Chapter 2: Framework and System Models

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

Framework Model

As an organizational tool, we have adopted a simple conceptual framework describing systems and domains of integration encompassed by the GBILM project (fig. 2.1). We represent the patterns and processes of landscape change in the Great Basin as they are reflected by complex interactions and feedbacks among four systems – the atmospheric system, dry and wet ecosystems, and human social systems. To effectively meet science-information needs of Great Basin decision makers during a period of rapid social and environmental change, landscape-level monitoring requires integration across all these systems and the multiple spatial and temporal scales that span their interactions. This challenge can best be met through the collaborative integration of all USGS disciplines. This conceptual framework model provides a foundation for organizing ideas and communicating with diverse stakeholders. More detailed scale- and process-specific conceptual models at subsystem levels, presented in Chapters 3 and 4, are used to identify monitoring indicators and their ecological underpinnings (Noon, 2003).

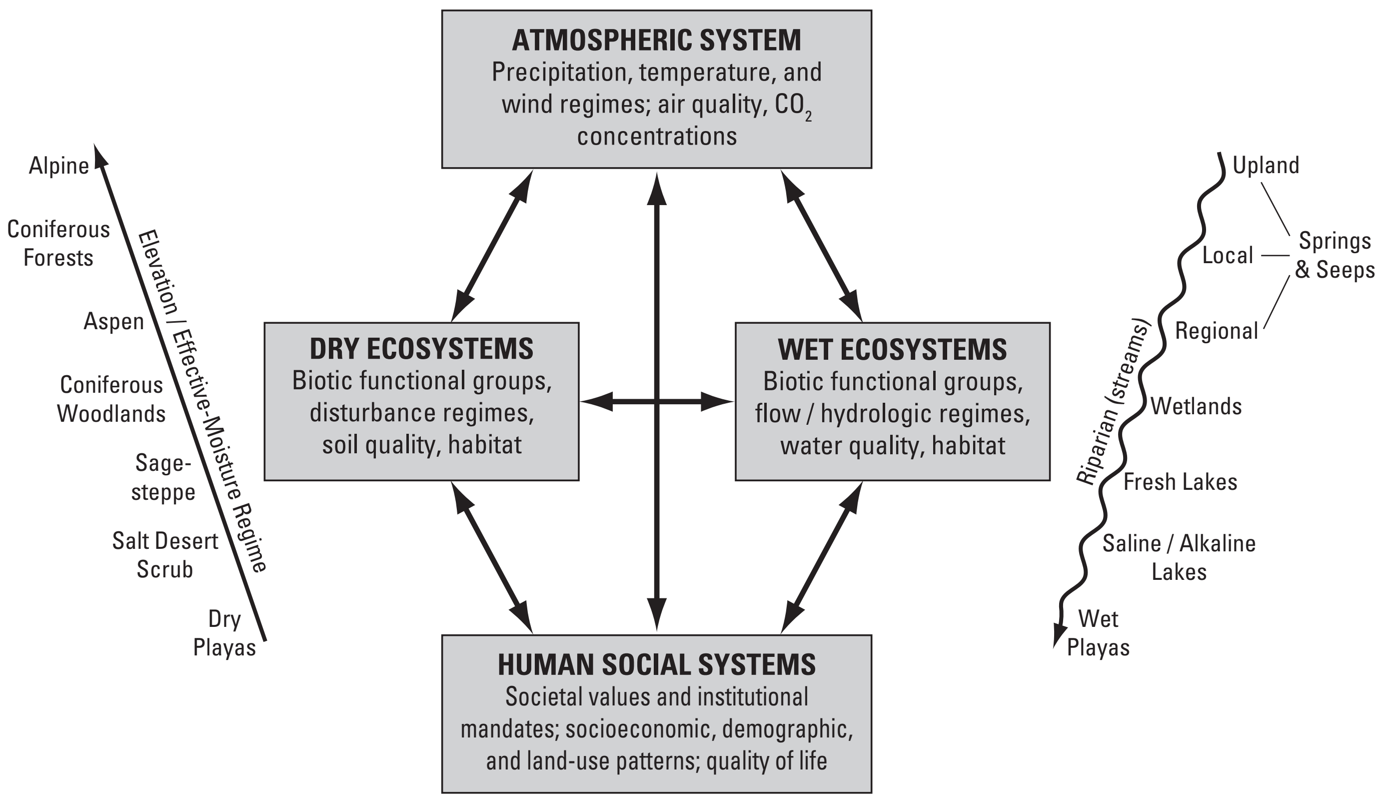


Figure 2.1. Framework model diagram illustrating the overall conceptual framework for the Great Basin project.

Ecosystems of the Great Basin can be described effectively by the interactions between climate and geology, which creates a template of water availability for biota. The framework model describes the fundamental division of ecosystems based on the fate of climatic resource inputs (precipitation) as runoff and recharge (wet systems) or as infiltrated soil moisture (dry systems). Similar partitioning of water affects surface sediment fluxes, and thus surface stability. The model therefore identifies the amount, persistence, and state (saturated versus unsaturated) of water as a basic structuring driver for Great Basin ecosystems. The ecosystems structured on a broad scale by water are modified in many ways by climatic, orographic, pedeologic, human, and biotic factors that combine with water to control the flow of energy and resources in Great Basin ecosystems.

Within each of these "wet system" and "dry system" divisions, a range of amount and quality of water, including the timing of when it is available, serve to subdivide them into finer categories. We describe the system models in this section and the critical subsystem models in Chapters 3 and 4. A few submodels are developed more fully to illustrate how the models can be used to develop monitoring goals. Remaining subsystem models will be developed in the future.

Atmospheric System Model

By D.M. Miller and M.E. Miller

Atmospheric System

The atmospheric system drives weather, whose long-term behavior is described as climate, and it is the system that conducts most mass and energy, including pollution, to and from the Great Basin (fig. 2.2). The atmospheric system therefore is a fundamental driver for the ecosystems of the Great Basin, but it is also highly dynamic at all temporal and spatial scales, making prediction (forecasting) a challenge. The atmosphere receives solar radiation (insolation), a process which is mediated by reflective aerosols and absorbent trace gases before reaching Earth's surface. It also receives water vapor from evaporation at the surface of oceans and the land, where heat exchange influences the vertical temperature gradient in the atmosphere (Bradley, 1985; Monin and Shishkov, 2000). Heat trapped by trace gases further modifies the temperature gradient. Although the atmosphere has low heat capacity, it couples with water bodies of much higher heat capacity, resulting in atmospheric energy being driven primarily by oceans and their circulation patterns. Interactions

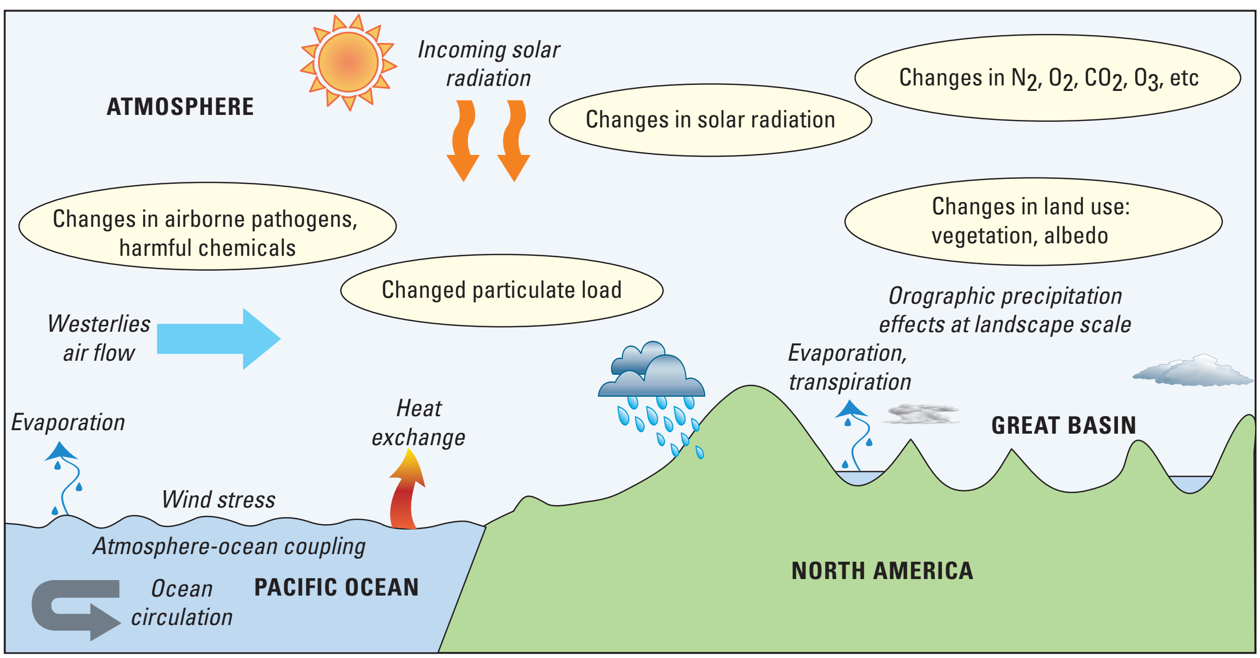


Figure 2.2. Sketch of the atmosphere system, depicting major components and processes, and some of the major changes in the atmospheric system that drive climate variability and change.

between the atmosphere and land include evaporation, reflected radiation, precipitation, wind, and heat exchange; albedo, plant cover and soil moisture are each important factors that interact with atmospheric systems.

The climate of the Earth as a whole depends on factors that influence the radiation balance, such as atmospheric composition, solar radiation, and volcanic eruptions. Insolation varies with orbital mechanics of many periods, from the familiar daily and annual cycles to millennial and longer periods. Because insolation is greater at the tropics than the poles, latitudinal zones exist within the atmosphere. Vertical zones, defined by temperature, moisture, trace gases, and dynamic properties, also exist. The atmosphere has low inertia, so it quickly responds to changes in ocean temperature. It also stirs the near-surface ocean and deposits evaporated water as rain and snow on land.

A number of trace gases, such as CO_2, methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons, absorb and emit infrared radiation. These so-called greenhouse gases, along with water vapor, play an essential role in the Earth's energy budget. Because these greenhouse gases absorb the infrared radiation emitted by the Earth and emit infrared radiation upward and downward, they tend to raise the temperature near the Earth's surface.

Components of the atmospheric system described in figure 2.2 and in above paragraphs are linked, and feedback among the components can dampen or amplify perturbations (that is, negative or positive feedbacks). Increased CO_2 and other trace gases induce a positive feedback by increasing absorption of terrestrial radiation, which increases atmosphere temperature. Increasing temperature in turn increases release of CO_2 by increasing ocean water temperature, creating positive feedback sometimes referred to as the "runaway greenhouse effect." Oceans can dampen perturbations because of their enormous heat capacity. The energy balance in the atmosphere results from a complex interplay of insolation (its reflection by clouds and water, ice, and land surfaces; its absorption by gases, dust, water vapor, and Earth's surface) and radiated heat from the Earth and its absorption by water vapor and gases. The complexity provides many opportunities for non-linear feedback processes, which makes it difficult to simulate atmospheric condition.

Climate Patterns in the Great Basin

Desert conditions prevail across the Great Basin because the region lies in a rainshadow created by the Sierra Nevada and the Cascade Range of California and Oregon. As air masses leaving the coast meet the mountain ranges they rise and cool, causing atmospheric moisture to condense and precipitate (fig. 2.2). East of the mountains, moisture-deficient air masses descend and warm. The rain and snow that precipitates on the Sierra and Cascades partly enters watersheds that drain into the Great Basin; the Truckee, Walker, and Owens Rivers are examples. Valley bottoms of the Great Basin receive as little as 100 mm of annual precipitation on average, whereas a few of the tallest mountains receive more than 1,000 mm.

Climate is influenced at the landscape and local scales by topography. The rainshadow created by Sierra Nevada and Cascade Range, in combination with other regional factors, creates a moisture gradient with drier conditions prevailing in the western part of the Great Basin grading toward somewhat greater total annual precipitation to the east. To the west, precipitation mostly results from regional winter storms originating over the North Pacific Ocean (fig. 2.3). Toward the east, there is increasing likelihood of summer precipitation resulting from localized convective storms originating in subtropical seas (fig. 2.3). During winter, several gradients related to freezing temperatures also are strong determinants of ecosystem condition. In general, winter temperatures decrease with increasing elevation and increasing latitude; average temperature decreases about 6 ºC for every 1,000 m increase in elevation (Rickleffs, 1990). Thus, effective moisture varies with elevation, producing patterns of plant distributions that were described in a conceptual model more than 100 years ago (Merriam, 1890). The result is a regional mosaic of temperature, precipitation, and seasonality of precipitation that drives plant community patterns (vegetation zones).

Temporal variability in precipitation is attributable to at least three different factors. First among these is random fluctuation (Baldwin, 2003). Random, interannual variability in precipitation tends to increase with decreasing mean annual precipitation; arid environments typically have the greatest relative degree of variability (Noy-Meir, 1973; Ehleringer and others, 1999). A second source of precipitation variability is the El Niño – Southern Oscillation (ENSO) phenomenon that is driven by variations in sea-surface temperatures (SSTs) in the eastern tropical Pacific Ocean (Cayan and others, 1999). ENSO influences the latitudinal position of winter storm tracks across western North America; thus, ENSO effects on winter precipitation in the Great Basin tend to vary latitudinally (Baldwin, 2003). The warm ENSO phase (El Niño) tends to result in relatively warm, dry winters in the northern Great Basin and relatively wet winters in the southern Great Basin. The opposite pattern occurs during the cold ENSO phase (La Nina), although ENSO effects in the Great Basin generally are much weaker than in the Pacific Northwest and the Southwest (Baldwin, 2003). There is some evidence that warm-season (April-October) precipitation is above average in the Great Basin during El Niño episodes (Ropelewski and Halpert, 1986). ENSO periodicity ranges from 2 to 7 years (Baldwin, 2003). The third source of variability operates over decadal-scale time periods, creating spatial and temporal patterns in precipitation across the conterminous United States related to phenomena known as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO; Mantua and Hare, 2002; McCabe and others, 2004). The AMO is

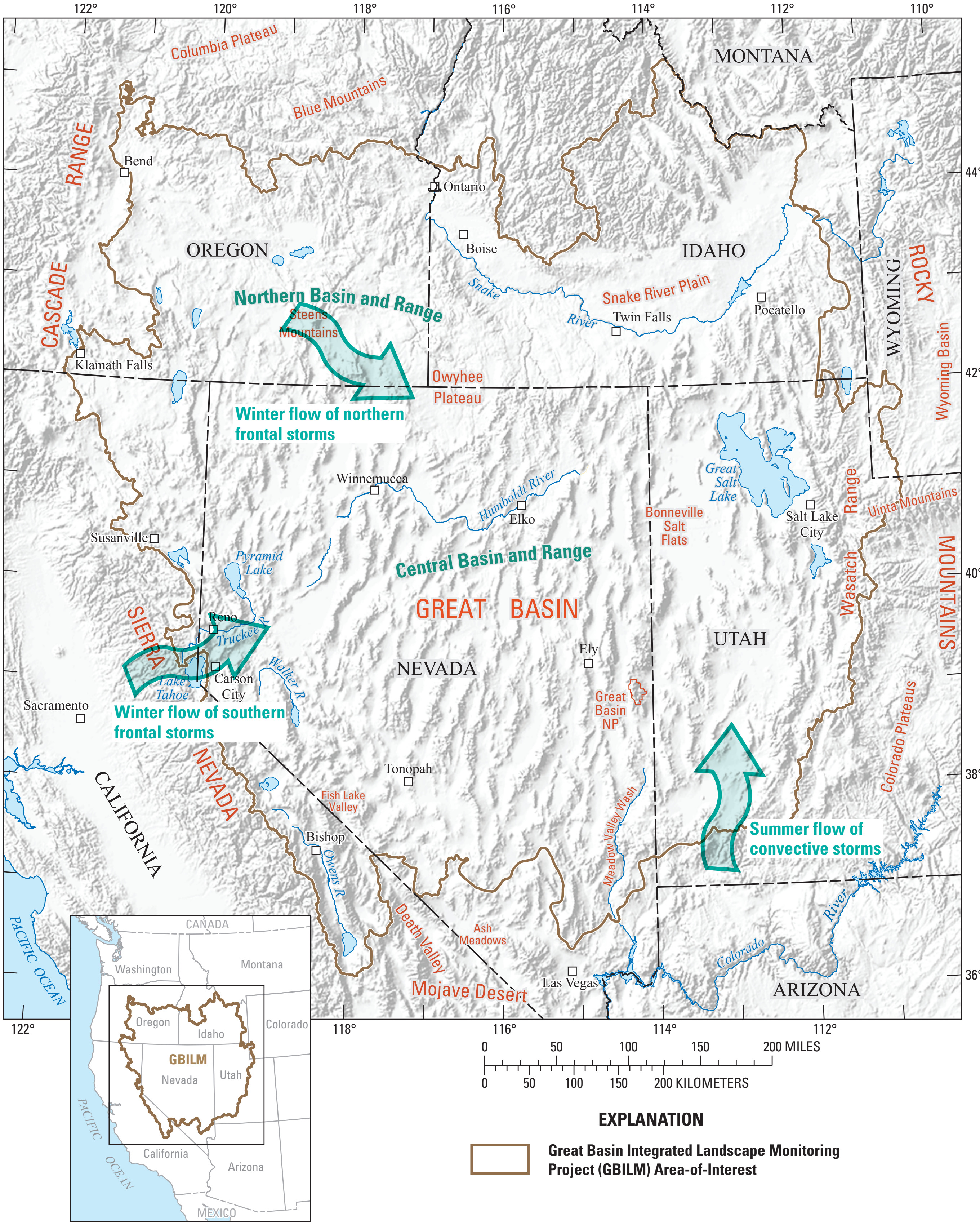


Figure 2.3. Major weather patterns of the Great Basin, showing the distinction between winter storms derived from the Pacific Northwest and those from the southwest, and the locus of enhanced summer convective storm precipitation in the eastern Great Basin.

an index of SST variations over the North Atlantic Ocean, whereas the PDO reflects SST variations over the North Pacific Ocean (Mantua and Hare, 2002; McCabe and others, 2004). The PDO and AMO are quasiperiodic and may be caused by internal variations in oceanic circulation patterns and associated patterns of heat transport (McCabe and others, 2004). In their analyses of 20th-century data, McCabe and others (2004) determined that 52 percent of the spatial and temporal variance in multidecadal drought frequency across the conterminous United States was attributable to variations in these two SST indexes.

In addition, closed basins such as the Basin and Range physiographic province cause temperature inversions. During nighttime, cold air descends from the surrounding mountains and accumulates in valleys, creating an atmospheric inversion of cold air under warmer air. As a result, nighttime low temperatures commonly increase with increasing elevation above valleys, then decrease toward the tops of mountain ranges. This temperature inversion can affect the elevational distribution of plants, but may disappear toward the northern Great Basin due to strong winter storms that mix the air more thoroughly and disrupt the inversions (Grayson, 1993).

Atmosphere dynamics also control patterns for air quality. Regional storm and air flow from coastal areas partition much of the pollution, haze, and particulate matter from central California, Reno, and Salt Lake City into patterns of wet and dry deposition, reduced visibility, and pollutants that can be monitored on the regional scale. Local variations in these air quality indexes must be monitored with local topography and atmosphere dynamics in mind.

Climate Change and Forecasts

Climate and weather vary with time scale, for example from changing wind direction in minutes, brief intense storms in hours, to wet winters, to multi-year drought, to multi-decade wet periods, and Little Ice Age cool periods. This climatic variability creates a complex framework for understanding past, current, and future climate-dependent features in the Great Basin, such as plant viability, plant-animal interactions, soil moisture availability, groundwater levels, and persistence of ephemeral and perennial streams. Additionally, short- and long-term human effects of climate change are superimposed on the background of natural climate variability. Examples include heat islands in and near cities, insulating effects of increased CO_2 and other gases, and decreased solar radiation by haze. We follow the United Nations Framework Convention on Climate Change by defining *climate change* as:

> "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."

"Climate change" thus is attributable to human activities altering the atmospheric composition, and "*climate variability*" is attributable to natural causes. Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events (fig. 2.4). Isolating the effects of climate change from climate variability is an essential, but daunting, requirement for managing Great Basin ecosystems. In addition to climate variability and change, singular events such as volcanic eruptions can cause short-term cooling by adding particulates and gases to the atmosphere, which reflect solar radiation.

Variability and change in climate have effects that we can measure locally, and these effects multiply and combine in complex patterns that potentially affect entire populations, species, and ecosystems at the regional level. Great Basin plant and animal communities can provide useful insight into long-term variations in climate variability. Plants in these communities are adapted to the short-term variability in climate but community composition is, in part, driven by long-term changes. Historical ecology is a particularly important approach to understanding climate variability to which plant communities respond (Swetnam and others, 1999) over time scales of centuries to a few millennia. Climate change has potential to drive many ecosystem processes outside the reference range of variability and Great Basin biota can serve as indicators for such change.

The net effect of human-caused climate change has become quite clear: global warming at an unprecedented rate (Giorgi and others, 2001). Many climate models predict increased temperatures and drier conditions for the Southwestern United States, but the various modeling approaches yield some variation in results. Three categories of models are used: analogs with past conditions, process-based models of climatic conditions with variable inputs of greenhouse gases, and models of the effects of land-use change.

Studies that are based on past analogs and on regional climate models using increased atmospheric CO_2 predict that dry conditions will prevail during the next couple of decades. Some predictions stem from observations that the PDO recently appeared to change phase (see http://topex-www.jpl.nasa.gov/science/pdo.html). The previous similar phase of the PDO was accompanied by prolonged dry conditions in the Southwest during the middle 20th century. By extrapolation, some climatologists predict future drought in the Southwest (Swetnam and Betancourt, 1998; Cole and others, 2002). Frequency of flooding, particularly in larger river systems, may decrease, and eolian activity in the Southwest may increase (Schmidt and Webb, 2001). Dynamic models of future climate that simulate physical oceanic and atmospheric systems can link global models with regional climate models to better address topographic complexity of areas such as the Great Basin. Most of these studies evaluated the effect of increased CO_2 in the atmosphere, and generally predicted that

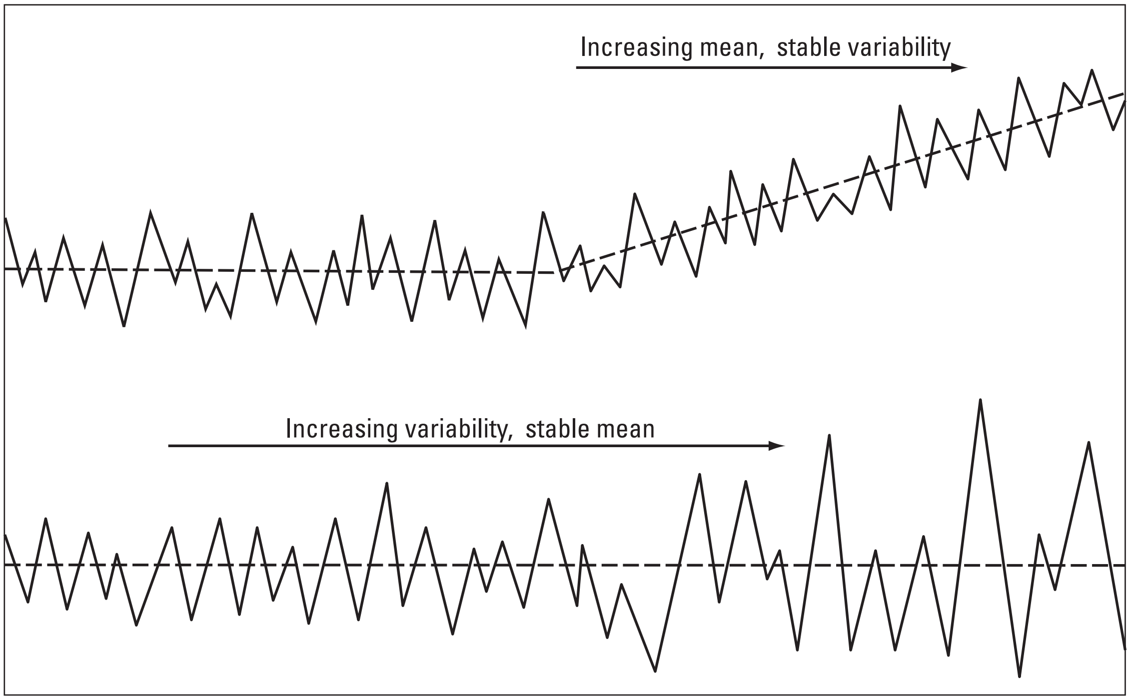


Figure 2.4. Representation of the concepts of variability and mean climate conditions. Climate forecasting models indicate that increases in mean temperature and increases in variability of many climate parameters are likely to occur as a result of anthropogenic alteration of the atmosphere. (Adapted from Bradley, 1985.)

dry conditions will prevail. These models are calibrated by running “hindcasts” to evaluate how well they simulate past climate changes and by comparing them among themselves. The hindcasts tend to show good fidelity for temperature predictions and less fidelity for precipitation predictions. The models provide insight into possible future changes in climate driven by greenhouse gases. A summary of the results indicated by both kinds of models includes:

- More intense, more frequent, and longer heat waves (Meehl and Tebaldi, 2004).
- Increased temperature of stream water (Thompson and others, 1998).
- Increased temperature and decreased precipitation in all seasons (Giorgi and others, 1998b; Thompson and others, 1998).
- Some simulations predicted increased temperature and precipitation (http://www.gcrio.org/NationalAssessment/index.htm, accessed June 22, 2009).
- Winter warming, reduced snowpack, more extreme winter storms (Leung and others, 2004).
- Winter warming, no change in precipitation, reduced snowpack (Snyder and Sloan, 2005).
- Increased storm intensity (Groisman and others, 2004).

Another approach for examining future climate is to model the effects of land cover change, such as expanded woodlands and decreased urban vegetation cover. One study predicted increased temperature due to modeled changes in land cover (Goddard Space Flight Center, 2004).

Although future climate trends are imperfectly predicted because climate systems are exceedingly complex and future scenarios are speculative, the model studies tend to agree on trends during the future 50 years toward climate that is warmer and probably drier, accompanied by increased storm intensity, increased precipitation variability, less snowpack, and earlier spring melting and runoff. The implications for ecological systems are considerable, underscoring the need for monitoring meteorological conditions as one way to evaluate and anticipate changes in the ecosystem.

Ecosystem Effects

Climate variability is the primary natural factor driving ecosystem patterns in the Great Basin (fig. 2.1). Precipitation regime is of particular significance because of the importance of precipitation inputs for driving water-limited ecological processes such as primary production, nutrient cycling, and plant reproduction (Noy-Meir, 1973; Comstock and Ehleringer, 1992; Whitford, 2002). Precipitation seasonality (that is, timing in relation to the annual cycle of potential evapotranspiration) and form (that is, snow versus rain) are key attributes because they strongly control the partitioning of precipitation among various compartments of the hydrologic budget – evaporation, transpiration, runoff, recharge, and soil-water storage. Because of their effects on hydrologic partitioning, precipitation seasonality and form are major determinants of ecosystem dominance by different vegetative life forms and functional groups (Comstock and Ehleringer, 1992). The prevalence of cool-season precipitation results in effective soil-moisture recharge and relatively reliable growing conditions during spring (Caldwell, 1985; Comstock and Ehleringer, 1992; West and Young, 2000).

Despite being remarkably adapted to the harsh and variable climate conditions of the Great Basin, biota nevertheless are limited by temperature extremes and precipitation timing (that is, seasonality and lengths of drought). Changes in climate created by anthropogenic increases in CO_2, particulates, aerosols, and other pollution have the potential to drive many ecosystem processes outside the reference range of variability (the range of variation during a reference period of consideration; see discussion in Chapter 1). If climatic conditions persist outside the reference range, novel ecosystem trajectories can be expected.

Plant and animal population distributions reflect recent climate, dispersal patterns, and a complex integration of past climate changes and disturbances. As a result, time scales of decades to millennia of past conditions are relevant to addressing modern threats to biota.

Summary Points

The relationship between climate, topography, and Great Basin landscape configuration is relatively well understood within the context of historic ranges of variation. However, many aspects of climatic effects on Great Basin systems are unknown despite a growing understanding of regional climate-change patterns. Global climate models generally are too coarse for local or regional analysis and 'downscaling' techniques (for example, Murphy, 1999) to regionalize climate models are partially limited by the scarcity of climate stations in the Great Basin. Data for many climate stations is of short duration, limiting knowledge over long climate cycles. Additional weather stations would enable more accurate regional and local models and, in turn, improve regional models. Establishing relations between local climate and soil moisture-runoff-recharge balances would significantly advance modeling capabilities for Great Basin ecosystems.

Human-Social System Model

By Alicia Torregrosa

Introduction

Humans (*Homo sapiens sapiens*) comprise a complex agent of change in the Great Basin (fig. 2.5) over multiple spatial and temporal scales. Unlike most other dominant ecosystem species, humans have extensive social constructions that use symbolic language, abstract thinking, and cultural inheritance. These constructs give rise to things such as money, property boundaries, institutions, and conceptual paradigms that in turn produce enduring physical infrastructure such as fences, irrigation canals, farms, factories, cities, roads, power grids, and telecommunication networks.

Human-induced landscape change is a sociocultural phenomenon (fig. 2.6). The way we think about the land governs our interactions with our environment and is shaped by our cultural, socioeconomic, and political systems. Evolving conceptual paradigms, social agreements, institutions, and regulations abet and constrain land ownership and land uses. For example, a social construct of the early 20th century was that fire destroys forests, which generated an institutional policy of fire suppression. The ecosystem response was a shift in vegetation composition and biomass which in many cases led later to uncontrollable fires. As managers and scientists investigated the response, a new understanding of the relationship between fires and forests led to a paradigm shift that fire is a part of healthy ecosystems. This new understanding has translated into management activities that include prescribed burns, thinning of trees within forests to mimic the effects of fire, and legislation such as the 2003 Healthy Forests Restoration Act (fig. 2.7).

From a biophysical perspective, the niche space occupied by humans is unusual compared to other species. Individual humans have the ability to harness the technological capacity built by extensive social systems and alter any ecological niche of the Great Basin. The importance of human impacts to the reproductive success of other species led Alberti and others (2003) to propose a reconceptualization of niche theory that explicitly integrates human effects into a species' realized niche (fig. 2.8).

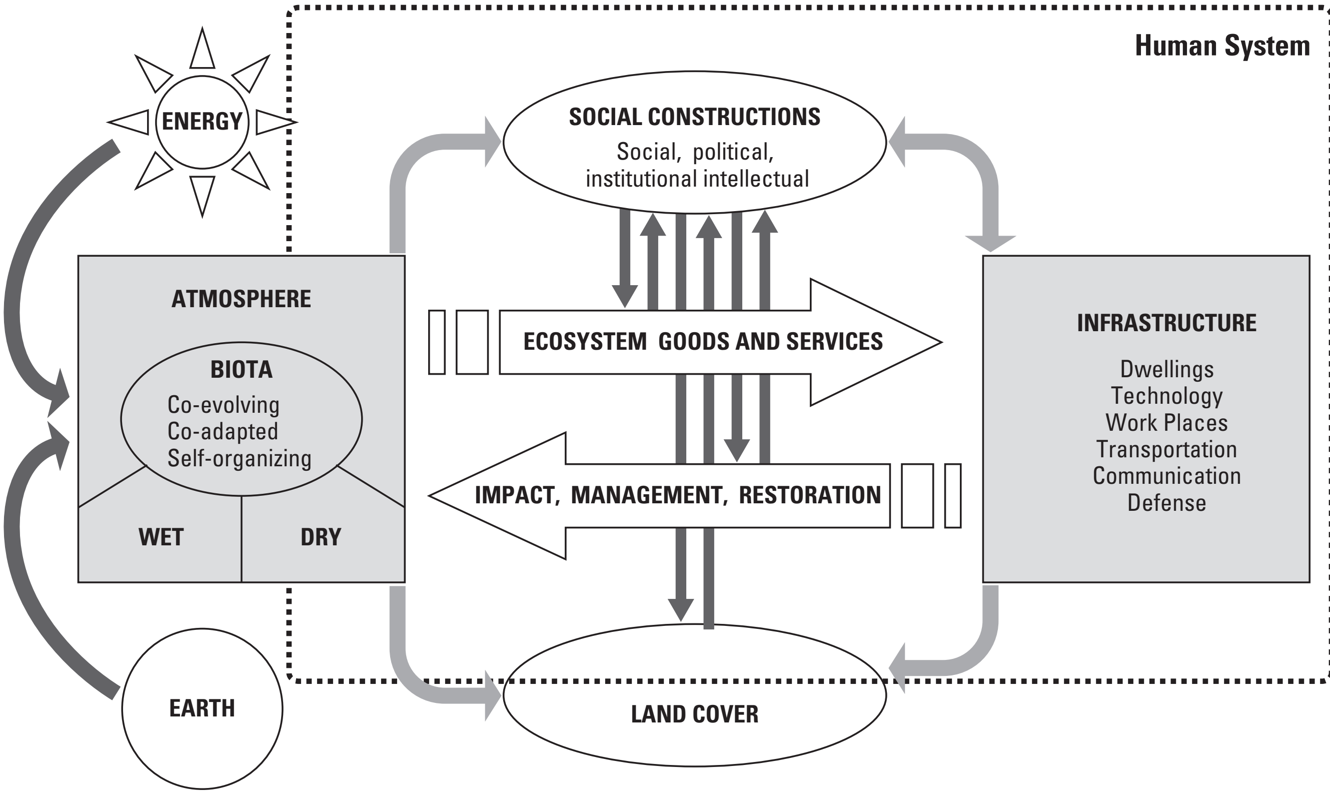


Figure 2.5. Human Systems model. The box on the left represents the Great Basin system at the framework model level (fig. 2.1), conceptualized by the team as an open system driven by solar energy and structured through Earth processes with four main conceptual components: atmosphere, wet and dry systems, and the human system. *Homo sapiens sapiens* is one of many biological species in the biota of the Great Basin, a system of biogeophysical interactions. An expanded view of the human social system is enclosed by the dashed line. Ecosystems goods and services (top block arrow) stem from social constructions that assign value to the natural capital of the Great Basin used by the human system including minerals, soil fertility, water, water purification, and biomass. Changes on the landscape are driven by social constructions (top oval) and its resultant anthropogenic activities such as the creation of infrastructure (box on the right of diagram), resource management and restoration activities (bottom block arrow). Only some land-cover change is a direct result of the human system; therefore, the dashed line does not cover the entire oval on the bottom of the figure representing landcover.

The human impact on the realized niche of species in the Great Basin is a function of the density of the human population and the intensity of anthropogenic impact from activities, such as agriculture, irrigation, infrastructure construction, and resource extraction. In addition to changing the available niche space for locally occurring species, anthropogenic introductions of species from regions outside the Great Basin has resulted in the emergence of new combinations of species. These novel ecosystems (Hobbs and others, 2006) have no known analogs. Understanding the persistence and dynamics of these novel ecosystems is a challenge and deciding how to manage them is even more challenging.

Human Presence in the Great Basin

People have lived in the Great Basin for millennia but what effect have they had on ecosystems? Evidence exists that aboriginal populations made extensive use of fire to manipulate landscape conditions for resource management (Miller and others, 1995; Vale, 2002; Anderson, 2005). The statistical analysis of lightning fires by Kay (2007) indicates that there were far too few natural incendiary events to account for documented fire frequencies. This information is relevant for understanding dynamics between sage brush steppe and juniper woodlands especially in the context of restoration efforts.

SOCIAL CONSTRUCTIONS

Values
Attitudes
Lifestyles
Affiliations
Visions
Goals
Knowledge

LANDSCAPE MODIFYING ACTIVITIES

RESULTING HUMAN FOOTPRINT ON THE LANDSCAPE

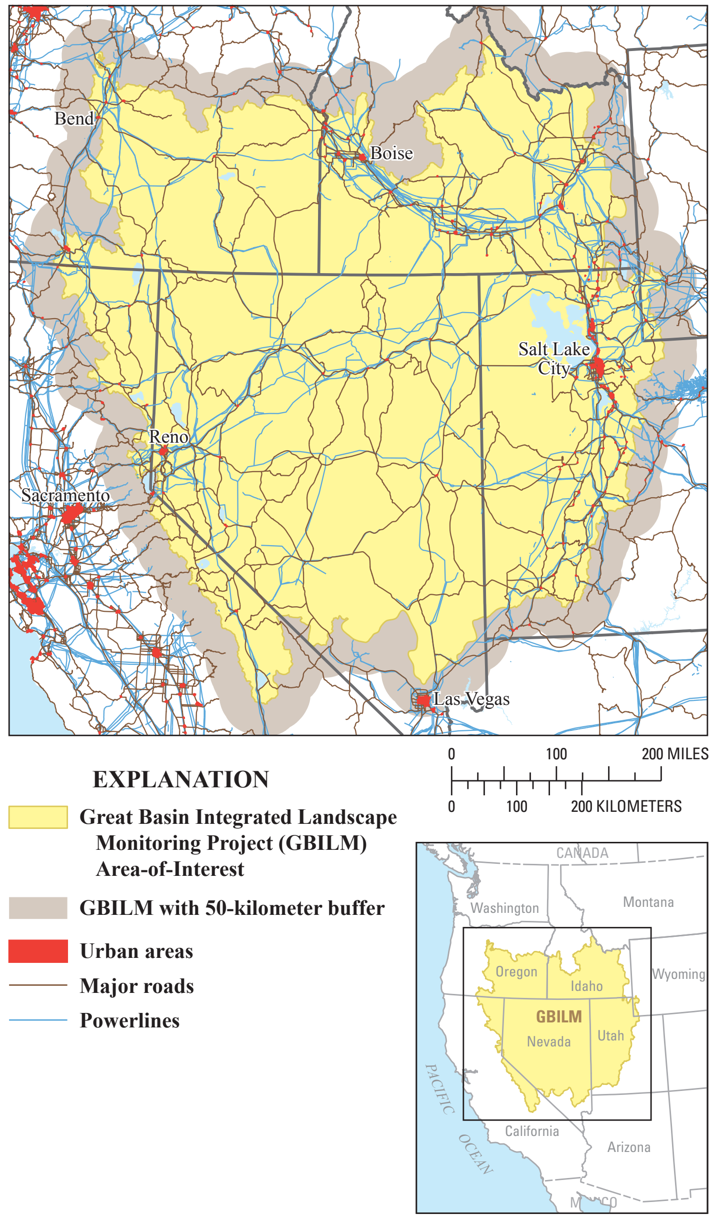


Figure 2.6. Illustrations of landscape change. Human social constructions within culturally defined norms govern interactions with the environment, leading to common landscape modifying activities such as (*A*) agriculture, (*B*) livestock production, (*C*) irrigation, (*D*) urbanization, (*E*) oil and gas production, (*F*) recreational vehicle use, (*G*) defense training exercises, and (*H*) energy distribution. These activities can be mapped to quantify the human footprint on the landscape, shown in the third panel by major highways and utility corridors connecting urban centers.

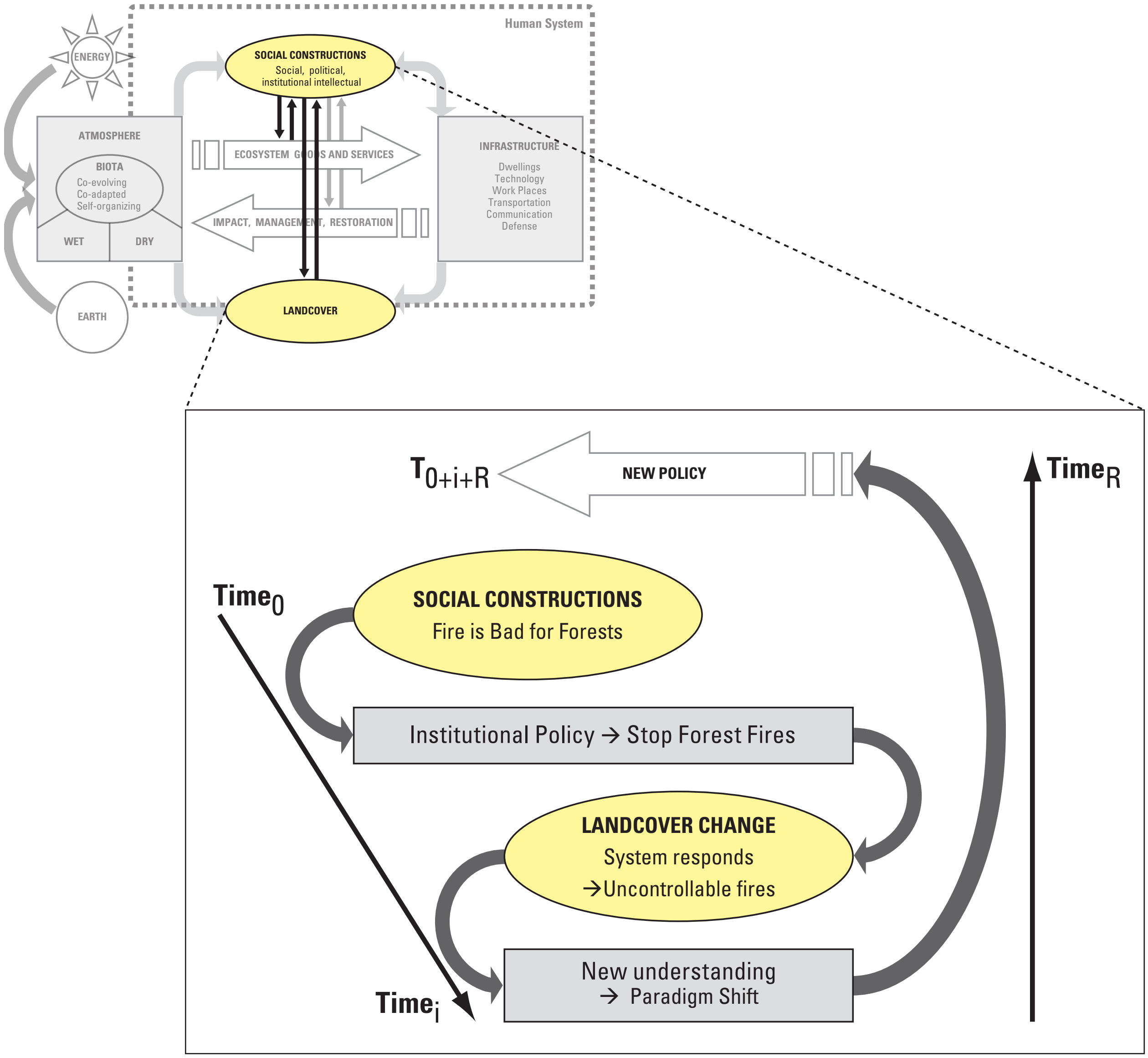


Figure 2.7. Social construction as a Great Basin ecosystem driver. An example of the linkage between social constructions and land cover (highlighted in the upper left box representing fig. 2.5) is the understanding of fire. The temporal dimension of this social model is especially important for forecasting landscape change in the Great Basin. $Time_0$ (at the top of the left time arrow) represents the emergence of the social construction. $Time_i$ represents the time interval for (1) managers to implement the first social construction, (2) the ecosystem to respond, and (3) an understanding of the results of fire suppression. $Time_R$ represents how long it takes for new understandings to effect change on the initial policy of forest suppression. Exploring cycles of paradigm shifts can lead to calculations of the total time required to change policy or social thinking (T_{0+I+R}). This would provide insights on how to realistically calculate $Time_R$, which could potentially improve adaptive management efforts.

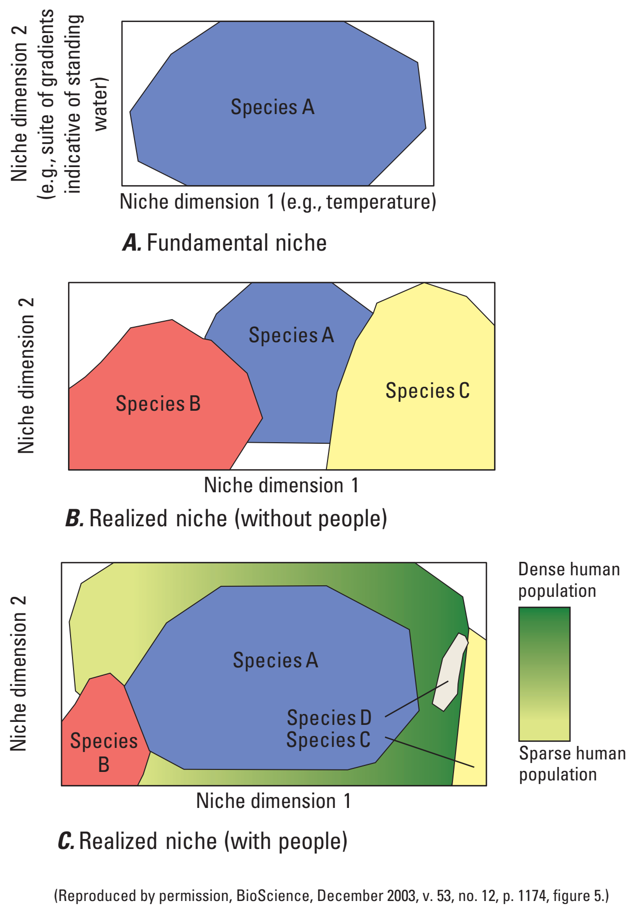


Figure 2.8. The fundamental niche of a species is n-dimensional, with each environmental gradient relevant to a species represented by one dimension (Hutchinson, 1957). (*A*) A two-dimensional view for species A. (*B*) The Hutchinsonian realized niche is that part of the fundamental niche not preempted by competitors, shown here for three species in the absence of people. (*C*) A realized niche with human involvement, in which Species A expands to fill its fundamental niche in the presence of people. Species B has a restricted distribution because the human-subsidized species A out-competes it. Species C is intolerant of humans and is confined to a small part of its fundamental niche where people do not exist. Species D is imported by humans into the geographic niche space.

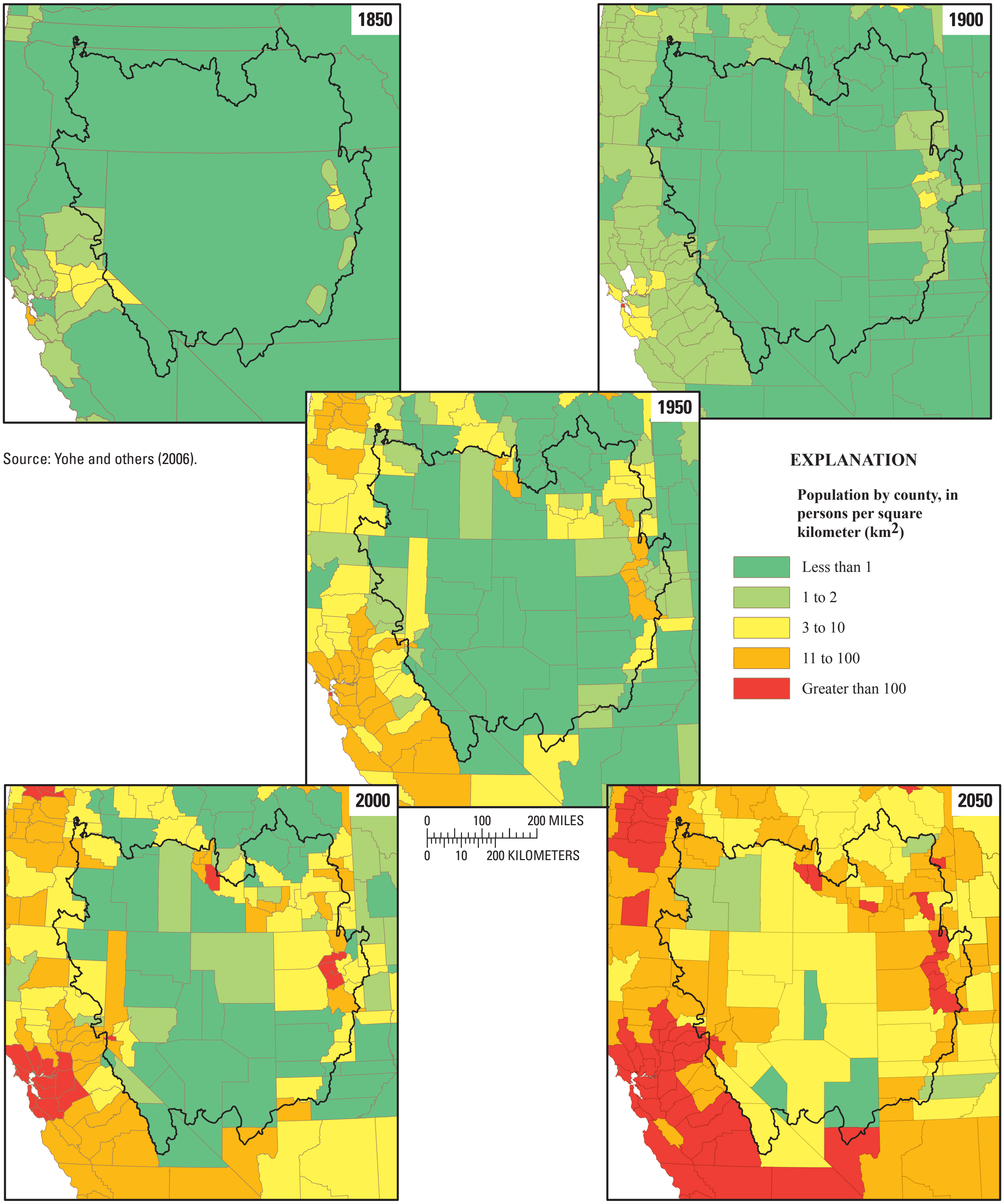
Estimates of Native American populations in the Great Basin prior to the 18th century range from 26,000 (Kroeber, 1937) to almost three times that number (Snipp, 1989). The current (2008) Great Basin population is estimated at 4.5 million and population is expected to increase 50 percent in the next 10 to 30 years (Population Profile of the United States, accessed June 22, 2009, at http://www.census.gov/population/www/pop-profile/natproj.html).

This massive population influx of the 20th century (fig. 2.9) was an outgrowth of two pivotal social constructions that strongly shaped land and water patterns in the Great Basin: the 1862 Homestead Act and the 1902 Reclamation Act. The Homestead Act framed modern American views of private and public property and continues to have a major impact on land management, land use, and urban planning. The Reclamation Act facilitated large irrigation and water reclamation projects and represented Congress' rejection of John Wesley Powell's recommendation to develop the arid lands of the West based on a local watershed stewardship model (Stegner, 1992). Water law is critical to the ecosystems of the Great Basin and the precedent-setting act of 1902 continues to dictate the boundaries of water law (Worster, 1985). A recent Supreme Court ruling (Hage versus United States, 2003) reaffirmed Congress' intent for States to define water rights irrespective of greater public benefit. The extraction of water, accomplished through precedent-setting laws, for human needs including agricultural irrigation, is a significant anthropogenic driver within the Great Basin and can be seen as land-cover change at the landscape level (fig. 2.10).

Historical events can be used as markers for the direction and timing associated with the anthropogenic drivers that result in ecosystem change. To better conceptualize these events, we developed timelines that relate to land use patterns and commodity production and water resources (fig. 2.11) with a focus on the Great Basin's wet and dry systems. Although these timelines describe separate historical events, many are interrelated and cumulative. The historic ecological perspective can be important for assessing the cumulative impacts of these events over time as well as to help to shape the dialogue for restoration efforts.

The extent to which human activity alters ecosystem function is not completely understood. For example, urban development alters ecosystem function by eliminating and altering habitats but what effect does exurban development have? Exurban expansion, characterized by large lots of 5–40 acres with a single dwelling per lot, is positively correlated with habitat fragmentation, but the direct and indirect impact of this expansion on biological communities is still a matter of controversy (Hansen and others, 2005; Bock and others, 2008; Milder and others, 2008).

Many anthropogenic impacts have a long temporal footprint, both physically and culturally. Roads and trails last a long time in the arid environments of the Great Basin, affecting drainage and erosion, encouraging off-road use, and facilitating development. Landscape alterations, such as riparian areas altered by livestock grazing, affect the additional ecosystem services that can be expected, which in turn impacts land values. A conceptual model that includes humans as an agent of change can better explore the effects of these changes on ecosystem sustainability. Models can generate exploratory scenarios of the future even in the absence of sufficient data for numerical computational approaches.



Source: Yohe and others (2006).

Figure 2.9. Maps showing population change in the Great Basin from 1850 to 2050 by county or territory. The Great Basin study area is shown as a black boundary in each pane. In 1850, most of the Great Basin did not have statehood and comprised portions of the Oregon, Utah, and New Mexico territories. Some county boundaries changed between time periods. Population totals for the study area are: 1850—42,374; 1900—333,867; 1950—275,000; 2000—3.6 million; 2008, 4.5 million. (Historical source data from the Minnesota Population Center, 2004. Recent population data from the U.S. Census Bureau, Population Division.)

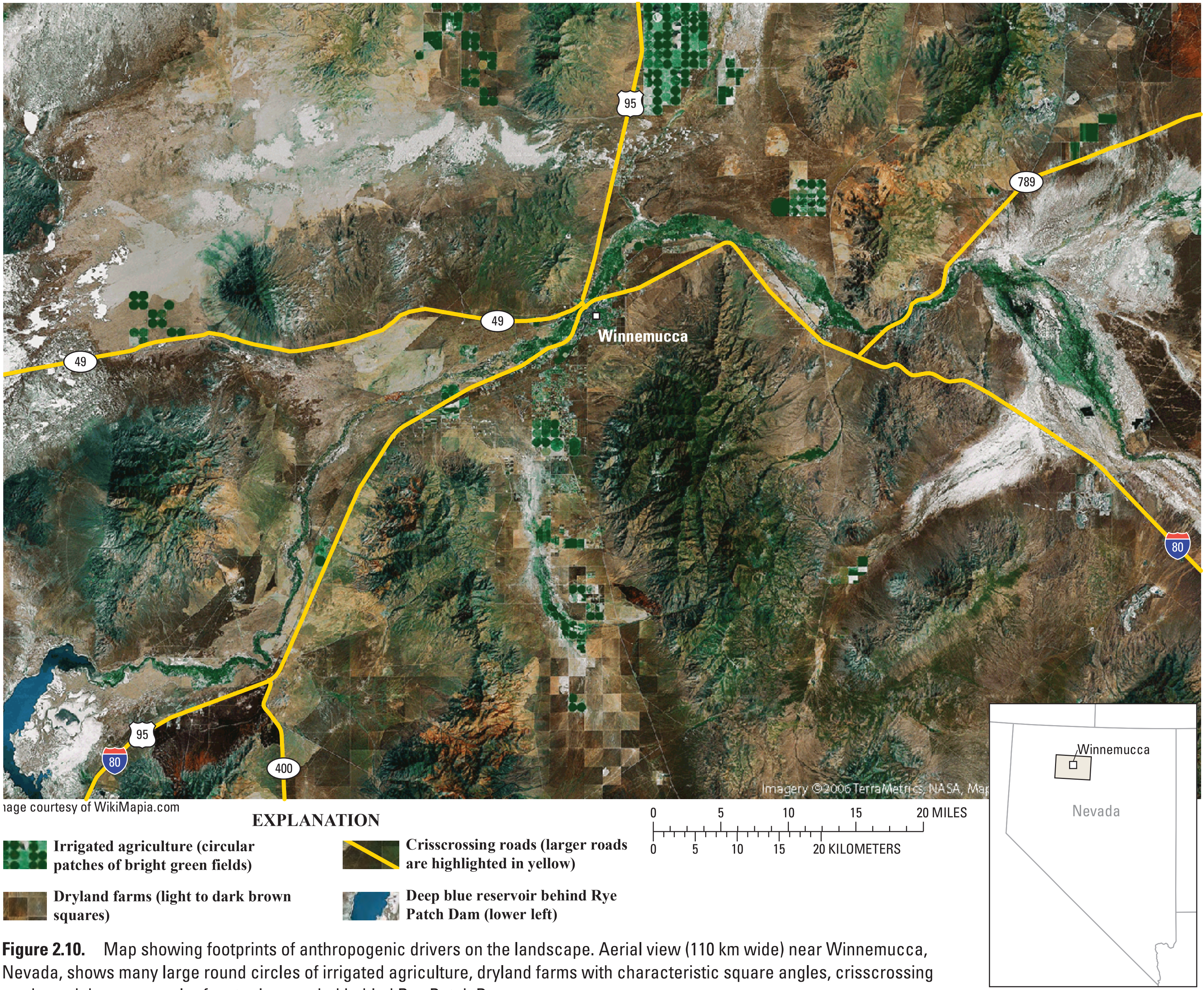


Figure 2.10. Map showing footprints of anthropogenic drivers on the landscape. Aerial view (110 km wide) near Winnemucca, Nevada, shows many large round circles of irrigated agriculture, dryland farms with characteristic square angles, crisscrossing roads, and deep reservoir of water impounded behind Rye Patch Dam.

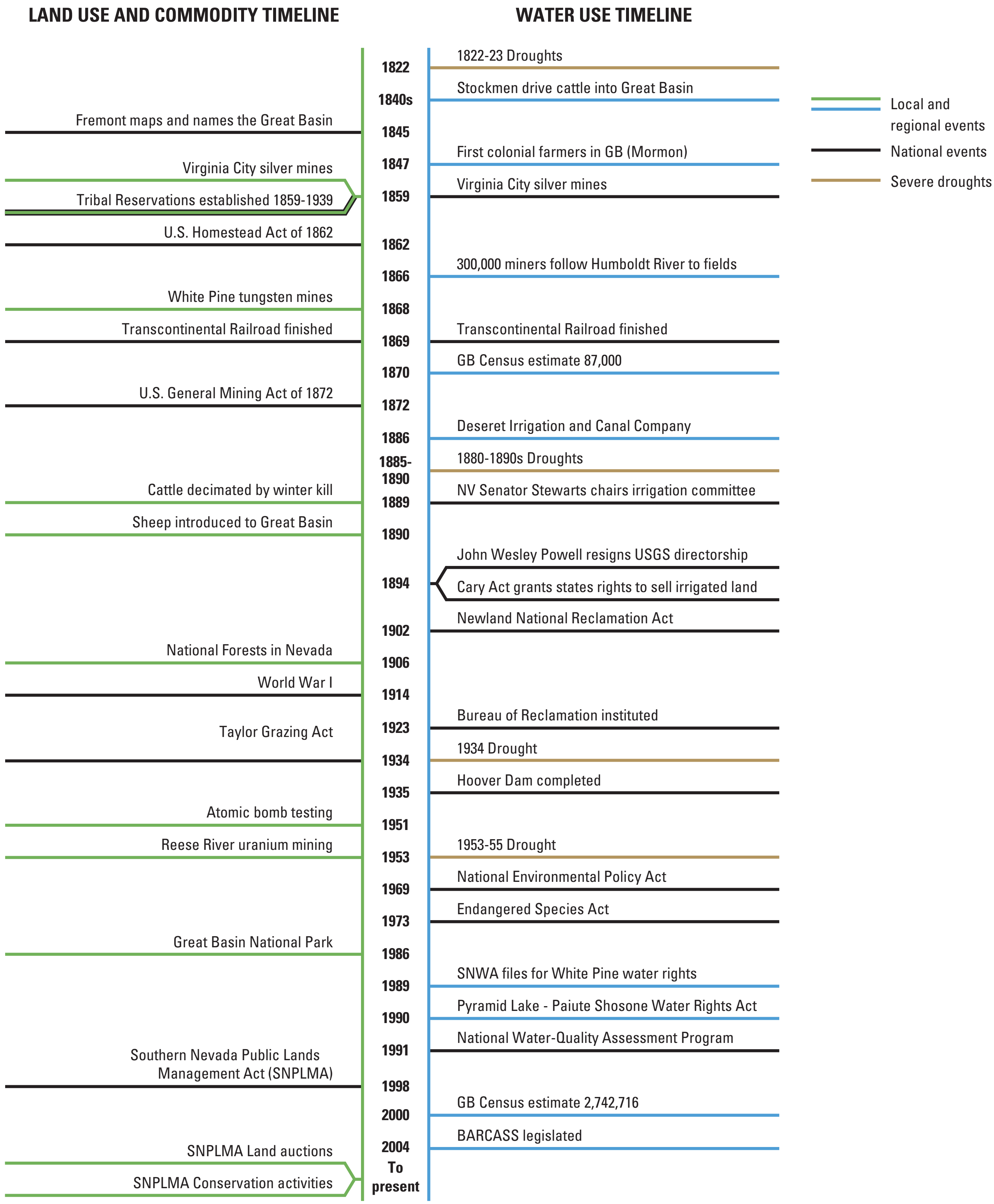


Figure 2.11. Diagrams showing timeline of events that shaped land-use patterns, commodity production, and water use in the Great Basin over the last two centuries. Most events are interwoven. For instance, the severe droughts of the 1880–1890s that led to the introduction of sheep and cheatgrass are pivotal events with increasing impacts on vegetation community structure a century later. Water related needs at the local and regional level resulted in national scale events that continue to affect Great Basin wet systems and water use (Lamm and McCarthy, 1982; Worster, 1985; United States, Western Water Policy Review Advisory Commission, 1998).

Modeling Approach

There are several approaches for including human activities within ecosystem models. Early Urban-Long Term Ecological Research approaches modeled ecosystem processes without an explicit human social systems component, adding anthropogenic activities as modifiers to the flows or processes between major components (Grimm and Redman, 2004). This modifier approach is useful for studies that focus on biogeochemical flows or changes in the rates and sources of nutrients, water, pollution, and other materials (Grimm and others, 2004). An alternative approach is to separate human activities into a submodel within the modeling diagram (fig. 2.5). This approach is especially useful for applying a systems science approach to human activities, framing humans as a component of the biotic community interacting with other ecosystem components (Plotkin, 2003; Robbins, 2004), and for modeling social mechanisms that impact ecosystems such as institutional directives and paradigm shifts. The GBILM team advocates this latter approach because of the need to address scientifically and politically difficult issues that are more tractable if framed through explicit attention on human activities.

Conceptualizing a human dimension to ecosystems by using a human systems approach also is useful for scaling between the spatial hierarchy of site → region → nation and the hierarchical parallel with human social units of individual → group → institution. All these levels need to be considered if one accepts the premise that understanding regional scale processes must include an understanding of the next larger and next smaller hierarchical system levels (Allen and Starr, 1982; Giampietro, 2003).

Information exchange and collaboration is an important human activity rarely integrated into models of ecosystem management. Collaborative environmental problem solving is increasingly being incorporated into monitoring and adaptive management activities. Collaboration and communication can be measured as an indicator of social capacity and approached as a social driver for problem-solving and decision-making processes. The social structures that are built over time, such as networks, organizations, and institutions (important components of social capital), and the ecosystem impacting processes these structures mediate, are important elements for a model of human social system.

Social capacity is an element in several models such as the Sustainable Rangeland Roundtable (Hamilton and others, 2003; Tanaka and others, 2003; Maczko and others, 2004). Recent examples of collaboration on Great Basin management issues include the Bureau of Land Management (BLM) Final Grazing Rule (http://edocket.access.gpo.gov/2006/pdf/06-5788.pdf), which improved relations between BLM and permit or lease holders, and the U.S. Fish and Wildlife Service's Protocol for Evaluating Conservation Effort (http://www.fws.gov/endangered/pdfs/FR/PECE-final.pdf), an important driver for local involvement in sage grouse conservation. The challenge in these examples of social capacity is to conceptualize the links among the social constructions, management objectives, and ecosystem responses.

Summary Points

The social systems model seeks to link the biophysical environment and the human dimension guided by four principles: (1) humans are part of the Great Basin ecosystem; (2) anthropogenic activities result from social constructions—which can be changed; (3) models should include only as much as is needed to understand the drivers and forecast landscape change; and (4) building upon existing research and knowledge best creates a model that is useful to the monitoring community.

Unlike the "wet" and "dry" system models that have considerable pre-existing modeling material to draw on, social system research and modeling to forecast ecosystem change at the landscape level is in its infancy. High priority objectives for further model development would include:

- Define and expand on the social system components that link to ecosystem functioning and integrate these with the model.
- Geographically map social structures that are drivers for models.
- Develop an approach to incorporate processes acting at different spatial and temporal rates, extents, or domains into models.
- Explore how a better understanding of social processes could improve a monitoring framework that tracks ecosystem change, such as by tracking policy measures.

Distinguishing direct and indirect human impacts on the Great Basin landscape from those caused by other drivers is one of the greatest challenges, despite improved systems science models (Gunderson, 1999; Warfield, 2006). Progress is being made to integrate social system processes into global systems to generate climate change scenarios, plan sustainable agriculture, and conduct natural hazard vulnerability research (deGroot and others, 2003). Scaling these models down to the region still needs considerable work. Creating a model of ecosystem drivers in the Great Basin also will require addressing non-resolvable uncertainties (Ritchey, 2002) and "complex judgments about the level of abstraction at which to define the problem" (Buckingham Shum, 1997).

Models that can meet these challenges will help resource managers better understand the leverage points within the whole system and perhaps discover unsuspected links between social constructions and ecosystem functioning for improved decision making.

Dry System Model

By M.E. Miller and D.M. Miller

We define dryland ecosystems as those ecosystems that are not dependent on the availability of groundwater or surface water, in contrast with wetland, riparian, and aquatic ecosystems. As a communication tool and to guide the development of more detailed conceptual models, we have adopted a general model for dry ecosystems (fig. 2.12*A*) that is patterned after the dryland ecosystem model developed by Miller (2005). A premise of this model is that regional climatic and atmospheric conditions, biotic functional groups, disturbance regimes, and soil resources are key factors that interactively control ecosystem structure, function, and sustainability in relation to human use and other drivers of ecosystem change (Chapin and others, 1996). At the center of the model are soil (including biotic and abiotic components) and vegetation, which are tightly coupled through interactive effects on hydrologic (soil moisture) and biogeochemical (nutrient cycling) processes. Soil, vegetation, and landscape configuration (the spatial arrangement of vegetation patches or ecosystem types) influence habitat quality for wildlife (vertebrates and invertebrates), and wildlife in turn affect soil and vegetation in many ways (fig. 2.12*A*), including seed dispersal, herbivory, pollination, soil disturbance, and excavation. Elevation and soil-geomorphic setting (including topographic position and soil-profile characteristics) provide the physical template for landscape-level spatial variations in ecosystem structure and function through effects on soil water and nutrient regimes experienced by soil biota and vegetation (Monger and Bestelmeyer, 2006), as well as by temperature controls.

Climate and the Physical Template

The extreme topographic relief of Great Basin landscapes creates diverse ecosystem patterns and processes due to greater precipitation, lower temperatures, and lower potential evapotranspiration rates at high elevations compared to low elevations. These elevation-dependent factors are responsible for the predictable sequence of dryland ecosystems that is repeated along elevational-moisture gradients from lowland environments to tops of mountains. Along this gradient, major types of upland ecosystems include salt desert scrub, sagebrush steppe, pinyon-juniper woodlands, aspen and conifer forests, and alpine meadows and tundra (figs. 2.12*B*, 2.13). Within each of these systems, climate (for example, interannual and decadal variations in precipitation and temperature) and disturbance (for example, fire and insect outbreaks) are major natural drivers of change and temporal variability. The model reflects the fact that vegetation structure and landscape configuration affect and are affected by most types of natural disturbances.

Abiotic factors including regional climate, elevation, and soil-geomorphic setting determine the potential distribution, biotic structure, and dynamics of terrestrial ecosystems through their combined effects on environmental conditions and resources (Jenny, 1980; Stephenson, 1990; Monger and Bestelmeyer, 2006; fig. 2.12). Climate encompasses a dynamic suite of variables that drives temporal patterns of ecosystem change and variability (Bonan, 2002; see Chapter 2, section "Atmospheric System Model" and fig. 2.2). In contrast, the physical template is a relatively static (or inherent) determinant of potential ecosystem and landscape structure and thus provides a useful spatial framework for ecosystem assessment, monitoring, and management (Rowe, 1997; Herrick and others, 2005; Pellant and Lysne, 2005; Herrick and others, 2006). The concept of the physical template encompasses elevation, topography, and soil physical and mineralogical properties controlled by parent material, geomorphic processes, and pedogenic processes (Monger and Bestelmeyer, 2006). Together, these abiotic factors exert strong control over biogeochemical and hydrologic processes that structure ecosystems through effects on soil water and nutrient regimes experienced by soil biota and vegetation. As determinants of potential ecosystem structure and landscape configuration, climate and the physical template are the basis for the ecological site land-type classification system of the U.S. Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS; accessed June 22, 2009, at http://esis.sc.egov.usda.gov/) that serves as a powerful method for describing the landscape.

Soil Resources, Functions, and Quality

Soils (including soil organic matter and biota) are responsible for the regulation of hydrologic processes and the cycling of mineral nutrients in dryland ecosystems. As the primary medium for storage and delivery of water and nutrients, soils are essential for sustaining the existence and productivity of plant and animal populations. The capacity of a specific kind of soil to perform these functions is described by the concept of *soil quality* (Karlen and others, 1997; Herrick and others, 2002; Norfleet and others, 2003). Soil functioning and soil quality are determined in part by inherent soil properties such as texture, depth, mineralogy, and profile development that are determined by parent

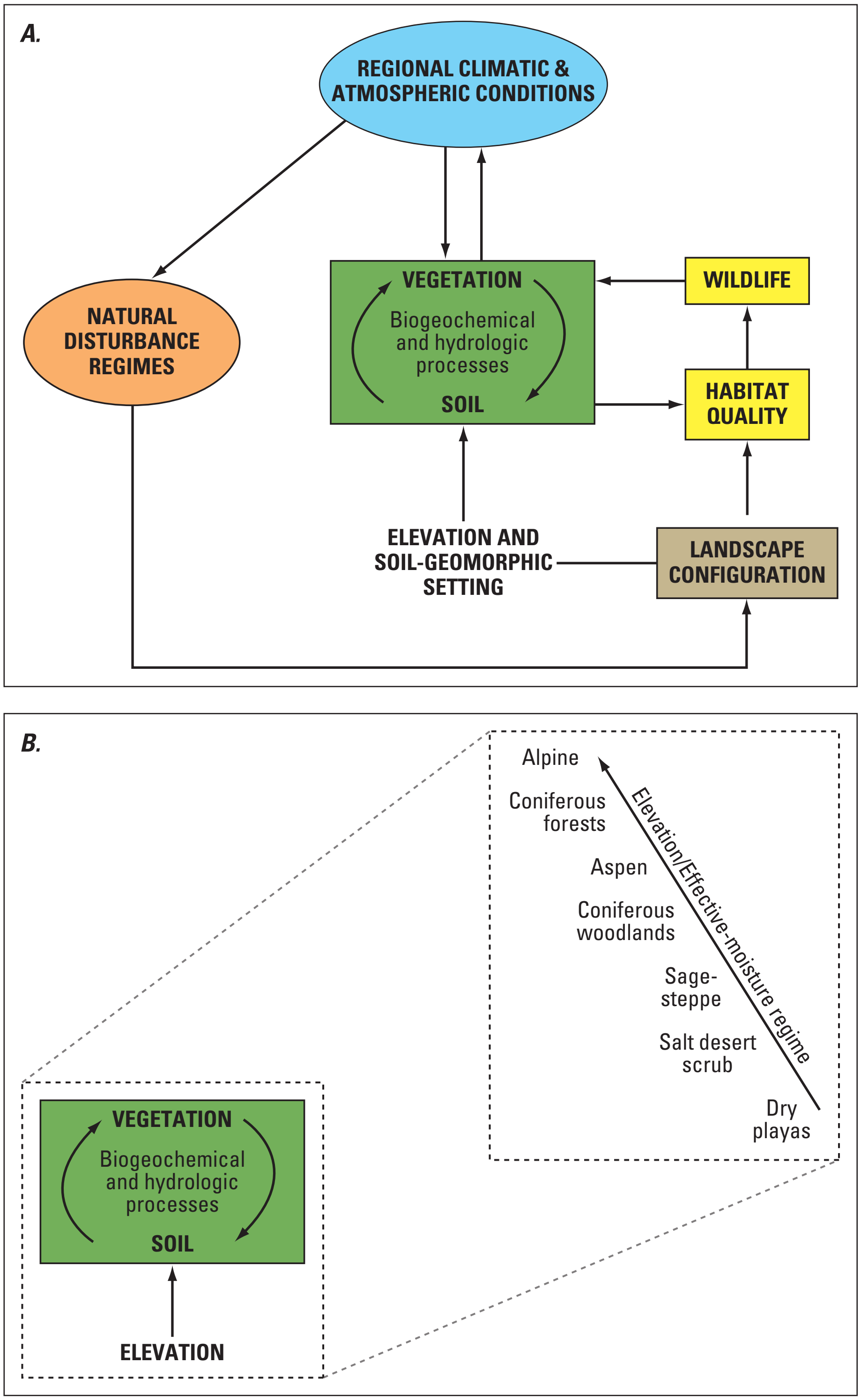


Figure 2.12. Diagrams showing general conceptual model of dry ecosystems. Panel (*A*) illustrates key structural components (rectangles), major drivers of ecosystem change and temporal variability (ovals), and functional relationships (arrows) (adapted from Miller, 2005). Structural components and drivers are ecological factors that are relatively dynamic at the centennial time scale, thus representing potential foci for long-term monitoring. Elevation and soil-geomorphic setting provide the underlying physical template that determines the potential structure, functioning, and spatial configuration of dry ecosystems in the Great Basin. Panel (*B*) examines the elevation-vegetation relationship, illustrating the typical zonation of dry ecosystems in the Great Basin along gradients of elevation and effective-moisture regimes.

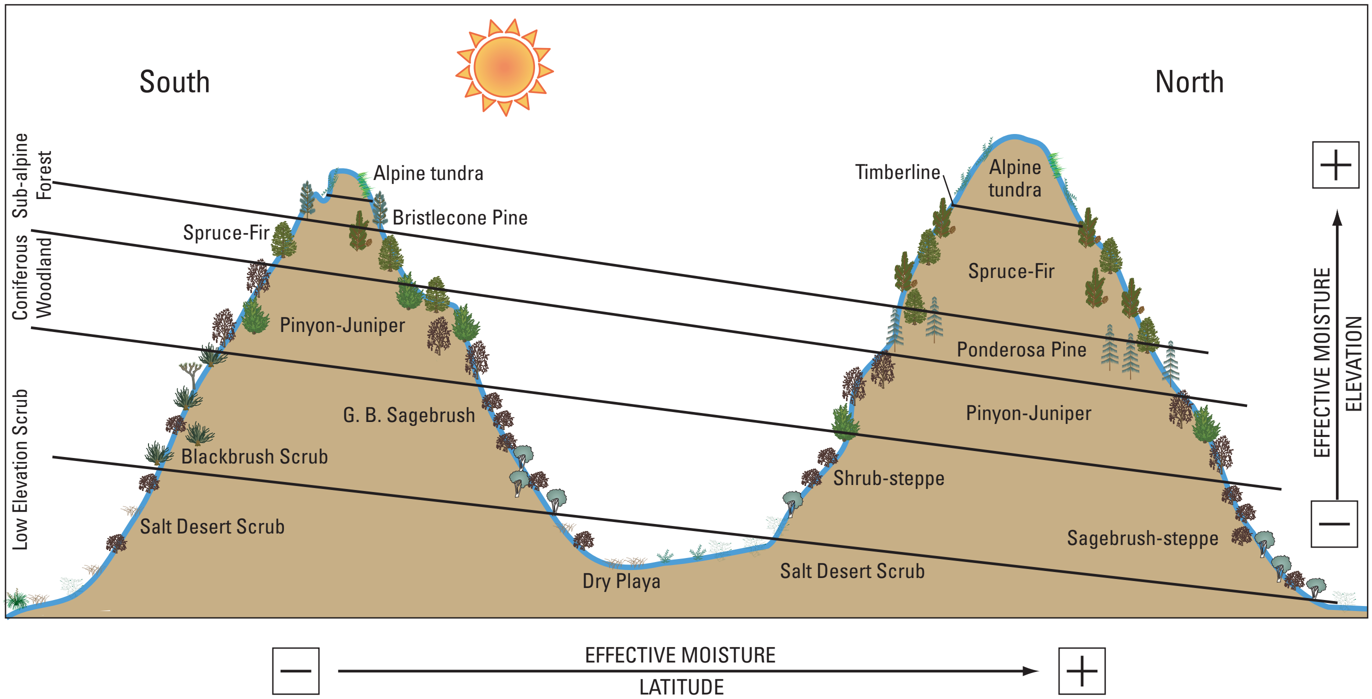


Figure 2.13. Diagram showing vegetation zones in the Great Basin. As latitude increases, vegetation zones descend in elevation due to decreasing temperature and increasing available moisture. Total vegetative cover is generally greater northward and upward, except at very high elevations.

materials, geomorphic processes, and soil formation (elements of the physical template, described above). For example, due to differences in geologic parent materials and past patterns of landscape evolution, Great Basin soils generally are characterized by finer soil texture and higher inherent fertility than soils of adjoining areas such as the Colorado Plateau (Comstock and Ehleringer, 1992). These differences in inherent soil properties have important implications for soil functioning and ecosystem dynamics, and may contribute to the high susceptibility of Great Basin ecosystems to invasion by exotic annual grasses such as Cheatgrass (*Bromus tectorum*) and Medusahead (*Taeniatherum caput-medusae*) (Blank and Sforza, 2007; Norton and others, 2007). Although inherent soil properties are considered to be relatively static, soil texture and depth can change and influence ecosystem structure and dynamics over relatively short time scales in response to land uses and management activities that reduce erosion resistance (for example, Neff and others, 2005).

Soil functioning and soil quality also are determined by dynamic soil properties that respond to land use, natural disturbances, and climatic fluctuations. For purposes of ecosystem management and monitoring, dynamic soil properties are particularly important because they represent a key pathway by which land use and management affect the condition of rangeland ecosystems (Seybold and others, 1999; Herrick, 2000; Herrick and others, 2002). Dynamic soil properties that are particularly important for sustaining hydrologic processes, nutrient cycling, plant growth, and erosion resistance include organic matter content, aggregate stability, surface roughness, and structure.

Vegetation Resources and Functions

Vascular plants perform important functional roles in dryland ecosystems (fig. 2.12). In addition to conducting photosynthesis, aboveground structures of plants protect soils from erosive raindrops, obstruct erosive wind and overland water flow, and thus enhance the capture and retention of soil resources. Litter from plants further reduces the erosive impacts of rainfall on soil surfaces and provides inputs to soil organic matter for soil stabilization and nutrient cycling. Roots stabilize soils, are conduits for resource acquisition and redistribution, and provide organic-matter inputs to soil food webs. Vegetation also provides fuel for fire, as well as resources and habitat structure for below-ground and above-ground organisms ranging from fungi and bacteria to birds and large mammals (Wardle, 2002; Whitford, 2002). Carbon storage and the mediation of earth-atmosphere energy and water balances are additional vegetation functions that are increasingly emphasized by researchers investigating processes of global climate change (Breshears and Allen, 2002; Asner and others, 2003). Plants and litter also intercept solar radiation and precipitation, thereby altering microclimatic conditions, mediating spatial and temporal patterns of soil water content and temperature (Breshears and others, 1997), and strongly affecting soil-resource conditions experienced by other organisms. Interspecific competition often is emphasized as an important factor shaping the composition and structure of plant communities (Goldberg, 1990). But facilitation also can be an important process in dryland ecosystems due to ameliorating effects of overstory plants on environmental conditions or herbivory experienced by understory plants (Callaway, 1995; Archer and Bowman, 2002; Brooker and others, 2008).

Wildlife and Habitat Quality

Vertebrates and invertebrates perform numerous functions in Great Basin dryland ecosystems. Activities related to granivory and herbivory are among those that have the greatest ecosystem-level consequences in dryland ecosystems because of their many effects on vegetation structure and soil processes. Through selective harvesting, consumption, and dispersal by caching and defecation, granivores can have considerable effects on the abundance, composition, and spatial distribution of the seed bank (Whitford, 2002). Over time, these seed-bank effects can be reflected in the composition and spatial structure of plant communities. For example, seed caching by birds and rodents is the primary mechanism of seed dispersal for pinyon pine and thus contributes to the dynamics and distributional patterns of pinyon populations in the Great Basin and elsewhere (Chambers and others, 1999; Chambers, 2001). Seed ingestion and defecation by frugivorous birds and mammals are important for the dynamics and distributional patterns of juniper populations (Chambers and others, 1999).

Large herbivores can affect individual plants directly and indirectly through various mechanisms. Direct impacts include altered physiological function and morphology attributable to defoliation and trampling (Briske, 1991; Briske and Richards, 1994). Defoliation and trampling by large herbivores may indirectly influence plant performance as a consequence of altered microenvironmental conditions, soil properties (Thurow, 1991), mycorrhizal relations (Bethlenfalvay and Dakessian, 1984), competitive relations, and through effects on ecosystem processes such as nutrient cycling and hydrology. Over time, combined direct and indirect impacts can result in altered plant population dynamics (for example, altered rates of reproduction, recruitment, and mortality) and consequent changes in plant community composition, structure, and distribution (Crawley, 1983; Archer and Smeins, 1991; Archer, 1994; Miller and others, 1994; Bich and others, 1995). Because of strong interactions of vegetation with nutrient cycling, hydrologic processes, disturbance regimes, and geomorphic processes, herbivore-driven changes in vegetation structure can have cascading effects on multiple ecosystem processes and properties.

The alteration of competitive relations among defoliated or differentially defoliated plants is one of the most significant ways in which herbivory affects the structure of plant populations and communities (Archer and Smeins, 1991; Briske, 1991; Briske and Richards, 1994; Crawley, 1997). Plants that possess a greater capacity for regrowth following defoliation experience a competitive advantage over defoliated competitors that possess a lesser capacity for regrowth. Similarly, plants that are defoliated less frequently or less intensively experience a competitive advantage relative to plants that are defoliated more frequently or more intensively due to relative differences in accessibility or palatability. For an individual plant, the most significant benefit arising from herbivory is the relative advantage gained when a neighboring plant has been reduced in size and competitive ability by an herbivore (for example, Caldwell and others, 1987). Through time, altered competitive relations eventually can be expressed in population dynamics and plant community structure (Briske, 1991).

Some workers have hypothesized that trampling by large herbivores has beneficial impacts on infiltration (Savory and Parsons, 1980; Savory, 1988). However, hydrologic research has failed to support this hypothesis (Spaeth and others, 1996; Holechek and others, 2000), indicating instead that trampling tends to result in lower infiltration rates, which leads to a deterioration of soil structure (Thurow, 1991). Hydrologic impacts of trampling by large herbivores vary with soil type, soil water content, seasonal climatic conditions, vegetation type, and the magnitude of trampling (Thurow, 1991).

Wet System Model

By D.M. Miller, D.R. Bedford, and A.M. Brasher

The wet systems of the Great Basin include springs, wetlands, streams, wet playas, and lakes (fig. 2.14). These components have in common the presence of "free" water on or near the ground surface. Despite their relatively small size and scarce distribution, aquatic and riparian systems play a critical role in the semi-arid Great Basin. As a result of abundant water, these locations constitute biological "hotspots" where biological diversity and abundance are concentrated into relatively small areas. Many drivers of Great Basin ecosystems relate to the wet components of the deserts, indicating their importance. Nearly all aspects of the wet systems are intimately interconnected to the groundwater regime, and groundwater systems control the behavior of wet features including the temporal and spatial availability of surface water and water chemistry. Thus, we feature groundwater systems in the model (fig. 2.15) as a basis for understanding the responses of aquatic and riparian habitat to hydrologic drivers and stressors.

Groundwater systems can be classified as one of three types based on their size: upland, local, and regional (figs. 2.14 and 2.15). Each occupies characteristic parts of the landscape and its underlying geology and these systems interact with each other as well as with surface-water systems. Surface water can result from point discharge of groundwater, such as springs, or broader areas of discharge such as gaining streams, wetlands and wet (discharging) playas. Gradients in groundwater systems often govern many characteristics of surface-water systems, and all are tied to climate parameters, land topography, geology, and human consumptive uses (fig. 2.15). Lakes are relatively rare in the Great Basin, but occur in alpine settings where they are fed by local snowmelt and runoff, and as terminal lakes fed by stream runoff. Groundwater recharge, transport and storage, and discharge are the key characteristics needed for understanding many wet systems features, as well as for predicting impacts.

Stream and streambank (riparian) ecosystems have attributes such as floodplain, channel bank, channel bed, and channel, the composition of which are important to vegetation, aquatic fauna, and wildlife. The function and distribution of these ecosystem components are driven by temporal and spatial variations in water flow discharge over time, commonly summarized as flow regime. These variations occur on many scales, from general longitudinal and lateral changes in discharge, flow, and streambed form, to temporal variations in discharge (for example, floods). Large streams and rivers are also complex networks in which the organization of channels and their tributaries uniquely shape flow characteristics (Benda and others, 2004). The flow regime shapes habitats through bed friction and sediment transport, temperature and light variations, and water chemistry (including nutrient concentrations) (Scott and others, 2005). Streams and riparian zones commonly are used by narrowly endemic and wide-ranging wildlife (such as mule deer and a wide variety of birds) and can act as corridors for invasive species such as tamarisk.

Springs and seeps can be classified according to a gradient in flow persistence, which is related to groundwater characteristics such as discharge and response time (fig. 2.15). Great Basin spring-fed systems can be broadly characterized as pools, streams, wetlands, wet meadows, and muddy or boggy areas. Extensive wetlands and multiple spring pools form where a regional aquifer system discharges, such as the carbonate aquifer discharging in the southern Great Basin. Springs tend to have smaller pools or marshy areas where associated with local aquifers. Upland aquifers most commonly exhibit wet meadows and small springs. Due in part to their isolation, springs are habitat for rare and endemic species, such as species of springsnails, frogs, and fish. Wet playas and alkaline seeps may occur low in desert basins. Orographic precipitation and snowmelt feed streams that flow off high peaks, forming small alpine lakes, disappearing into fissures in carbonate rocks and valley fill sediments along the outflowing streams.

Spring-fed wetlands form a wide variety of important riparian and aquatic habitat (Stevens and Springer, 2004). Biological diversity generally is correlated with the size of the wet area—brook length for flowing streams and size of pools—which are in turn a function of spring discharge. Groundwater discharge at springs is thus a key indicator of riparian biologic health and integrity. The factors influencing groundwater discharge at landscape levels primarily are climate and partitioning between recharge and runoff. More locally, discharge is affected by groundwater extraction, distribution of contaminants, and disturbance—especially paving and diversion—of recharge zones. Because streams in arid lands are intimately connected to groundwater, they are affected by the same drivers and stressors, but also are susceptible to surface diversions and contamination. Spring-fed wetlands and stream systems are affected by invasive plants [for example, tamarisk (*Tamarix ramosissima*)] and animals [for example, mosquitofish (*Gambusia affinis*) and Asian tapeworm (*Bothriocephalus acheilognathi*)], as well as by direct human disturbance and fire. Many of the drivers for wet systems are important for endemic and at-risk populations of fish, amphibians, and riparian bird and aquatic macroinvertebrate communities.

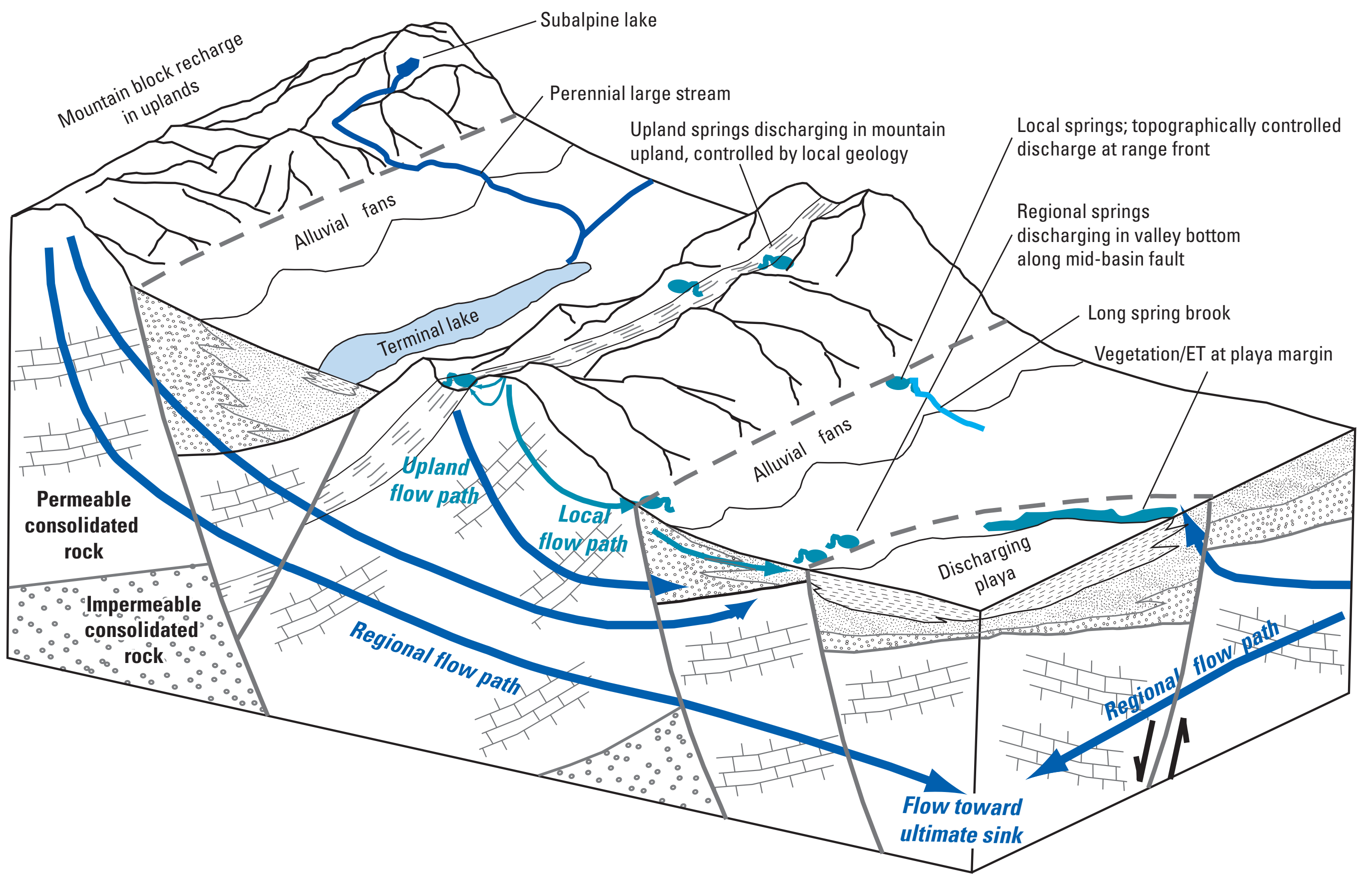


Figure 2.14. Block diagram showing flow systems associated with groundwater and surface water parts of the wet systems, illustrating how the systems are connected between ground and surface in some cases and compartmentalized in other cases between basins and parts of the highlands.

Subsystem Models

Control models present mechanistic views of the operation of subsystems within the wet and dry systems that are useful for developing monitoring methods for the key drivers. The models describe the linkages among system components and how processes will change with influence by drivers, and provide a basis for developing stressor models. Chapters 3 and 4 present control and stressor models for highest priority ecosystems and those with the greatest knowledge levels. For clarity of communication and for eventual quantitative models of these systems, it is helpful to include state-and-transition models, as exemplified by the sagebrush steppe and pinyon-juniper models. Subsystem models presented in Chapters 3 and 4 vary widely in level of detail, which reflects a combination of: (1) resources with GBILM for developing the model, (2) status of knowledge, and (3) importance of the subsystem for Great Basin land managers.

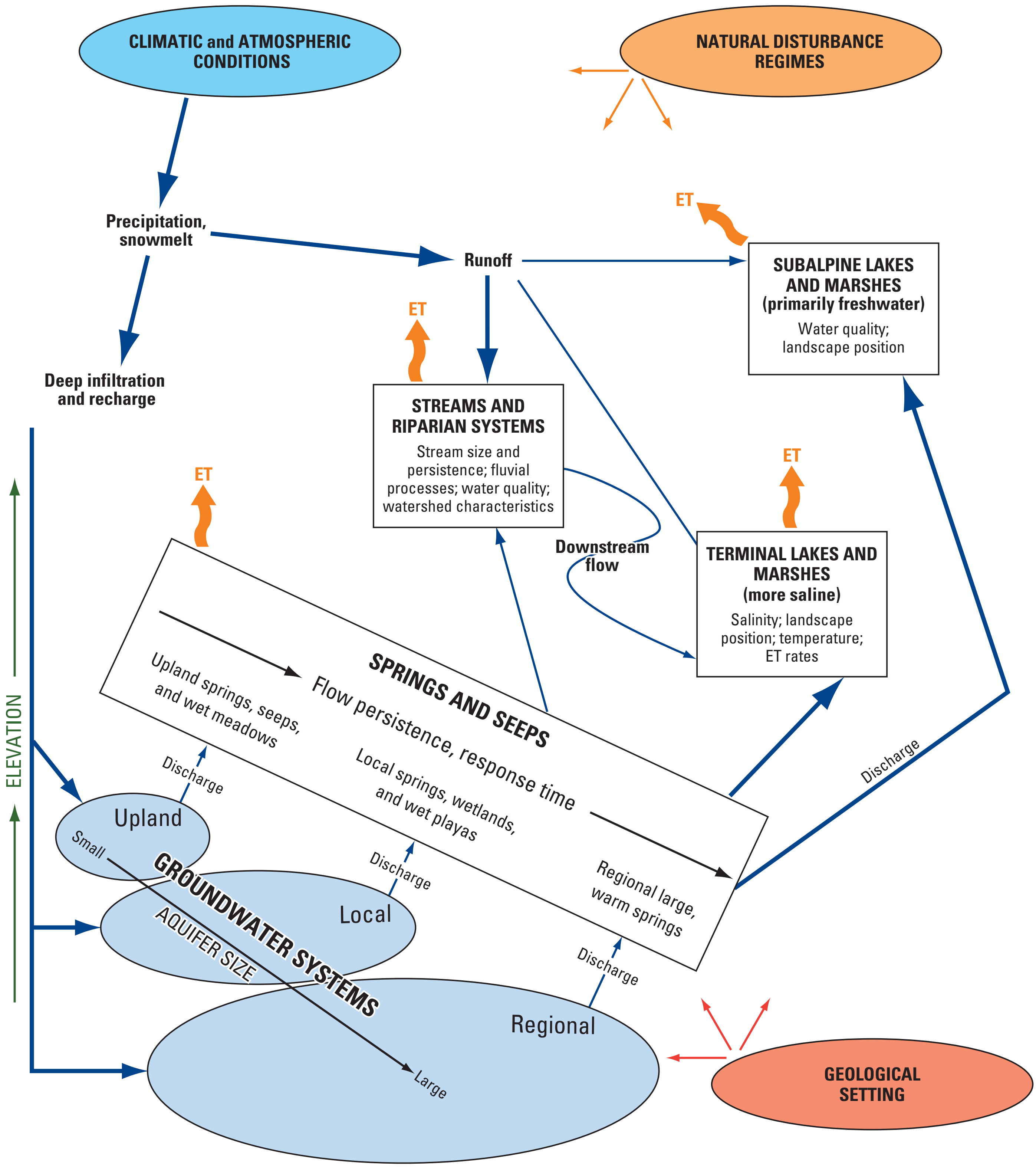


Figure 2.15. Diagram showing wet systems model. Groundwater is a major driver for many wet systems of the Great Basin, thus recharge for upland, local, and regional aquifers is a key process. Important variables to monitor are noted for main surface-water systems.