. We reviewed 11 existing descriptions of the Great Basin's spatial extent, mapped these descriptions, and explored and described which geographic boundaries best encompassed the potential critical components for which managers most need monitoring information. Next we constructed a two-way matrix of subsystems versus key ecosystem components, stressors, drivers, and potential monitoring attributes to make initial predictions regarding which subsystems were significantly impacted by multiple (or intense) stressors and therefore were good candidate focal systems for conceptual models. We identified a 50-year future time span of consideration for the ensuing models based on this matrix, our knowledge of Great Basin landscape change, and resource manager needs. We later considered the legacy of land-use impacts (200-year bound) and pre-historic impacts by people and climate changes (2–5 millennia) as important precursor time windows. We maintained a common language throughout the process by agreeing to specific definitions for all terms and concepts used during the process (see sections "Common Language" and "Glossary").

Team members identified key model components, subsystems, and interactions by reviewing existing models describing arid and aquatic ecosystems in the Western United States and cross-referencing them to our system-driver matrix. As part of the iterative process, we reevaluated potential model components, subsystems, and interactions in an expert roundtable discussion at the 2-day workshop.

An overall model structure was developed using a hierarchical approach. Based on the system-driver matrix we drafted a 'Framework Model' that coarsely describes systems and interactions operating in the Great Basin. One important principle that emerged during discussions was the significance of water to systems throughout the Great Basin and the distinction between precipitation-event-driven systems ('dry' systems) and surface- and groundwater systems ('wet' systems, which respond to precipitation at long time scales). We reviewed the prevalence and importance of key dry and wet subsystems at local and regional scales and identified where system-specific models would be most useful to managers. The team agreed that key models for an integrated understanding of landscape level functioning of the Great Basin are: stream and riparian areas, groundwater dominated wetlands and springs, freshwater lakes and marshes, saline lakes and marshes, salt desert scrub, sagebrush steppe, pinyon-juniper woodlands, aspen forests, conifer forests, and alpine tundra. This list excludes several systems such as dry and wet playas, sand dunes, caves, hot springs, and badlands, all of which play important ecological roles but have smaller spatial footprints.

During the expert roundtable discussion, the team identified a suite of 30 natural and anthropogenic drivers and stressors (appendix A). We selected a subset of nine stressors as being critical to Great Basin ecosystem functioning and as being top priorities for further monitoring. These nine stressors are: water extraction, flow regime, livestock grazing, invasive exotic species, fire regime, invasive plant-fire interactions, land treatments, motor vehicle use, and climate change and variability. Next, we described the relationships of the top stressors to each of the 10 subsystems independent of the previous system-driver matrix to validate our assumptions and identify draft components of the subsystem models.

Finally, we identified teams to develop subsystem models for six focal subsystems: sagebrush steppe/pinyon-juniper woodlands; mixed conifer forest; alpine tundra; groundwater; stream and riparian; and wetlands and springs. These models: (1) serve as stand-alone models for the respective subsystems, (2) provide 'straw men' for further iterative critique and review of our process, and (3) are representative examples for modeling the other key subsystems.

GBILM Project Area

The Great Basin forms a wedge between the Sierra Nevada and Rocky Mountains (fig. 1.1). Bounded to the north by the Columbia Plateau and Snake River Plain and to the south by the Mojave Desert, the defining feature of the region is its internally draining surface hydrology. This closed hydrographic system exceeds 500,000 km^2 in area and includes nearly all of Nevada, and parts of eastern California, western Utah, southeastern Oregon, and southern Idaho. The Great Basin may be spatially defined by hydrologic, geologic, biologic, or cultural definitions which all vary slightly. Anthropologists define the region by cultural attributes of the aboriginal inhabitants (d'Azavedo, 1986), botanists by species composition of the vegetation (Billings, 1951; Vasek and Barbour, 1977), geologists by the structure of the land

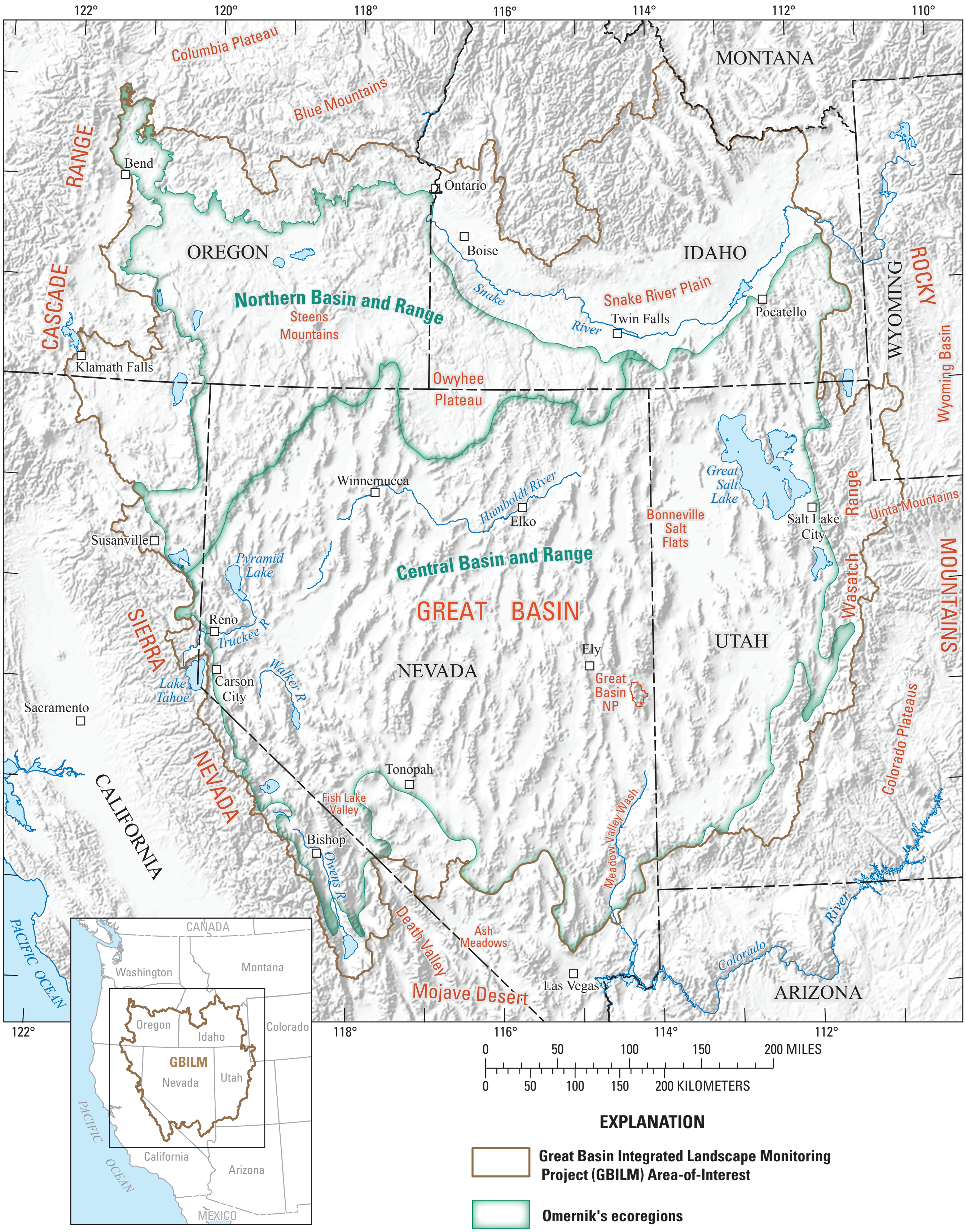

Figure 1.1. Map showing GBILM Area-of-Interest including the Great Basin and the floristically similar Snake River Plain. Area was delineated by overlapping Omernik's northern and central Basin and Range provinces (Omernik, 1987) with the Bureau of Land Management's (BLM) Great Basin Restoration Initiative focal area.

(Hunt, 1967), and hydrologists by the position of aquifers and surface-water flow. For regional monitoring, GBILM defines an area-of-interest that includes an overlay of Omernik's (1987) northern and central Basin and Range Provinces and the Great Basin Restoration Initiative's focal area [http://www.blm.gov/id/st/en/prog/gbri/map.html] (fig. 1.1). GBILM's boundary includes areas outside of but adjacent to the hydrologic Great Basin that are floristically and ecologically similar to the interior basins. Throughout this document, we will refer to the area depicted in figure 1.1 as the 'Great Basin.'

Topographic relief in the Great Basin creates elevation gradients and associated gradients in air density, solar radiation, and precipitation. The interaction of these factors creates many temperature and moisture regimes, which significantly affects plant distribution (Billings, 1970) and animals that depend on them (Hall, 1946). The high, cold (relative to other American deserts) Great Basin desert historically has received most of its moisture as snow (McMahon, 1988; see Chapter 2, section "Atmospheric System Model" for more climate details).

The mountainous terrain, paleo-history, varied climate, and human settlement in the Great Basin provides many opportunities and challenges for a multitude of organisms with diverse life strategies. The composition of biota in the region is a blend of species in common with surrounding regions and a suite of endemic species specifically adapted to life in this cold desert. This combination produces high biological diversity but poses threats to some species' existence. For example, the Great Basin contains more than 130 endemic plant species or subspecies, 95 of which are imperiled. A driver of this high endemism is the patchy nature of many habitat types and the fluidity of patch connectivity across the landscape over geological time. Within 20 km, a single basin-range unit can host environments that range from treeless alpine bogs and rocky slopes to montane coniferous forests, diverse mountain shrublands, woodlands of pinyon pine (*Pinus edulis*) or juniper (*Juniperus spp.*), lower slopes of sagebrush (*Artemisia spp.*) and grasses, lake shores that support an entirely different array of shrubs and flowers, barren sand dunes, and playas. Dozens of montane habitat islands in the region now are separated from each other by arid lowlands. Major metropolitan areas are connected by transportation and utility arteries, which contrast with the sparse ranch and farm land uses in much of the Great Basin.

Common Language

The degree of interdisciplinary cross-fertilization used by groups as they meet multidisciplinary challenges has been shown to affect the type of product that results (Westly and Miller, 2003; Lawrence and Despres, 2004; Hinkel, 2008; Klein, 2008). Teams that strongly adhere to disciplinary boundaries tend to merge their results into an overarching model after the individual disciplinary results are finalized. An example is the traditional approach to flood control which first engineers a flood-control (dam/reservoir) structure based on watershed drainage and subsequently mitigates the negative effects on salmonids using measures such as fish ladders. Teams that encourage more flexibility between disciplinary structures tend to use whole-systems approaches that take into account seemingly disparate causal relationships. A well documented example is the recent tobacco research that investigates the effects of smoking from genetic, neurobiological, social, and economic perspectives to conclude that previous understanding of addiction was inadequate to address the problem of tobacco usage by informing effective public policy (Stokols and others, 2003).

The group challenge of developing a common language is especially acute for teams with disciplines that use terms (or jargon) in incompatible ways and where the terms have a long or strong theoretical disciplinary basis that is at odds. For example, the term 'scale' to a geographer refers to the ratio between a map and the landscape it represents. To a geographer, a map at 1: 24,000 scale is at a much larger scale than a map at 1:1,000,000 scale. For scientists in many other disciplines, a large-scale map refers to a map that shows a large area, necessitating a small map scale. These two opposed uses of the term 'scale' illustrate the potential difficulty in thinking across disciplines and foreshadows the shifts in perspective that can make way for new and different types of conceptualization.

The interdisciplinary nature of the GBILM team required that we agree to a common language drawn from a monitoring literature that is replete with terms and distinctions that vary among users. Consequently, we explicitly defined a vocabulary for this report and in the process we became more discerning in our use of terms such as 'stressor' and 'driver'.

Definitions

We define **landscape change** to be changes in the types, relative proportions, and 'condition' (health, integrity, resiliency, functioning) of Great Basin biophysical systems, particularly as these changes relate to mandates and/or management objectives of land managers. Landscape changes include changes to soils, geomorphic processes, hydrologic systems, and atmosphere as they pertain to ecosystems.

We define **ecosystem (system) drivers**, both natural and anthropogenic, as the events and processes that are most responsible for ecosystem change in the Great Basin. These may be related to global or regional climate, natural disturbance regimes, nutrient cycling, or human activities. **Control models** describe our present understanding of how ecosystems and their subsystems respond to the drivers. At the point that drivers exceed the range of variation beyond which the current biological communities can survive (commonly taken as exceeding the long-term or reference range of variation), the drivers become **stressors** to the system. Examples include extreme climate change (driver) that results in the conversion of shrub lands to grasslands or polluting levels of nitrogen fertilizers (driver) in streams that results in oxygen deprivation of the aquatic subsystems. Although we do not define precise thresholds beyond which drivers become stressors, we use **stressor models** to hypothesize what kind of ecosystem changes we expect the driver to cause. The predictions from stressor models and the critical processes, components, and drivers described in control models can inform the choice of monitoring indicators.

We define drivers as **'natural'** when the ecosystem has evolved with their effects. Natural drivers commonly are quasi-cyclical and in a state of dynamic equilibrium in the absence of excessive human pressures. In contrast, **'anthropogenic'** is used when we wish to highlight that the driver is a result of human activities. Although anthropogenic activities are in many cases accompanied by losses in biodiversity or functional integrity, they also can have positive effects, for example restoration and mitigation. Making a distinction between natural and anthropogenic drivers is fraught with the potential for disagreement and good arguments can be made that any human action is natural. We make the distinction to allow us to make simpler models with better explanatory power.

Implicit in the 'natural' aspect of these definitions is the need to identify ecosystem-specific reference conditions that are framed with respect to a particular time period and place (White and Walker, 1997; Landres and others, 1999). In addition to these temporal and spatial bounds, it is desirable to explicitly identify associated goals, assumptions, and value judgments when adopting a particular set of reference conditions as the "natural" standard for management and monitoring (Truett, 1996; Landres and others, 1999). Late-Holocene, pre-European conditions often are identified as the standard for defining natural disturbance regimes, although it is important to recognize the potentially important role of pre-European human populations in shaping disturbance regimes and ecosystem conditions before European contact (Anderson and Moratto, 1996; White and others, 1999). In addition, periods of climate variability during the late Holocene such as the Medieval Warm Period (ca. 800–1350 AD) and Little Ice Age (ca. 1350–1850 AD) caused significant changes in hydrological systems (for example, lake levels and river flow) and human adaptations to the environment (for example, shifts in subsistence mechanisms and locus of habitation) (Benson and others, 1990). The dynamic nature of ecosystems is a vital concept for understanding the Great Basin.

Ecosystem Drivers

We listed and prioritized system drivers based on expert opinion in order to focus our conceptual models on those parts of Great Basin ecosystems most subject to change (appendix A). We rated every driver according to its scope or magnitude as a factor contributing to management relevant landscape change across the Great Basin. The final list of high priority drivers (five for wet systems, six for dry) is given below along with justifications. We recognize that this prioritized list may be too ambitious, and that further stakeholder input and changing societal conditions may change the priorities. Nevertheless, this list provides focus for developing the current subsystem models.

Wet Systems Drivers

Water Extraction. Withdrawal of groundwater is widespread in the Great Basin in agricultural settings and for municipal use. Groundwater withdrawal lowers water tables because recharge rates generally are very low, and the lowered water table can lead to loss of springs and wetlands. The possibility of accelerated groundwater withdrawal associated with urban development highlights this driver as one of special concern.

Flow Regime. Diversion of streams for irrigation, disruption of streamflow by roads and levees, channel changes for flood control or other reasons, and climate change resulting in changing precipitation and altered snowmelt patterns all contribute to altered flow regime. Flow Regime describes stream function and therefore biotic habitat condition.

Livestock Grazing. Livestock trample streambanks and wetlands, altering habitat in these critical riparian zones and changing hydrologic function. In addition, livestock may alter species composition and water quality by nutrient loading. Most of the Great Basin is subject to livestock grazing and large areas host feral horses.

Invasive Exotics. Introduction of invasive aquatic species has altered most water systems in the Great Basin. Specifically, sport fish have been introduced to nearly every stream. Invasive plants have altered the structure, function, and habitat value of many riparian and wetland systems.

Climate Change and Variability. Global warming and accompanying increased climate variability has altered snowmelt periods, reducing water available for stream flow and lakes, and increasing impacts from intense storms, such as floods.

Dry Systems Drivers

Fire Regime. Altered fire regimes attributable to past livestock grazing (fuel removal) and fire-suppression efforts have caused significant changes in vegetation structure and the function of associated ecosystem processes. Mediated by changes in vegetation structure, ecosystem-level consequences of altered fire regimes can include diminished hydrologic functioning and increased erosion rates, as well as increased ecosystem susceptibility to drought (Miller, 2005).

Invasive-Fire Interaction. Introduction of Mediterranean annual grasses has led to infilling of intershrub spaces with highly combustible grass, increasing intensity and frequency of fire in shrublands of the Great Basin. Increased fire frequency alters natural fire cycles, promoting invasive grasslands over native shrubs, impacting soil properties, and altering wildlife habitat.

Livestock Grazing. Grazing alters species composition, vegetation structure, and animal habitat through many mechanisms. Trampling by livestock destabilizes soils, alters hydrologic processes and nutrient cycling, and facilitates the establishment of invasive exotic plants.

Land Treatments. This driver ranges widely in type and scope but all treatments are meant to improve land utility. Examples of land treatments are roads and trails, agriculture, crested wheatgrass and other introduced grass plantings, chained shrublands and woodlands, timber harvested forests, and even flood-control basins. All treatments cause vegetation change, alter wildlife habitat, and alter soils and nutrient cycling.

Motor Vehicle Use. Motor vehicles, used on road and off, are potential vectors for invasive species and toxic contaminants, and effectively introduce refuse and accelerated human visitation in all but the most remote mountain areas. Off-road vehicle use promotes soil compaction, plant mortality, soil erosion, increased carbon dioxide (CO_2) and dust emissions, and reduced air quality.

Climate Change and Variability. Global atmospheric changes attributable to anthropogenic emissions of CO_2 and other greenhouse gases are expected to have significant environmental consequences during this century (Houghton and others, 2001). Increasing levels of atmospheric CO_2, increasing soil and air temperatures, and altered precipitation patterns (including a potential increase in the frequency of extreme events) are likely to affect physiological processes and competitive relationships of vascular plants, nutrient cycles, hydrologic processes, and disturbance regimes. All these changes have the potential to greatly alter the structure and functioning of dryland ecosystems and the sensitivity of these systems to other anthropogenic stressors (Miller, 2005).

Cumulative Effects of Ecosystem Drivers

Developing a predictive understanding of the effects of ecosystem drivers in the Great Basin requires the realization that drivers typically have effects that interact and accumulate in space and time. Depending on the temporal and spatial circumstances, these cumulative effects can appear as a stressor accumulating over space (for example, low levels of a water pollutant in tributaries accumulating in a river), a stressor accumulating over time (for example, repeated land treatments of the same area), and combinations of single and multiple stressors (fig. 1.2) accumulating over time and space. Interactions also can occur between natural and anthropogenic drivers or disturbances (White and others, 1999; Archer and Stokes, 2000). Because disturbance cycles play such an important role in shaping the structure and functioning of ecosystems (for example, by strongly interacting with soil resources and vegetation structure), disturbance-regime alteration is one of the most significant ways by which human activities affect ecosystems (Chapin and others, 1996).

The climate change/variability driver interacts with nearly all other key drivers, mostly by influencing how they operate on the landscape (fig. 1.2). For example, long-term changes in precipitation in the region, as well as changes in timing of snowmelt and intensity of storms, are likely to affect base streamflow rates causing changes in flow regimes and in the volume of water available to extract. Similarly, changing air temperatures influence evapotranspiration rates causing changes in soil and fuel moisture, and potentially influencing fire return intervals. Climate change also may create favorable conditions for the proliferation of disruptive species that previously were limited by water or air temperature. In general, relatively persistent shifts among ecosystem states commonly are triggered by synergistic interactions between two or more drivers of ecosystem change (Paine and others, 1998; Scheffer and others, 2001; Folke and others, 2004). Characteristically, one driver acts to decrease system tolerance of another driver and thus enables subsequent changes (for example, soil disturbance can reduce ecosystem resistance to the establishment of invasive exotic grasses).

Interactions among stressors and drivers are scale dependent and may accumulate to affect multiple systems. Fine scale (site-specific) drivers, generally anthropogenic, also are likely to interact, and the results accumulate to potentially significant consequences at the landscape-scale and in systems other than those in which they occur. For example, livestock grazing in sagebrush-steppe may alter plant species composition, potentially increasing vulnerability to invasion by exotic species and, perhaps, altering fire and flow regimes. The altered fire and flow regimes in turn impact other systems, such as pinyon-juniper, riparian, and salt desert scrub communities. Some widespread effects (for example, climate change) also may have differing impacts in different systems depending on the dynamics of cumulative effects within or among subsystems. Therefore, we need to consider the relative scale at which stressors and processes work,

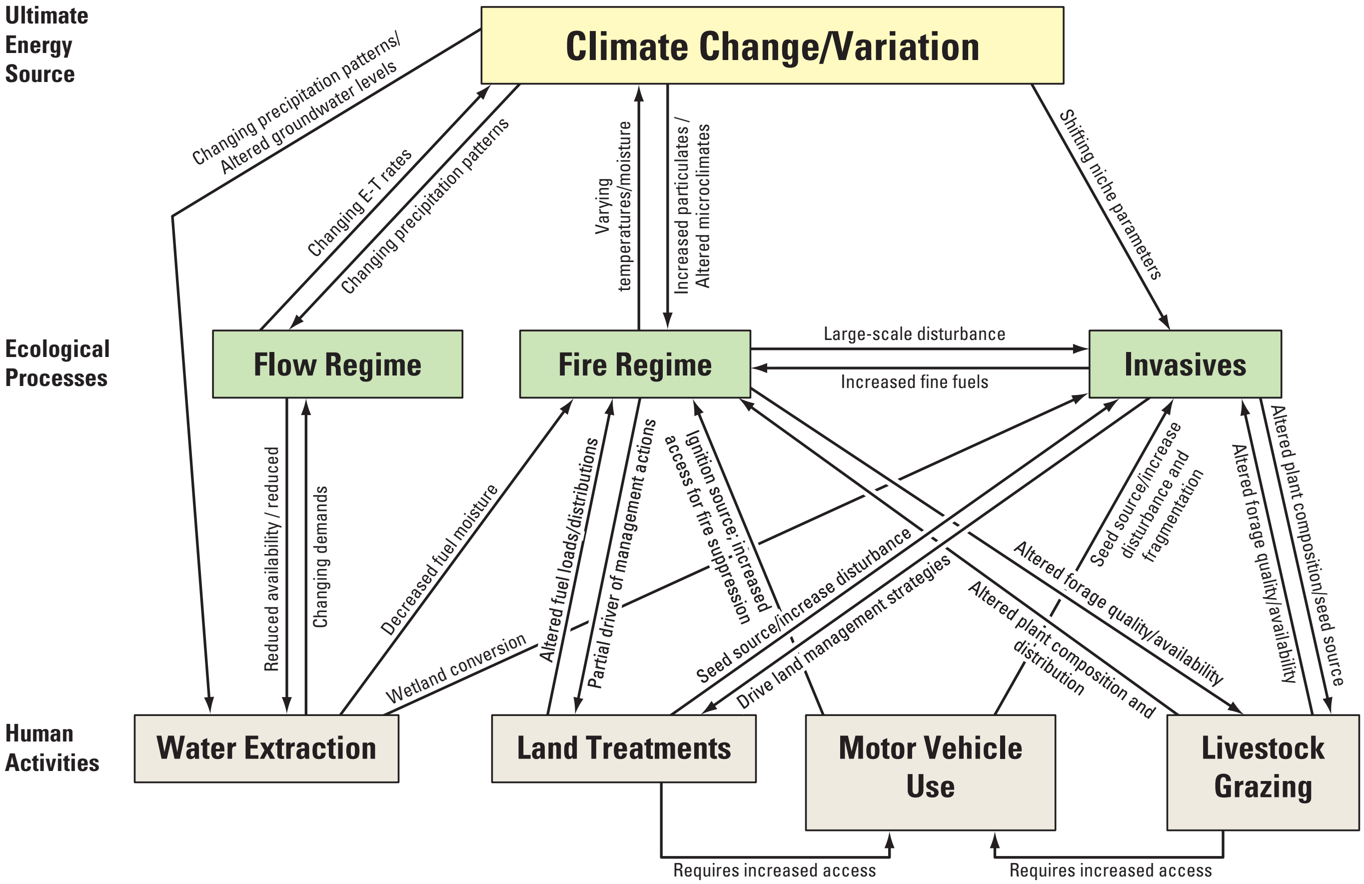

Figure 1.2. Diagram of principal interactions among ecosystem drivers in the Great Basin.

and their functional relationships (for example, non-linear, exponential, etc.). For example, fine-scale stressors such as land treatments could affect fire regime and invasion dynamics leading to changes in vegetation structure and composition in the surrounding landscape.

Our stylized conceptual model of stressor and driver interactions (fig. 1.2) identifies potential interactions among systems to better understand how to efficiently approach monitoring the changing landscape, to stimulate hypothesis development, and to identify gaps in our knowledge of ecosystem processes. We acknowledge the incompleteness of this diagram, which is due to the limitations of graphically portraying interactions of such complexity, and more significantly, a lack of current knowledge of the relevant interactions among many drivers. Two urgent questions require investigation. First, will Great Basin ecosystems be able to respond to increasing CO_2 concentrations, temperature, and changing precipitation regimes without irreversible change? Second, will the response of Great Basin ecosystems to changing climatic and atmospheric conditions be excessively compromised by the multiple drivers associated with human land-use activities?

Structure of Conceptual Models

Multiple conceptual models are required to describe the Great Basin in enough detail to suggest and justify monitoring indicators. Consequently, we divided the Great Basin into hierarchical units that we described with sufficient detail to model the effects of the priority drivers. The hierarchy includes four levels (fig. 1.3).

Framework Model. The highest level of the hierarchy is the overall model, which we termed the Framework Model. It identifies the major biotic and abiotic systems of the Great Basin and how they are related.

System Models. We created a system-level model for each of the four systems described in the Framework Model. These are graphic and narrative models that describe how the system operates at the broad landscape scales and how it is divided into subsystems by major abiotic gradients, such as elevation and precipitation.

Subsystem Models. These models describe our understanding of the important components and drivers of each subsystem and present our current understanding of the processes that shape the subsystem. In some respects, these models are aspatial in that they ignore interactions

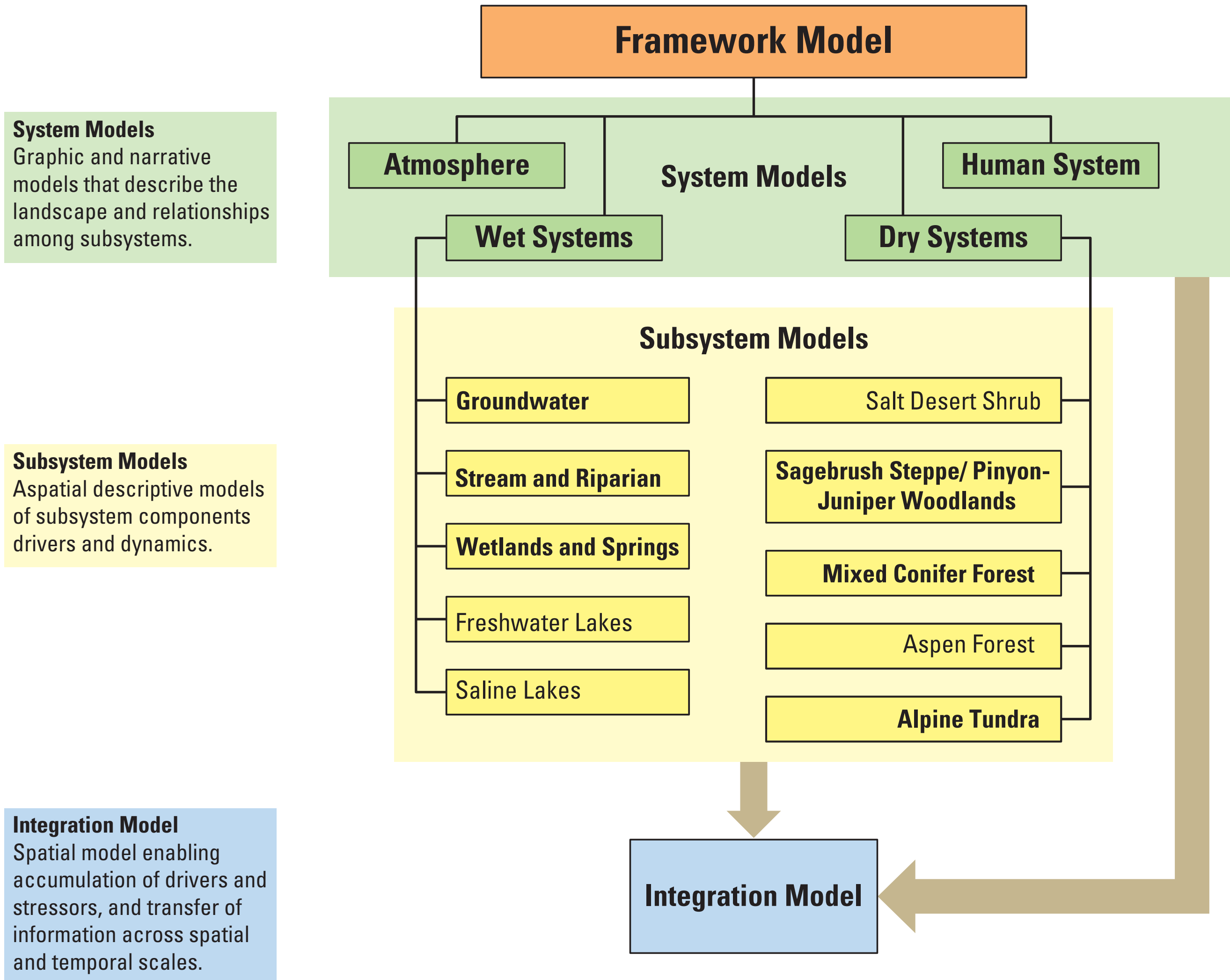

Figure 1.3. Hierarchy of conceptual models used to explain and justify the choice of monitoring questions and indicators. The hierarchy consists of one framework model, four system models, ten subsystems, and one model that integrates the others. Models developed in this report are shown in bold.

among adjacent systems and may de-emphasize aspects of geographic distribution that are important for understanding the subsystem. Each subsystem is modeled using some or all the following model structures: structural control model, state-and-transition model, and mechanistic stressor model (fig. 1.4).

Control Model. Different drivers predominate in each subsystem and each subsystem responds to different suites of drivers in different ways. Control Models describe our understanding of how the subsystems work in response to the inherent variation of drivers by depicting the principal components and processes of the subsystem. These models were built with a focus on the priority drivers.

State-and-Transition Model. Ecological systems are naturally dynamic as they respond to effects of stressors and drivers and to inherent cycles. Ecosystem changes occur along a continuum of time and space, but for the purposes of quantitative modeling, it is helpful to categorize the changes in terms of discrete potential states. Subsystem categories essentially do this for ecosystems in space; state-and-transition models make it possible to illustrate these changes in time. Mechanisms for switching between ecosystem states are provided by the control and stressor models.

Stressor Model. For most Control Models, there is at least one Stressor Model describing how the subsystem is expected to respond to changes induced by drivers that are out of the reference range of variation (stressors). The number of models for each subsystem will depend on how well we understand the subsystem and how adequately one model can describe all relevant stressors (fig. 1.3).

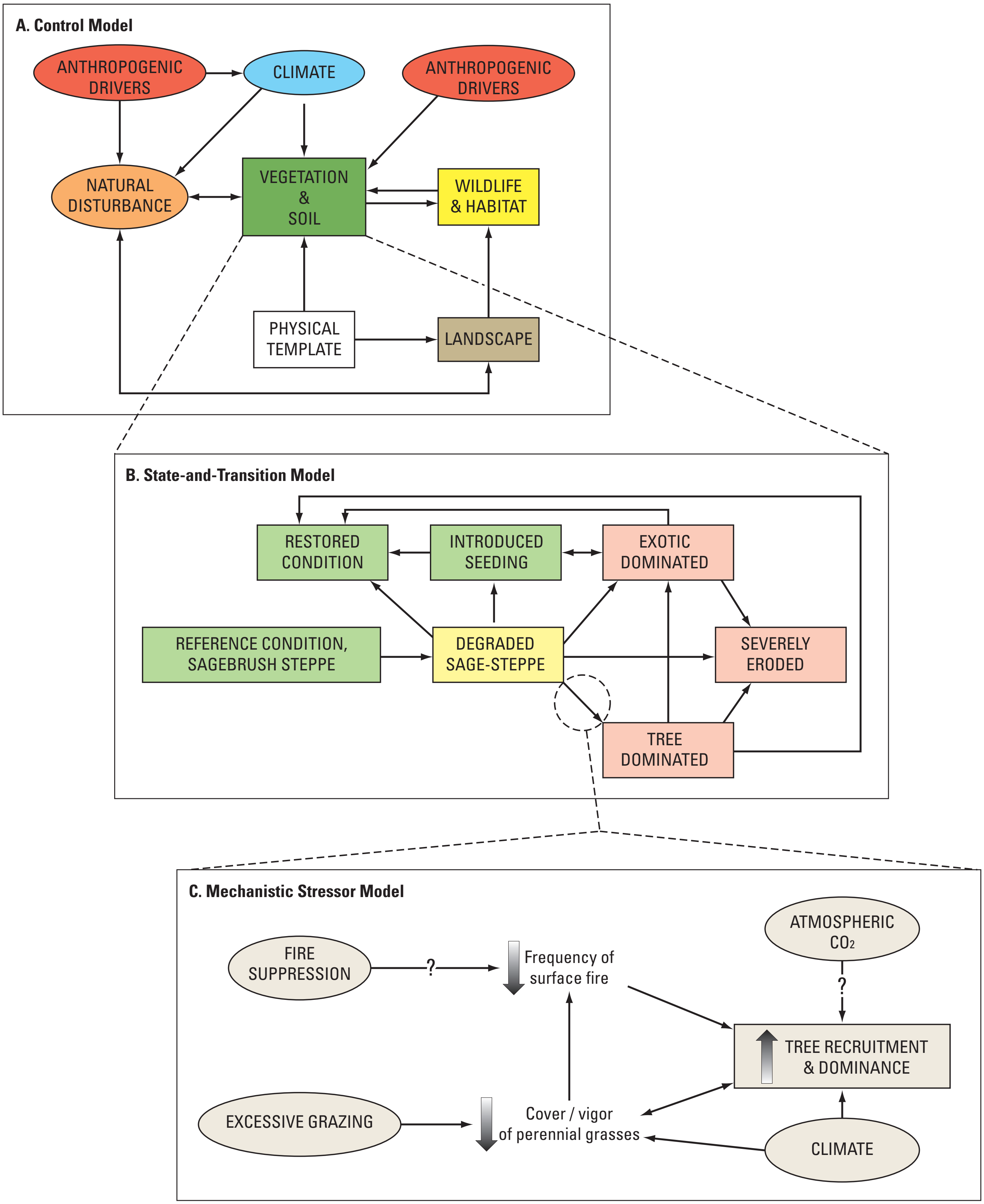

Figure 1.4. Diagrams illustrating relations among control, stressor, and integration models used to describe the structure and dynamics of sagebrush steppe and pinyon-juniper ecosystems in this report.

Integration Model. We recognize the need to accumulate and integrate the effects of multiple stressors and drivers through time and space. Without doing so, we will miss such effects as those of patch dynamics on wildlife, including the proportional amount and distribution of habitat types, and the soil and climate constraints on ecosystem potential. Integration includes scaling, such as transferring data across the range of spatial scales, between the scales at which data are collected and then applied, and scaling to the appropriate level to address the management questions being asked. Integration provides templates for addressing the multiple temporal scales at which ecosystem processes, drivers, and stressors operate. In Chapter 5, we provide a conceptual model for how we intend to accomplish these integration steps.

One of the modeling challenges faced by the GBILM team was to conceptualize the human dimension. Chapter 2 describes the human dimension at the System Model level along with the other three models (atmosphere, dry systems, and wet systems) that are relevant at this level. Although subsystem models within the dry and wet systems are developed in greater detail, models of the atmospheric and human dimension are not developed in comparable detail. This is not to imply that atmospheric or human-induced effects are not included within control and stressor models; to the contrary, anthropogenic activities and climate are acknowledged as important factors in all Great Basin ecosystems and in all subsystem models. Nevertheless, we recognize that, especially for the human dimension, more needs to be done to effectively integrate an understanding of anthropogenic drivers into the conceptual models to guide the GBILM effort.

This document includes the framework model, system models, several subsystem models for parts of the Dry and Wet Systems, and the Integration Model. With this hierarchical approach, we aim to focus on the effects of our high priority drivers in an efficient manner while acknowledging those parts of the Great Basin we will not be addressing. This model structure forms the basis for quantitative models that can be developed in order to create local, landscape, and regional predictions of ecological change. Similarly, the conceptual and quantitative models can be used to identify, justify, and explain monitoring indicators.

Dividing the landscape into discrete units based on water sources and outlets, dominant plant species, or elevational bands is convenient for conceptual modeling. However, we recognize this approach also can be misleading because systems and their shared ecotones are interdependent at multiple spatial and temporal scales. Thus, the Great Basin more accurately may be characterized as a continuum with constant exchange of materials and energy among systems and subsystems where each species responds uniquely to underlying environmental gradients (Austin and Smith, 1989; Shugart, 1998; Euliss and others, 2004). By using discrete, system-based models, we do not imply that systems lack interaction, nor do we wish to blur important connections within or among systems. Rather our deconstructions in Chapters 2 to 4 attempt to simplify our conceptualization of the ecological continuum and focus system-specific management and monitoring targets. More incisive analyses and holistic reconstructions of Great Basin ecosystems are presented in Chapter 5.

This page left intentionally blank