An Ecosystem Services Framework for Multidisciplinary Research in the Colorado River Headwaters

D.J. Semmens, J.S. Briggs, D.A. Martin

Abstract

A rapidly spreading Mountain Pine Beetle epidemic is killing lodgepole pine forest in the Rocky Mountains, causing landscape change on a massive scale. Approximately 1.5 million acres of lodgepole-dominated forest is already dead or dying in Colorado, the infestation is still spreading rapidly, and it is expected that in excess of 90 percent of all lodgepole forest will ultimately be killed. Drought conditions combined with dramatically reduced foliar moisture content due to stress or mortality from Mountain Pine Beetle have combined to elevate the probability of large fires throughout the Colorado River headwaters. Large numbers of homes in the wildland-urban interface, an extensive water supply infrastructure, and a local economy driven largely by recreational tourism make the potential costs associated with such a fire very large. Any assessment of fire risk for strategic planning of pre-fire management actions must consider these and a host of other important socioeconomic benefits derived from the Rocky Mountain Lodgepole Pine Forest ecosystem. This paper presents a plan to focus U.S. Geological Survey (USGS) multidisciplinary fire/beetle-related research in the Colorado River headwaters within a framework that integrates a wide variety of discipline-specific research to assess and value the full range of ecosystem services provided by the Rocky Mountain Lodgepole Pine Forest ecosystem. Baseline, unburned conditions will be compared with a hypothetical, fully burned scenario to (a) identify where services would be most severely impacted, and (b) quantify potential economic losses. Collaboration with the U.S. Forest Service will further yield a distributed model of fire probability that can be used in combination with the ecosystem service valuation to develop comprehensive, distributed maps of fire risk in the Upper Colorado River Basin. These maps will be intended for use by stakeholders as a strategic planning tool for pre-fire management activities and can be updated and improved adaptively on an annual basis as tree mortality, climatic conditions, and management actions unfold.

Keywords: research integration, mountain pine beetle, wildfire, risk assessment, ecosystems

Semmens and Briggs are research scientists with the U.S. Geological Survey, Rocky Mountain Geographic Science Center, P.O. Box 25046, DFC MS-516, Denver, CO 80225. Martin is a research scientist with the U.S. Geological Survey, Water Resources Division, 3215 Marine St, Suite E-127, Boulder, CO 80303. Email: dsemmens@usgs.gov.

Introduction

Ecosystem services are concisely defined as the benefits people obtain from ecosystems: "*provisioning services* such as food, water, timber, and fiber; *regulating services* that affect climate, floods, disease, wastes, and water quality; *cultural services* that provide recreational, aesthetic, and spiritual benefits; and *supporting services* such as soil formation, photosynthesis, and nutrient cycling" (Millennium Ecosystem Assessment 2005, p. v).

The goods and services provided by the ecosystems of the Upper Colorado River Basin are of national significance. Water provided from Grand and Summit Counties alone totals approximately 1.1 maf (million acre-feet) per yr on average to 16 U.S. and 2 Mexican states. The same area also boasts a wide array of cultural services that generate significant revenue for local businesses and the State: eight world-class ski areas, whitewater rafting, hunting, fishing, mountain biking, camping, and general outdoor recreation. These and other services are dependent in some measure on the forest, and a comprehensive effort to quantify and value them is particularly important in the face of large-scale changes to the forest ecosystems.

The Colorado Headwaters Project (CHP) plans described in this paper employ the assessment of ecosystem services and their value for the purpose of wildfire risk assessment and the prioritization of mitigation efforts. To reconcile landscape and service conservation with aggressive risk-management actions, it is essential that the ecological, sociocultural, and economic values of a landscape be fully accounted for in forest management planning prior to potential fires. The CHP builds upon a preexisting, multidisciplinary U.S. Geological Survey (USGS) Fire Science Demonstration Project that is addressing the numerous hazards associated with the Mountain Pine Beetle (MPB) epidemic and potential for large-scale fire, with the goal of mitigating effects on people, property, and natural resources in the Colorado River headwater forests. The CHP provides a framework for integrating discipline-specific research contributions into a comprehensive analysis of the risk posed by fire. It will further result in the development of a common, actionable set of products (maps of fire risk) that can be delivered to Federal, State, and local managers to assist with pre-fire decision support. These products can be updated adaptively on an annual basis prior to each fire season.

The U.S. Department of Agriculture–Forest Service (USFS) has, out of necessity, often prioritized tactical operations over long-term strategic planning in their approach to fire readiness. Rapid Assessment of Values At Risk (RAVAR) and other Wildland Fire Decision Support System (WFDSS, http://wfdss.usgs.gov/) tools are designed to assist fire managers and agency administrators in making decisions regarding responses to active wildland fires; they are not specifically designed to assist with pre-fire management planning. In addition, the WFDSS tools focus on structures and infrastructure in assessing values at risk. Although they can account for threatened and endangered species habitat and cultural sites, broader ecosystem services and their associated values are not presently considered. Recently, however, the USFS has proposed using the concept of ecosystem services as a framework for (1) describing the many benefits provided by public and private forests, (2) evaluating the effects of policy and management decisions involving public and private forest lands, and (3) advocating the use of economic and market-based incentives to protect private forest lands from development (Kline 2007). Forest Service research is therefore closely aligned with the objectives of the CHP, and we anticipate that many collaborative opportunities for adaptive management will arise as we develop our study.

Study Area

The Colorado River originates in the mountains of central Colorado within the Southern Rocky Mountain physiographic province. Ecosystems within the upper basin are closely associated with elevation and range from alpine tundra at the highest elevations down through spruce-fir, lodgepole pine, aspen, and sagebrush shrubland.

The original USGS research focus on Grand County, CO, combined with the need to model hydrologic services, led us to adopt a watershed boundary for the project whose outlet is located on the county line. The watershed encompasses almost all of Grand County, as well as the adjacent Summit County to the south; both county boundaries are defined primarily along the drainage divides (Figure 1).

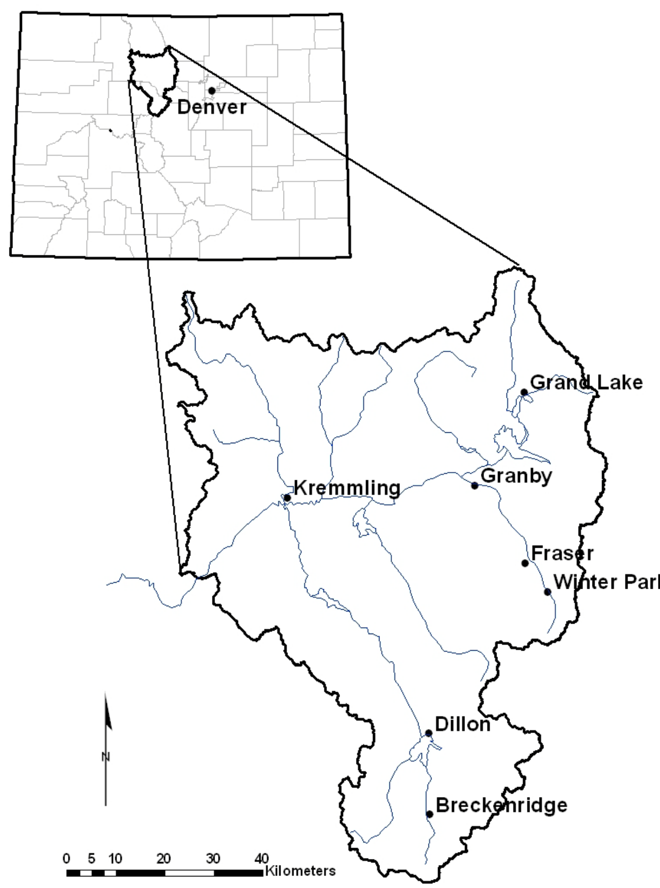

Figure 1. Map showing the preliminary boundary for the Colorado River headwaters study area.

Methods

The CHP will comprise five main steps: (1) service identification, (2) scenario development, (3) ecosystem goods and services assessment, (4) valuation, and (5) integrated risk assessment. Each of these is described separately below.

Service identification

An ecosystem functions analysis approach similar to that described by de Groot (2006) will be used in combination with conceptual modeling of ecosystem components and interactions to translate the complex ecology (structures and processes) into a more limited number of ecosystem functions and their associated goods and services. In this context, ecosystem functions are defined as the capacity of natural processes and components to provide goods and services that satisfy human needs (de Groot 2006). This process is expected to identify the most influential or valuable services provided by the lodgepole forest ecosystem, as well as important service transfers to other ecosystems.

Scenario development

Scenario development is a critical component of ecosystem service analyses because it provides the means to explore the consequences of alternative actions or conditions. Given the regional emphasis on Mountain Pine Beetle and the effects of fire, scenario development will likewise reflect the conditions these stressors will affect. We will not address mitigation of these conditions through the incorporation of forest management scenarios. However, concurrent USFS research in the Upper Colorado River Basin will focus on the analysis of management/harvest alternatives, their cost, and ultimate impacts in terms of selected ecosystem services. It is hoped that further collaboration with the USFS will ultimately lead to a synthesis of the two projects, which would permit a cost-benefit analysis of management alternatives.

Due to the stochastic nature of fire initiation, it is impossible to forecast specific fires and thus inappropriate to consider specific fire scenarios. For strategic planning at large spatial scales it will be more productive to explore the consequences of fire throughout the project area given the fuel loading conditions associated with different extents and stages of tree mortality from Mountain Pine Beetle. Scenario development will thus focus on the extent of beetle-killed trees and the likely severity of potential fire. A total of 5 scenarios will be developed: (1) pre-MPB; (2) current extent of the MPB epidemic, no fire; (3) future 100 percent tree mortality, no fire; (4) current MPB, fully burned; and (5) future 100 percent tree mortality, fully burned.

Tree mortality

After trees are attacked by beetles they progress through several stages of physiological senescence: (1) needles fade from green to red as they lose moisture; (2) needles drop from the trees, but fine twigs remain; (3) all twigs drop from the trees; and (4) trees fall. Each stage is characterized by distinct fuel loads and thus distinct fire behavior. Three land-cover scenarios will be developed to represent the different stages of tree mortality. The first will be a pre-epidemic scenario representing conditions in the early 1990s that will serve as a baseline for evaluating effects associated with tree mortality alone. The second will represent current conditions and be derived from a map of the stage and extent of beetle-killed trees throughout the basin that is currently under development. The third will represent the maximum potential extent of beetle-killed trees—100 percent lodgepole mortality. This last scenario will be a simple projection from current conditions.

Fire

The development of fire scenarios that are meaningful for landscape-scale risk assessment requires the evaluation of both the likelihood of fire occurring at any given point and the probable severity of that fire should it occur. This requires a two-step process: fire probability modeling followed by an assessment of first-order fire effects to estimate severity. The former will serve as an input to the risk assessment, and the latter will represent the fire scenarios to be assessed in terms of their impact on ecosystem services. These are described further below.

Assessing the probability of fire at any given point in the landscape is a necessary component of being able to define risk. The Fire-Climate-Society (FCS-1; Moorehouse et al. 2006) model, for example, has combined five map layers, or indices, to define fire probability on a relative scale according to user-defined importance: fuel moisture stress index, fire return interval departure, large fire ignition probability, lightning probability, and human factors of fire ignition. In the present analysis, a collaborative arrangement with the USFS Fire Modeling Institute (FMI) will permit the estimation of fire probability using the Fire Behavior Simulation Model (FSIM), a new research model that accounts for ignition probability and weather conditions based on historical observations. FSIM runs thousands of simulations for potential ignitions across the basin under a range of historic weather conditions and reports the frequency with which each cell burns as a proxy for probability. As such, the resulting fire probability is still defined on a relative scale, but the process-based fire modeling will remove the subjective importance of fire indices. USGS-USFS joint field surveys are being conducted during the summer and fall of 2008 to establish the fuels information needed to run FSIM for forests with varying degrees and stages of beetle-induced tree mortality.

Another important output of FSIM is the intensity (temperature) with which each grid cell burns, which is averaged for all simulated fires in each cell. This will be used as the basis for creating the fully burned scenarios associated with each beetle-kill scenario. These burn-intensity maps will be input to a new GIS-based version of the First Order Fire Effects Model (FOFEM). FOFEM predicts tree mortality, fuel consumption, smoke production, and soil heating caused by forest fires, and the resulting maps of fire effects can be input to ecosystem assessment models (e.g., watershed and biogeochemical cycling models). FOFEM output will thus represent the base data layers associated with fully burned scenarios. These will be generated for two of the beetle-kill scenarios—current conditions and maximum potential extent.

Goods and services assessment

The ultimate goal of assessing ecosystem services in the CHP will be to identify the areas characterized by the greatest diversity and magnitude of services. Assessments will focus on quantifying services derived from local forest ecosystems, as well as identifying where the fate of local ecosystems affects the services rendered from others. This goal draws an important distinction between services within the area of interest and those elsewhere that are affected by processes and conditions that originate in the area of interest. The study will not consider the local effects, direct or indirect, of processes or conditions beyond the study area.

The general methodology for assessing ecosystem services will involve a combination of process and landscape modeling approaches. Results of USGS studies associated with the Fire Science Demonstration Project will be directly employed in this process. These studies include:

- Hydrology—Carbon and nitrogen from dying/dead forest runoff; post-fire sediment/chemical impacts from ash and debris flows; basin-scale water-yield modeling
- Geology—Site-specific post-fire landslide hazards
- Biology—Impacts to aquatic habitat and fish population dynamics; sociocultural services assessment
- Geography—Mapping/monitoring the progression of tree mortality from Mountain Pine Beetle with remote sensing

Applying this research on a landscape scale will involve a combination of regression modeling (observations used to develop a model that can be applied across the basin) where sufficient data exist, and process modeling (observations used for model calibration) where observations can be used to define empirical response relationships. The work on landslide/debris flow and associated chemical component is already designed to be applied at the landscape scale; it provides information that cannot be derived from process models designed to be applied at this spatial scale.

Selected services can be assessed on a unit-area basis (grid cell), including food/fiber/fuel and pollination provisioning, biogeochemical cycling (including nitrogen and carbon), and nonmarket services such as wildlife habitat and cultural amenities. The remaining services, namely water quality/quantity and flow regulation, require process modeling to evaluate their accumulation within hydrologic units and translation downstream. Most basin-scale hydrologic models are quasi-distributed, subdividing basins into hydrologic units (subwatersheds) for which outputs are reported.

The relatively simple representation of rivers and streams within basin-scale hydrologic models should be sufficient for the purposes of a regional assessment in the Upper Colorado River Basin. In other areas characterized by extensive riparian forest, levies, and (or) floodplain agriculture, a more detailed hydraulic model of flow, sediment transport, and water quality might be required. The main concern in the Upper

Colorado River Basin, however, is the quantity and quality of water in reservoir storage. The latter can be addressed using a variety of water quality and hydrodynamic models.

Valuation

Once services have been assessed, the determination of service values (in terms of $/area) will require compiling information from a wide range of sources, including published literature, market sources, and stakeholder surveys. Previous work by Costanza et al. (1997) and de Groot et al. (2002) has identified the most common valuation methods for ecosystem goods and services. Provisioning services are most commonly valued through direct market pricing and factor income methods, with the latter being applied when ecosystem services enhance incomes. Regulating services are mainly valued by indirect market valuation techniques, notably avoided cost associated with maintaining an ecosystem service and replacement cost of artificially providing a service. Cultural services are valued by means of hedonic pricing (e.g., increased property value with proximity to services), contingent valuation (e.g., social surveys of willingness to pay), and market pricing (e.g., recreation fees and tourism revenues).

Where previously published valuation information is available and appropriate, spatially explicit value transfer will be employed to estimate service values for which no primary data are available. Value transfer, also known as benefit transfer, estimates economic values by applying existing benefit estimates from studies already completed for a similar location and (or) context. Although little work has been conducted on the spatial dimension of economic valuation, a recent paper by Troy and Wilson (2006) outlines a generalized process for mapping ecosystem service values through benefit transfer. This process combines service assessment and valuation into one step by assigning fixed service values directly to a customized, project-specific land-cover typology. As such, it will only be applied for services that cannot be quantified directly via modeling or primary research. Where services can be quantified and published service values are linked directly to quantified services, the spatial benefit transfer process will be more direct. When neither primary data nor suitable published values are available to assign service values, the service will be ignored in the final cumulative value estimation process.

Structure and infrastructure (i.e., home and power line) values will be incorporated into the assessment to permit the comparison of risk assessments conducted with and without the inclusion of broader ecosystem service values. A similar study in California, commissioned by the Bureau of Land Management, used this approach to demonstrate that accounting for both market and nonmarket ecosystem services in cost-benefit analyses of forest treatments prior to fire would yield a net economic benefit in the two counties they examined (Ganz et al. 2007). In one of the two counties, including nonmarket goods and services in the analysis revealed the net economic benefit of pre-fire treatment, thus justifying treatments for the protection of additional structures.

All valuation work will be completed for both fully burned and unburned scenarios to permit the assessment of cost due to lost services that is associated with fire. This assessment of cost difference (consequence) is an important component of the risk assessment described in the next section.

Given the proposed assessment methodology, service values, although consistent in terms of scale ($/area), will be based on a variety of spatial assessment units: grid cells, subwatersheds, ecosystem units, census tracts, and potentially other political or management units. These layers will be combined additively in a GIS to evaluate cumulative service values across the landscape. This will be accomplished by taking the union of all polygonal assessment units and then summarizing gridded results within each resulting polygon. These polygons will thus be the ultimate reporting unit for cumulative service value.

Integrated risk assessment

Fire probability and ecosystem service values will be brought together to develop basin-wide maps of fire risk that can be used to prioritize treatment areas. Fire risk will be determined for each reporting unit (polygon) via the following simple equation:

$$risk = probability \times \Sigma(consequences) \tag{1}$$

In this case the consequences are defined as the lost service value associated with fire, which can be estimated as the difference in total service value between baseline, unburned scenarios, and complete burn scenarios (Figure 2). As described previously, the fire probabilities will be relative (ordinal scale) rather than quantitative (ratio scale). This will render it impossible to assign quantitative risk values, but for the purpose of targeting treatment areas the results will be very useful.

Fire risk will be computed using both the established RAVAR approach (i.e., including only the value of structures and infrastructure) and with the addition of ecosystem service values. This combination will facilitate comparison between the two risk assessment methodologies and illustrate exactly how the inclusion of broader ecosystem services changes risk calculations and, in turn, management priorities.

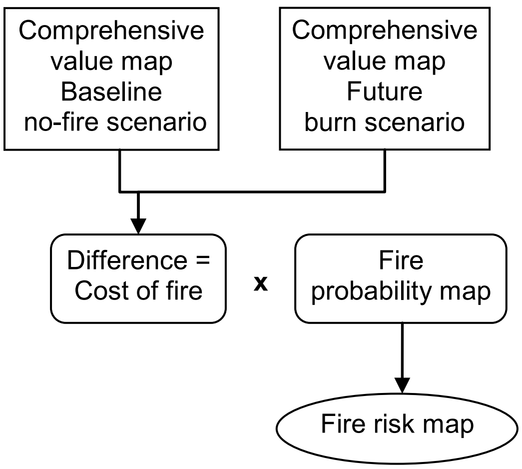

Figure 2. Flow diagram illustrating the risk assessment mapping process.

Conclusions

The assessment of ecosystem services provides a useful framework for integrating multidisciplinary research results into a format that is more readily applied by stakeholders and managers for planning and decision support. This paper outlines a plan to combine cumulative service values with modeled fire probability to evaluate fire risk on a landscape scale. Principal data outputs from this project will be maps of fire risk that can be directly employed for management planning by stakeholders to ensure that environmental and economic impacts to communities are minimized.

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