A framework for setting land conservation priorities using multi-criteria scoring and an optimal fund allocation strategy

Frank W. Davis
David M. Stoms
Chris J. Costello
Elia A. Machado
Josh Metz
Ross Gerrard
Sandy Andelman
Helen Regan
Richard Church

University of California, Santa Barbara
National Center for Ecological Analysis and Synthesis

Report to The Resources Agency of California
August 2003
EXECUTIVE SUMMARY

The California Legacy Project (CLP) mission is “to enable the State and its partners in conservation to develop and implement a strategic and inclusive approach to conserving and restoring California’s lands and natural resources.” In Spring 2001 The Resources Agency of California contracted with the National Center for Ecological Analysis and Synthesis at UC Santa Barbara to convene a working group to help bring systematic conservation planning theory and methods to bear on the design and implementation of CLP. The framework described in this report is one of the products from that working group.

The framework is intended to serve the dual purpose of helping decision makers to evaluate current opportunities (e.g., current proposal applications for State conservation funds) and to help planners develop longer term conservation strategies that highlight general areas, species and communities for more focused analysis and collaborative planning. We do not present a plan or “blueprint” for future conservation activities. Instead, we offer an analytical, data-driven planning process that could be applied to ongoing conservation assessments and evaluations by State conservation planning staff and collaborating organizations over the State or regions of the State.

We organize the planning framework based on a hierarchy of conservation goals and objectives, each of which is further elaborated in terms of specific objectives, criteria, and sources of evidence. At the highest level we distinguish three categories of conservation goals: Resource Production Capacity, Natural Capital, and Public Open Space. Under Natural Capital we distinguish terrestrial biodiversity from wetland and aquatic biodiversity. This report focuses on terrestrial biodiversity.

The framework applies GIS technology to map conservation value and investment priorities based on available spatial data, derived indices and simple algebraic functions. A planning region is divided into sites and each site is scored in terms of its marginal conservation value, that is, the incremental value added to the current system of conservation lands by making the next conservation investment in that site. Site prioritization depends on the resources the site contains, the threat to those resources, and the conservation cost of mitigating that threat. The strategic objective is to allocate conservation funds among a set of candidate sites such that there is the greatest possible resource value remaining at the end of the planning period.

We present a measure of ecological condition based on land use, land cover, roads, housing density and forest structure. The condition index is mapped for 2000 A.D. and 2040 A.D. (based on projected patterns of housing development) and the difference between the two is applied as a measure of threat to biodiversity. We then present formal measures for five different values that places can have for conserving terrestrial biodiversity: 1)
hotspots of rare threatened and endangered species, 2) areas supporting vulnerable habitat types, 3) unique landscapes, 4) wildlands for area dependent species, and 5) areas to expand the size of existing reserves.

We apply the framework to prioritize new conservation investments on private lands in the Sierra Bioregion. Our purpose is to demonstrate the end-to-end use of the framework and attention should be focused on the process, not the actual products. We first use existing, readily available data to map resource values and threats to produce maps of marginal conservation value without consideration of site cost. Spatial patterns in site value differ considerably among the five conservation criteria. We then use a crude estimate of land prices and allocate a hypothetical budget of $44 million to 50 sites scattered across the region.

The framework can also be applied to other conservation concerns such as aquatic biodiversity, production lands, public open space, cultural resources and recreational opportunities. In a separate report we demonstrate its application for cropland conservation in the Bay Delta Bioregion. Our initial experiences in applying the framework to terrestrial biodiversity and cropland are very encouraging, but testing and refinement of the indices and value functions models are still needed and are currently underway.
ACKNOWLEDGEMENTS

We gratefully acknowledge the financial and logistical support of The Resources Agency of California and the National Center for Ecological Analysis and Synthesis, a Center funded by NSF (Grant #DEB-0072909), the University of California, and the Santa Barbara campus.

We thank Secretary of Resources Mary Nichols, California Legacy Project Director Madelyn Glickfeld, Resources Agency Science Advisor Greg Greenwood, California Fish and Game Senior Biologist Marc Hoshovsky, and Bill Stewart, Chief of the CDF Fire and Resource Assessment Program, for their guidance and advice throughout the project. Thanks also to California Legacy Project staff members Rainer Hoenicke and Mike Byrne for their collaboration and technical support.

We would like to recognize and thank the participants in the NCEAS workshops who contributed a great deal to the development of the framework for terrestrial biodiversity:

Pete Dangermond Dangermond and Associates
Diana Hickson The Resources Agency of California
Matthew Cahn University of California, Santa Barbara
Chris Field Carnegie Institution of Washington
Bill Fulton Solimar Research Group
Sarah Gergel University of California, Santa Barbara
Dennis Grossman NatureServe
John Landis University of California, Berkeley
Dennis Machida California Tahoe Conservancy
Ray McDowell The Resources Agency of California
Mark Nechodom USDA Forest Service

Contract administration and accounting were provided by the UCSB Marine Science Institute. We are especially grateful to Deb Owens, Arlene Phillips and Marie Cilhuaga for their excellent support.
# TABLE OF CONTENTS

Executive Summary ........................................................................................................... 2

1. Introduction .................................................................................................................... 7

2. The California Legacy Project ....................................................................................... 10

3. A General Framework for Setting Conservation Priorities ........................................... 12
   Guiding Principles ........................................................................................................... 12
   A Hierarchy of Multiple Conservation Goals and Criteria ........................................... 13
   A Spatial Analytical Framework ..................................................................................... 14
   Conservation Value .......................................................................................................... 15
      A stepwise solution procedure ..................................................................................... 16
   Marginal Conservation Value ............................................................................................ 17
   Target-based conservation ............................................................................................... 17
   Calculating marginal and total utility ................................................................................ 19

4. Applying the Prioritization Model at the Bioregional Scale in California ..................... 20
   Five Conservation Objectives for Terrestrial Biodiversity ............................................ 20
      A Simple Index of the Ecological Condition of Lands for Maintaining Native Terrestrial Biodiversity ........................................................................................................... 21
         Land conversion (C) ...................................................................................................... 22
         Residential housing impact (H) .................................................................................... 23
         Road effects (R) ............................................................................................................. 24
         Forest structure (F) ....................................................................................................... 25
      A composite ecological index of land condition ............................................................ 25
      Measuring the Conservation Value of Sites ..................................................................... 26
         Objective 1. Hotspots of rare, endemic, threatened and endangered species (M<sub>1</sub>) ................................................................................................................................. 26
         Objective 2: Underrepresented habitat types (M<sub>2</sub>) .............................................. 29
         Objective 3: Biophysical Landscapes (M<sub>3</sub>) .......................................................... 30
         Objective 4: Wildlands for area-dependent species (M<sub>4</sub>) ..................................... 32
         Objective 5: Expanding existing reserves (M<sub>5</sub>) ..................................................... 33
      Composite utility ............................................................................................................ 35

5. Prioritizing Conservation Investments Based on Site Costs and Budget Constraints ........ 36
   Estimating Conservation Costs ........................................................................................ 36

5
1. INTRODUCTION

Systematic conservation planning (Margules and Pressey 2000) is now conducted at all geographic scales from global to local. Specific conservation goals and objectives vary but the general purpose of such planning is to guide efforts to protect productive ecological systems, conserve native biological diversity and associated ecological and evolutionary processes, and maintain wild species of special interest. Research in systematic conservation planning is concerned with theory and techniques to improve the scientific basis of planning and the cost-effectiveness of conservation actions.

Conservation planning over large regions requires answers to a series of interrelated questions:

- What resources (ecological features and processes) do we seek to conserve in the planning region? [Conservation Goals]
- What is the current extent and condition of those resources? [Resource Assessment]
- What are the key environmental and social drivers affecting resource extent and condition? [Process Models]
- How are resource extent and condition likely to change in the future? [Scenarios of threatening processes]
- What conservation tactics are available for different places and conservation concerns and how do they compare in terms of cost and likelihood of success? [Conservation Alternatives]
- What are the highest priority areas for investing today’s limited conservation funds? [Conservation system design]
- Are ongoing conservation projects effective? [Monitoring and Evaluation]

Development of conservation plans entails addressing these questions iteratively and at multiple scales through an overall planning framework (Steinitz 1990, Cowling 1999, Margules and Pressey 2000, Noss 2000, Cowling and Pressey 2001, Kautz and Cox 2001, Groves et al. 2002, Theobald and Hobbs 2002). In practice, conservation planning varies widely depending on the political and organizational context (e.g., single vs. multiple landowners, top-down vs. collaborative planning process, project mitigation vs. strategic planning), ecological goals, data availability and socioeconomic constraints.

Recently published conservation planning frameworks offer several distinctive approaches for developing regional conservation plans. For example, Theobald and Hobbs (2002) present a collaborative planning framework for evaluating land use alternatives and biodiversity conservation, and demonstrate its use in a rural county in Colorado. Areas with high biodiversity value are identified using a multicriteria additive scoring
approach (Malczewski 2000) and threats to biodiversity are evaluated based on alternative scenarios of land development and the predicted effect of development on the various biodiversity criteria.

In a more expert-guided approach, Cowling (1999) and Cowling and Pressey (2001) outline a framework for protecting the biodiversity and evolutionary processes in South Africa’s succulent Karoo desert. They set conservation targets (desired levels of formal protection) for biophysical features at multiple spatial scales from local edaphic features to broader ecological landscapes, corridors and climatic gradients. They develop alternative plans that achieve the conservation targets and, recognizing that implementation will take decades, prioritize areas for conservation based on “irreplaceability” (the importance of the site for achieving the stated targets) and “vulnerability.”

Noss (2000) and Noss et al. (2002) lay out a three-pronged approach to conservation planning based on protecting areas that support special elements such as rare species hotspots, representing all habitats at targeted levels within the final reserve network, and meeting the needs of focal species that may require large tracts of land with low levels of human activity. In planning for the Greater Yellowstone Ecosystem these focal species included four carnivores with large area requirements and a large ungulate that migrates seasonally over large distances.

The Nature Conservancy has developed a 7-step conservation planning framework that includes identifying conservation elements (e.g., species, community types, ecological systems), information gathering, conservation goal-setting, evaluation of persistence, reserve system selection, and site prioritization (Groves et al. 2002). In this framework, a regional portfolio of sites is identified that achieves the stated conservation targets. Individual sites are subsequently prioritized for action based on threat, cost and feasibility.

These examples of conservation frameworks illustrate some distinctive features and differences in conservation planning approaches. Some frameworks are designed for collaborative planning (e.g., Theobald and Hobbs 2002) while others are designed to facilitate planning by specialists and experts (e.g., Cowling and Pressey 2001). Some involve reserve system selection to achieve quantitative conservation goals for each conservation element (Davis et al. 1999, Cowling and Pressey 2001, Groves et al. 2002) while others do not select a “representative” reserve network but instead identify areas with high biodiversity value (“hotspots”) and evaluate threats to those areas (Sanderson et al. 2002, Theobald and Hobbs 2002). Some approaches involve formal scenarios of land use change (Steinitz 1997, White et al. 1997) while most are based on current patterns of land use and land management (Stoms 2000). Many approaches involve some consideration of biodiversity persistence based on reserve size and proximity to other reserves, but only a few address the habitat needs of selected focal species by formal viability analyses (Kautz and Cox 2001, Noss et al. 2002). None of the frameworks described above includes economic analysis of tradeoffs.
between conservation and other uses of the land (Faith et al. 1996) although all recognize the need for conservation to be efficient in terms of the total area or cost of new conservation sites.

In this paper we describe a conservation planning framework that we developed for the State of California’s Legacy Project (http://legacy.ca.gov/) to help set conservation priorities over large geographic regions using available, relatively coarse biological and environmental information. Our approach is similar to that of Noss (2000) in recognizing multiple tracks of conservation planning, although given our statewide scope we do not include formal viability analysis for focal species, and we add two additional tracks (landscape conservation and expanding of small reserves). Like Theobald and Hobbs (2002) our framework is intended to facilitate collaborative land use planning for private lands and thus employs a multi-criterion scoring approach to accommodate the conservation preferences of a range of agencies and stakeholders. Following the example of Cowling and Pressey (2001) we develop criteria that take both current biodiversity and evolutionary processes into consideration. To evaluate biodiversity threats we utilize scenarios of future land use, but unlike previous studies we apply a measure of threat directly in estimating a site’s conservation value.

What is perhaps most distinctive in our approach is that instead of designing plans that achieve all specified conservation targets (e.g., Groves et al. 2002, Pressey and Cowling 2001), we set conservation goals and measure the marginal value of adding any individual site to the current system of conservation areas. The site’s marginal value is calculated based on the incremental progress towards stated conservation goals and evaluated relative to the estimated cost of site conservation. The marginal value approach helps reveal short-term priorities but does not identify the set of sites that collectively are optimal for achieving the conservation goals. To help address this issue, we use a simple heuristic that seeks to maximize the total conservation value remaining at the end of the planning period based on the geography of threats, estimated site costs and subject to a budget constraint. This approach contrasts with the more traditional approach of maximizing the value in protected areas.

In the remainder of this paper we provide a brief background on the California Legacy Project, present the details of our planning framework and illustrate its implementation in the Sierra Nevada Region of California. Our focus here is on conservation of native terrestrial biodiversity (species, communities and ecosystems), but the framework can also be applied to other conservation concerns such as aquatic biodiversity, production lands (cropland, timberland, rangeland), public open space, cultural resources and recreational opportunities (Machado et al. In preparation; Metz et al, In preparation).
2. THE CALIFORNIA LEGACY PROJECT

California is made up of an extraordinarily diverse set of environments, species and ecological communities, including 6300 native plants (species, sub-species and varieties) and 673 native vertebrates. Citizens derive enormous benefits from natural resources and associated ecosystem services, including agricultural production from 10.5 million ha (27% of land area) worth over $30 billion per year and commercial timber production of roughly 2 billion board feet per year (California Agricultural Statistics Service 2002). Outdoor recreation is vital to the State’s 34 million residents but also attracts more than 50 million tourists per year, bringing revenues of around $55 billion per year and making tourism the second largest industry in California (California Environmental Dialogue 1999).

There are many threats to California’s biodiversity, notably land and water development, invasive exotic species, air and water pollution, road traffic, non-sustainable use of renewable resources and rapid climate change. Human population is currently growing by roughly 0.5 million per year and is projected to reach 58.7 million by 2040 (California State Department of Finance 1998). To meet projected demand by 2020 for new housing, California homebuilders would have to construct an average of 220,000 additional housing units every year. By 2020, road use is projected to rise from the current 310 billion vehicle miles traveled (VMT) per year to 475 billion VMT per year (California Department of Transportation 2001).

The ongoing decline of California natural resources and ecosystem services has been well documented and will not be described here (Jensen et al. 1993, California Environmental Protection Agency - California Resources Agency 2002). Crafting effective conservation strategies to address this decline is difficult because of the seemingly irresistible social, political and economic pressures for continued development and the lack of coordination and cooperation among public and private organizations involved in land and water planning (Fulton 1999).

Nonetheless, enormous resources have been and continue to be invested to conserve California. Roughly half of the State’s 40 million hectares (100 million acres) is in public ownership and perhaps 20% of the State is in formally designated conservation areas (Davis and Stoms 1999). Much of the new development pressure is focused on remaining private lands near existing urban areas and major transportation corridors in southern coastal California, the San Francisco Bay area, the western Mojave Desert, the southern San Joaquin Valley, and the foothills of the central Sierra Nevada (Landis and Reilly 2002). In these areas conflicts between development and endangered species have already spawned detailed regional conservation assessments and in several instances led to sub-regional natural community conservation programs and habitat conservation plans for multiple species (Fulton 1999).
In California, hundreds of different public and private organizations are involved in prioritizing and acquiring new conservation lands (California Environmental Dialogue 1999, California Continuing Resources Investment Strategy Project 2001). These organizations include the major federal resource agencies, several state agencies in The Resources Agency of California (e.g. Department of Fish and Game, Department of Parks and Recreation, Department of Forestry and Fire Protection, Wildlife Conservation Board), seven State conservancies (e.g. California Tahoe Conservancy, Santa Monica Mountains Conservancy), county and local governments, national non-governmental organizations such as The Nature Conservancy and the Trust for Public Lands, large philanthropic foundations such as the David and Lucile Packard Foundation, and more than 100 local and regional land trusts and conservancies.

Although the State of California owns less than 3% of the land (Davis and Stoms 1999), it plays a significant role in conservation of biodiversity, public open space, and commodity production lands. State government funding for land acquisitions and conservation easements comes from a variety of sources, including special funds, park-related bonds and water-related bonds. Recent bonds include Proposition 12-2000, which provided $2.1 billion for “Safe Neighborhood Parks, Clean Air, and Coastal Protection,” Prop 13-2000, which provided $1.97 billion for “Safe Drinking Water, Clean Water, Watershed Protection, and Flood Protection,” and Proposition 40-2002, which provides $2.6 billion for “Clean Water, Clean Air, Coastal Protection and Safe Neighborhood Parks.” Although these represent considerable funding for conservation they fall far short of what most agencies and conservation groups believe is required to meet even short-term demands for farmland, open space and habitat conservation (California Environmental Dialogue 1999). Thus there is intense competition for these public funds and the need on the part of the State funding agencies to make decisions in what are often acrimonious public forums.

In its 1996 analysis of land conservation activities by State agencies, the California Legislative Analysts Office found that the State was unable to set clear conservation priorities because it lacked a comprehensive and cohesive statewide land conservation plan, suffered from poor coordination among departments, and had limited ability to formally evaluate conservation opportunities as they arose (California Legislative Analyst's Office 1996). In response the California legislature mandated the creation of a new conservation planning program known as the California Legacy Project (formerly named CCRISP, the “Continuing California Resource Investment Strategy Project”) under The Resources Agency. The California Legacy Project (CLP) mission is “to enable the state and its partners in conservation to develop and implement a strategic and inclusive approach to conserving and restoring California’s lands and natural resources” by addressing five fundamental questions:

1. What are California’s significant lands and natural resources?
2. What are key emergent threats and opportunities to improve our lands and natural resources?

3. What are the highest priorities for protection and restoration?

4. What is the most appropriate way to protect and restore these important, high-priority lands and resources?

5. How effectively are the State of California and its partners in conservation implementing this strategic approach to conservation?"

As described previously, these questions are already being addressed at some level by a very large number of public and private organizations. The purpose of CLP is not to serve as a substitute for these existing efforts. Instead, CLP is envisioned as a distinctive new strategic planning process to provide consistent, statewide information and analyses that will help guide the State’s financial investments in resource conservation and restoration and will also promote effective conservation actions through partnerships with non-State organizations.

In 2001 The Resources Agency contracted with the National Center for Ecological Analysis and Synthesis (http://www.nceas.ucsb.edu) to convene a working group to help bring systematic conservation planning theory and methods to bear on the design and implementation of CLP. The framework described below is one of the products from that working group. The design of the framework arose through a series of workshops and other interactions designed to elucidate the specific objectives of the program and current methods of priority setting by state agencies, and through extensive deliberations by working group members over the pros and cons of different methods and approaches.

3. A GENERAL FRAMEWORK FOR SETTING CONSERVATION PRIORITIES

Guiding Principles

Guiding principles for the framework design include the following:

1) *Flexibility.* We expect that regional conservation strategies will be developed through collaborative processes engaging a representative cross-section of stakeholders with varying criteria and desired outcomes. Any methodology should help to reveal multiple alternatives and solutions.

2) *Accessibility.* CLP methods and products should be comprehensible to both experts and non-expert stakeholders. While we do not expect the lay public to understand the details of the various measures and models, the public does need to know what kind of evidence and reasoning are being used to prioritize investment of public funds and should be able to interpret CLP products.
3) **Explicitness.** Terms must be defined unambiguously, data inputs and outputs must be obvious and well documented, and the methods must be clear, accountable, and repeatable by others.

4) **Feasibility.** The prioritization method must be practicable using existing knowledge, data and information.

5) **Accounting and communication of uncertainty.** Methods should include qualitative or ideally quantitative estimation and communication of sources of error, bias, and uncertainty in CLP inputs and products.

6) **Enhanceable over time.** CLP methods must be robust to changes in data and improvements in models and analytical approaches.

7) **Driven by theory, data and knowledge.** Often conservation priorities are established by polling “experts.” Engaging expert knowledge and judgment is key to successful conservation planning. CLP planning should strengthen and support analysis of specialists and local experts by synthesizing appropriate data and information over entire planning regions.

8) **Encompassing of ecological and socioeconomic considerations.** It is important to recognize that there are social, economic, and ecological tradeoffs in pursuing any particular resource conservation strategy. CLP should aim to the maximum extent possible to represent and quantify those tradeoffs.

9) **Evaluated by effective performance monitoring.** The CLP method should identify specific measures of success and performance targets that are readily observable and amenable to pre- and post-project monitoring.

In considering these principles and based on feedback from the NCEAS workshops we developed a framework that is intended to serve the dual purpose of helping decision makers to evaluate current opportunities (e.g., current proposal applications for State conservation funds) and to help develop longer term conservation strategies that highlight general areas, species and communities for more focused analysis and collaborative planning. Our objective was not to produce a plan or “blueprint” for future conservation activities, as has been done in several other statewide analyses (Defenders of Wildlife 1998, Kautz and Cox 2001). Instead, we designed an analytical, data-driven planning process that could be applied to ongoing conservation assessments and evaluations by State conservation planning staff and collaborating organizations over the state or regions of the state.

**A HIERARCHY OF MULTIPLE CONSERVATION GOALS AND CRITERIA**

We organize the planning framework into a hierarchy of conservation goals and objectives, each of which is further elaborated in terms of specific objectives, criteria, and sources of evidence. At the highest level we distinguish three categories of conservation goals: Resource Production Capacity, Natural Capital, and Public Open Space (Table 1). We recognize the
high level of interrelatedness among these three concerns, but in our experience individual conservation programs and stakeholder groups tend to emphasize one over the other two and the logic of priority setting is somewhat different among these concerns. Within production capacity we include conservation of cultivated lands, rangeland and timberland, what are sometimes collectively referred to as “working landscapes.” Production capacity could also be considered a class of ecosystem services (Daily 1997). Under natural capital we include terrestrial biodiversity and aquatic biodiversity. Our focus in this paper is on terrestrial biodiversity.

**A Spatial Analytical Framework**

Conservation planning requires description and mapping of the salient features of the planning area at levels of detail and accuracy that are adequate to evaluate alternative conservation strategies (Steinitz 1990, Margules and Pressey 2000). There are three interrelated issues of scale that must be considered: thematic detail (the degree of biological, ecological or socioeconomic detail in the classification systems used to describe biodiversity and other aspects of the planning area); the spatiotemporal resolution at which the classification systems are mapped (i.e., minimum mapping unit); and, the size of the conservation sites (or “planning units”) that are analyzed as potential building blocks of the conservation plan (Pressey and Logan 1995, Pressy and Logan 1998). These components, which ultimately depend on the stated goals and objectives, are interrelated in that finer thematic classifications tend to be associated with finer-resolution mapping and with smaller sites. Spatial and temporal scale are also generally considered to be strongly interrelated, because coarser descriptions are expected to change more slowly over time than finer descriptions.

Selecting the appropriate scale or set of scales for description and analysis is one of the most important and difficult decisions at the outset of any conservation planning process. In selecting our final set of spatial units we considered five general criteria (Davis et al. Manuscript in Preparation):

- Underlying basis for defining the boundaries of the units (e.g., ecological variation, hydrological processes, political or administrative boundaries, spatial grids)
- Type of Classification System (hierarchical vs. non-hierarchical)
- Spatial grain (resolution)
- Consistency in the geographical properties of the sites (spatial consistency and environmental heterogeneity)
- Use by related planning efforts

The framework described in this paper involves four different kinds of spatial units: planning region, site, reference region, and observation.

The *planning region* encompasses the entire area under consideration for conservation investments. This could be a country, an ecological region, a
state, or more local area. For our application we have elected to use the system of 10 bioregions for California that are defined by ecological and political boundaries and are already in use by State resource agencies.

Sites are discrete spatial units that are the candidate areas being prioritized for conservation investments. In our formulation these areas have fixed boundaries (Cocks and Baird 1989). Here we employ township quadrants from the Public Land Survey System. These roughly 3x3 mile areas conform closely to broad patterns of land ownership and management and their relatively uniform size and shape facilitates analysis of biodiversity patterns and spatial neighborhoods. Unfortunately, some areas of the State were excluded from the original survey, so we manually subdivided some of the larger excluded areas based on surrounding section lines. Also, in less accessible areas that were poorly mapped in the original 19th C. surveys (e.g. the southern Sierra Nevada), there are some narrow slivers of land between neighboring quadrants that are not assigned to any survey unit. Because these tend to be in areas of remote public lands we ignored them in the analyses presented here. Subdividing the larger polygons resulted in 18,234 sites statewide.

A reference region is the area that is considered when evaluating a site with respect to a particular conservation concern. For example, the river basin could be a reference region when evaluating a site’s value for aquatic biodiversity conservation. An ecological region (Bailey 1983) could be the reference region for evaluating how well a species is represented in existing reserves. The immediate area around an existing reserve could be the reference region for evaluating whether a site has value for expanding a reserve. Observations and sites are nested within reference regions. A reference region may or may not be nested within the planning region (or could be the region itself) but, as these examples demonstrate, reference regions for different concerns can be non-nested and based on very different criteria. For this demonstration reference regions include the State of California, the bioregion, ecological subsections, wildland blocks, and neighborhoods around existing reserves, depending on the conservation concern.

Observations are data pertaining to a particular resource concern that are available across the entire planning region at some minimum spatial resolution. This resolution could be the minimum mapping unit of a map of irregular polygons or the cell size of a regular grid such as those produced by classification of remotely sensed imagery. For this demonstration the observation unit for most of the data is a 100m grid cell. We also utilize point observations of some threatened and endangered species and 5x5 km grids of current and projected housing density.

Conservation Value

Our approach to measuring conservation value is based on a cost-effectiveness framework similar to that of Hyman and Leibowitz (2000). The planning region is divided into a set of $I$ sites in which conservation
investments can be made. The size and spatial configuration of the sites can be very influential. A conservation investment in a site could be the cost of outright acquisition, purchase of development rights, stewardship incentives, or whatever action is deemed necessary to remove the threat. In Sections 5 and 6 below we will demonstrate our approach considering only one type of conservation investment (outright purchase). The column vector of site costs is given by $C = [C_1; C_2; \ldots; C_I]$. Denote by $X_i$ an indicator variable that determines whether site $i$ is conserved ($X_i = 1$) or not ($X_i = 0$) and by the vector $X = [X_1; X_2; \ldots; X_I]$.

The conservation budget, $B$, is to be spent to minimize the loss of a natural resource, whose amount in the region is associated with a level of “utility,” by conservation investments made today. Let the utility level $t$ periods in the future given that conservation action $X$ takes place today be given by $\Phi_t(X)$. We have formulated the conservation planning problem such that the objective is to spend the conservation budget to maximize the difference between future utility ($T$ periods ahead) that would be realized with conservation and the future utility that would be realized in the absence of conservation. Mathematically, we seek to solve the following optimization problem:

$$\max_{X} \Delta(X) = \Phi_T(X) - \Phi_T(0)$$

subject to $XC \leq B$.

Depending on the form of $\Phi_t(X)$, its dependence on resource features of the sites, and the number of sites $I$, this can be an extremely complex problem to solve. This is a classic integer-programming problem, and several heuristic algorithms are available to ease implementation of the model for large problems. As will be described below, our formulation of $\Phi_t(X)$ is fairly complicated and the number of sites is relatively large (thousands to tens-of-thousands). For the time being we have employed a heuristic that involves a stepwise procedure in which the site that provides the greatest utility per conservation dollar (i.e., conservation “bang for buck”) is chosen first, all resources and values are recalculated on the basis of that conservation action, and the procedure is repeated until the budget has been spent. This is a version of the “greedy algorithm” in integer programming. Below we describe the algorithm in general. Its specific application to data from the Sierra Nevada bioregion is described in Section 6.

A stepwise solution procedure

Our problem involves selecting from a potentially large set of sites a subset of sites in which to take conservation action in order to most effectively offset threats to resources in the planning region. For the Sierra Nevada bioregion we consider approximately 3000 sites. Assuming 50 sites may be chosen for conservation, we would have to evaluate more than a duotrigintillion ($10^{39}$) combinations of possible portfolios to find the optimal allocation of funds. The greedy algorithm described above is a simple
iterative solution that will almost certainly not find the globally optimum solution but that can perform well under some circumstances. Other search methods such as simulated annealing or genetic algorithms are likely to achieve better results (Possingham et al. 2000) and we are currently examining their application to this problem.

One justification for using an iterative greedy heuristic has to do with the way conservation budgets are often allocated in practice. Typically there is considerable uncertainty over how threats and resource values will change in the future, especially as conservation decisions are made through time. Therefore resource managers and decision makers must continually update information and re-assess priorities rather than committing inflexibly to a specific portfolio and pursuing that portfolio through time. There is an emerging literature that lends theoretical justification to a stepwise approach (Costello and Polasky 2003).

**Marginal Conservation Value**

During the past two decades considerable research has been conducted to develop reserve siting models for conservation planners. Arguably the most important feature of any such model is the specification of the performance measure (or utility function). In most models the performance measure has been based on either (1) measurable attributes such as species composition or area in habitat types or (2) scoring systems that combine attribute measures to create composite indices. The advantage of the first approach is that, in principle, you can define a utility function over the measurable attributes. In practice, however, the relationship between measurable attributes and the arguments of the utility function are often elusive. The advantage of scoring systems is that you can include information about many features of sites that are considered important in setting conservation priorities. One of the major disadvantages of scoring systems is that, unless great care is taken in their derivation, scores cannot be operated on mathematically (for example, it may be impossible to interpret the sum of two scores). In our model we combine aspects of both approaches but ultimately develop scores that we treat as measures of utility.

**Target-based conservation**

Many conservation planners have promoted conservation strategies based on providing some minimum “target” level of protection to species and/or ecosystems (e.g., Scott et al.1993). Target-based conservation involves 1) setting explicit conservation goals and targets (the level of conservation deemed necessary for each conservation element), 2) assessing the degree to which those goals and targets have been achieved, 3) identifying new conservation areas needed to achieve target levels of conservation in the planning region, and 4) plan implementation and monitoring (Margules and Pressey 2000).

The idea of target-based conservation planning has spawned a considerable body of research on methods to maximize the amount of conservation accomplished under an area or budget constraint or to minimize the cost or
area of land allocations, given specified conservation targets (Cocks and Baird 1989, Pressey et al. 1993, Church et al. 1996, Possingham et al. 2000, ReVelle et al. 2002). ReVelle et al. (2002) review these methods and demonstrate their close relationship to facility siting models developed in location science. Recent research has focused on how to bring greater biological detail into site selection models to assure that conservation targets are set and areas selected to best provide for the long term persistence of species (Williams and Araujo 2000, Cabeza and Moilanen 2001, Rodrigues and Gaston 2001).

Advantages of target-based conservation lie principally in the fact that the entire candidate reserve system is evaluated so that the value of any given site depends on the system as a whole. This allows one to exploit the biological “complementarity” of sites and their spatial relationships to arrive at more cost-effective and biologically robust reserve networks. There are strategic advantages to rendering “complete” conservation solutions for an area as opposed to scoring approaches that would simply indicate “where to act next.” There are a variety of approaches to generate alternative solutions to provide some flexibility to decision makers (Pressey et al. 1993, ReVelle et al. 2002).

There are also some potential disadvantages to target-based portfolio solutions. Meeting stated targets may require so much additional area for conservation that the resulting plan cannot be implemented in the near-term with existing resources. Planners and decision makers still need a means of prioritizing sites for action. One approach is to measure the “irreplaceability” of individual sites (Pressey et al. 1994). Another potential problem is the arbitrary nature of fixed targets and the sensitivity of site selection to small changes in target level.

In our approach, the conservation value of protecting a site \( i \) for a particular resource is a function of the conservation goal for that particular resource (expressed as area, fraction of total resource in the region, number of occurrences of the resource, or some other quantity), the amount of the resource that is predicted to remain in the region in future time \( T \) in the absence of conservation action, and the additional amount that would be remaining in time \( T \) if new conservation actions were taken to protect the resource wherever it is currently threatened in site \( i \).

Target-based conservation stipulates a relationship between the amount of a resource that is protected and the utility associated with that level of protection. For example, an algorithm developed by Hugh Possingham and Ian Ball (SPEXAN) that is in wide use specifies a linear relationship between utility and level of protection of a given resource until the target level of conservation is achieved, at which point utility remains constant with additional conservation (but conservation cost continues to increase) (Possingham et al. 2000) (Figure 1a). One can also view this relationship in terms of the marginal utility of conservation as a function of current level of protection (i.e., the rate at which utility changes as a function of protection level) (Figure 1b). Suppose, as is illustrated in Figure 1, that the
conservation target is set at protecting 25% of the current extent of a resource (e.g., a wildlife habitat type). The marginal utility of conservation is constant from 0-25% protection, and then shifts to 0 for any additional protection given to that type.

Our approach also requires establishing a relationship between utility and resource but takes a somewhat more general form. We measure utility with respect to the amount or level of a resource in the reference region, rather than the level of protection of the resource. We assume that the total utility level of the resource will decrease as the resource is reduced in the region through the action of threatening processes. In principle the utility level could also be increased through rehabilitation and restoration activities. An infinite variety of shapes are possible for this utility function, but we will assume that utility is gained or lost most steeply at low levels of the resource and changes relatively less at very high levels of the resource (i.e., there are “diminishing returns” on increasing amounts of the resource in the region). There may even be a socially agreed upon goal beyond which increasing levels of the resource are seen as adding no utility. A utility curve and associated marginal benefit curve that capture these ideas are shown in Figures 1c and 1d. Utility is zero when the level of the resource is zero, increases at a constant rate to some specified level of the resource and then increases in a quadratic form up to a target level beyond which no additional utility accrues. This produces a piecewise linear form for the marginal benefit curve.

Calculating marginal and total utility

The curve in Figure 1d can be used to estimate the marginal utility of conserving a site or set of sites (see Equation 1) as shown graphically in Figure 1e. We define a function \( u(y) \) that gives the marginal utility of a conservation action that would result in achieving a level of the resource \( y \) in the future, where resource level could be measured as area or amount of the resource. We will let the function take the following piecewise-linear, non-increasing form:

\[
 u(y) = \begin{cases} 
 1 & \text{if } y < A, \\
 \frac{G - y}{G - A} & \text{if } A \leq y \leq G, \\
 0 & \text{if } y > G
\end{cases} 
\]  

Here \( A \) is a user-defined minimum level of the resource below which there is constant marginal utility from new conservation and above which marginal utility diminishes with each increment of conservation. \( G \) is a user-defined conservation goal for the level of the resource in the reference region. If the resource level exceeds \( G \) then additional conservation is defined to provide no additional utility. The total benefit of moving from some level of the resource \( y = X \) to some higher level \( y = X+x \) is given by the integral:
For the specific form of \( u(y) \) given above, the total benefit function becomes:

\[
U(X, x, A, G) = \begin{cases} 
    x - 0.5[\max(0, \min(G, X + x) - A)][1 - \frac{G - \max(A, X + x)}{G - A}] & \text{if } X < A, \\
    \frac{0.5(G - X)^2}{G - A} - 0.5[\max(0, G - (X + x))][\frac{G - (X + x)}{G - A}] & \text{if } A \leq X \leq G, \\
    0 & \text{if } X > G
\end{cases}
\]  

We will make use of this function for the remainder of the analysis. Consider a hypothetical example where conservation value comes simply from the area of a habitat type in the region. In the absence of any conservation the future area of habitat is projected to be \( X = 25 \) units. If site \( i \) is conserved, it would add an additional 7 units of habitat \( (x) \) for a total of 32 units. Now suppose \( A \) has been set at 30 units and the regional goal \( (G) \) set at 80 units. Then \( u \) is a piecewise linear function with a flat portion up to 30 and then declining linearly to 0 at 80 units. The value \( U(25, 7, 30, 80) \) is the integral of that function between 25 and 32. In this case, because \( X < A \), the function evaluates to \( 7 - 0.5 \times (1 - 48/50) \), which equals 6.98.

4. APPLYING THE PRIORITIZATION MODEL AT THE BIOREGIONAL SCALE IN CALIFORNIA

Five Conservation Objectives for Terrestrial Biodiversity

As stated above, we have adopted a multi-criteria approach to evaluating terrestrial biodiversity. Based on participant inputs at the NCEAS workshop and a review of the recent conservation planning literature, we have identified five general objectives that are commonly applied in prioritizing sites for conserving terrestrial biodiversity:

1) Protect hotspots of rare, endemic, threatened and endangered species (Dobson et al. 1997, Noss 2000);

2) Protect underrepresented species and community types (Cocks and Baird 1989, Pressey et al. 1993, Scott et al. 1993, Margules et al. 1994);

3) Protect wildlands for large carnivores and other “area-dependent species” (Soule 1991, Noss et al. 1996, Noss 2000);

4) Protect biophysical landscapes to maintain ecological and evolutionary processes (Belbin 1993, Forman and Collinge 1996);

5) Expand existing reserves (Cowling et al. 2003).

Obviously these goals are not completely independent, however, each represents a different policy for prioritizing conservation investments and
each invokes a somewhat distinctive set of biological and spatial criteria. Different stakeholder groups place greater weight on one or more of these goals, so it is important that they be distinguished to support collaborative planning. Furthermore, the reference regions for different criteria may vary. For example, if the objective is to protect under-represented species and/or community types, the level of current protection and threat must be evaluated for each element over the planning region or biogeographical subregions (Davis et al. 1999). Alternatively, if the objective is to protect wildlands for area-dependent species, ecological condition and threat must be evaluated with reference to large contiguous blocks of land that would typically be smaller than an entire bioregion. As we shall see in the example for the Sierra Nevada, site conservation values for these different objectives may exhibit very low correlation with one another.

We developed simple functions to estimate the conservation value of each site with respect to each of these goals based on the current conservation status of the reference region and goal-specific measures of resource value and threat, as summarized below. These functions all require information on both the extent and the condition of terrestrial biodiversity resources. In the next section we introduce a simple measure of ecological land condition that we have used in measuring resource value and threats to that value.

**A Simple Index of the Ecological Condition of Lands for Maintaining Native Terrestrial Biodiversity**

Human activities impact biodiversity in a host of species- and ecosystem-specific and scale-dependent ways. Many ecological indicators have been proposed and applied to monitor ecological health and condition (The Heinz Center 2002). Our choice of indicators is guided by the criteria laid out in a recent National Research Council report (National Research Council 2000), in particular:

- General importance (informative about major environmental changes);
- Conceptual basis (ecological effects relatively well understood);
- Reliability (demonstrated utility in previous uses);
- Temporal and spatial scales (appropriate for regional to statewide assessments);
- Data requirements (readily measured and monitored with existing technology);
- Skills required (based on data that are familiar to and can be analyzed by conservation planners and informed stakeholders);
- Data quality (well documented and with known sources of uncertainty or bias).

All of the variables used in our index are routinely mapped and monitored by state and federal agencies in California. Because our focus is on setting conservation priorities for private rural lands over large areas, we have
focused on relatively generic measures that can be reliably obtained by operational remote sensing and that do not require detailed site surveys, including land conversion (C), residential housing impact (H), road effects (R), and forest structure (F). Techniques have been developed for forecasting the future state of these variables, providing a means of formally estimating the threat to resource values over the planning period. These variables are assessed at relatively fine scale (the observation level) and integrated over larger areas such as sites and reference regions. Below we describe how we derive maps of each variable and integrate them into a composite measure of ecological condition via Boolean logic.

**Land conversion (C)**

Land conversion from native ecosystems to urban and agricultural uses is a major contributor to biodiversity loss because it both reduces the amount of habitat as well as the size, quality, and connectedness of remaining habitat patches (Simberloff 1988, Hanski and Gyllenberg 1997, Wilcove et al. 1998). Predicting the effect of land conversion on species and ecosystem processes has proven challenging because the responses depend on the pattern of conversion and are species- and ecosystem-specific. Nevertheless, there is ample theoretical and empirical evidence of the general impacts of land conversion on native species and communities through studies of rural to urban gradients (Blair 1996, Hostetler and Knowles-Yanez 2003, Green and Baker In Press), and analyses of populations and communities in habitat fragments (Hanski and Gyllenberg 1997, Bender et al. 1998).

For the purposes of regional-statewide assessment we chose not to adopt a species-specific index of habitat conversion. Furthermore, although there are degrees of modification from native habitat to complete conversion, we use a simple binary classification scheme to distinguish converted from non-converted areas. We assume this classification would be applied at relatively high resolution (e.g., 10-100 m) and would be obtained from remotely sensed imagery. Given the objective of protecting native terrestrial biodiversity, we include the following general land use/land cover types as converted lands: urban, cropland, orchard, vineyard, improved pastures and exotic tree plantations. Other kinds of conversion such as roads or forest clearing are addressed separately (see below).

Although we recognize that many species persist in urban and agricultural environments, we assume that conservation efforts will be focused on native species and communities that are not associated with these land use/land cover types. Thus for conservation planning purposes, we set the habitat value of converted areas to 0 and all other areas to 1 as follows:

\[
C'_o = \begin{cases} 
0 & \text{if observation unit } o \text{ is converted} \\
1 & \text{otherwise} 
\end{cases}
\]  

The subscript indicates that the index is evaluated for each observation unit (o) and the superscript indicates the time for which the index is evaluated (e.g., the present or at the end of the planning period). We will also use this
convention for other indices described below (see Appendix for summary of notation).

To map land conversion in California we recoded the 100 m Multi-source Land Cover Data (2002, V.2) provided by the California Department of Forestry and Fire Protection Fire and Resource Assessment Program (CDF-FRAP) (http://frap.cdf.ca.gov/data/frapgisdata/select.asp). At this resolution approximately 5% of the Sierra Nevada region is mapped as converted.

**Residential housing impact \(^{(H)}\)**

Rural residential and suburban development affect native species in many ways, including introduction of exotic species, predation from domestic pets, artificial lighting, altered hydrology, chemical pollution, road effects, and by reducing available habitat for animals that avoid human activities, to name a few (Blair 1996, Buechner and Sauvajot 1996, Germaine et al. 1998, Germaine and Wakeling 2001, Maestas et al. 2001, Odell and Knight 2001, Theobald and Hobbs 2002).

We are especially concerned with the impact of relatively low-density rural residential development, which is affecting extensive areas of the rural western U.S. (Maestas et al. 2001). A simple means of estimating the cumulative effects of such development on biodiversity was proposed by Theobald et al. (1997) based on empirical studies of how biodiversity changes as a function of distance from individual houses. Measurable effects on plant and animal community composition have been detected to distances of 50-500 m. Following Theobald and Hobbs (2002), if we assume a radius of influence of 100 m from each residence and also assume that at housing densities of less than one house per two hectares (5 acres) the zones of influence do not overlap, then the impact of housing can be crudely modeled as a function of housing density in observation unit \(o\) \((h_o)\) as:

\[
H_o = \min(1, 0.0125 \times h_o) \tag{7}
\]

At housing densities at or above 128 houses per square mile (1 house per 5 acres (2 ha)) the entire area is predicted as impacted by residential activities. Depending on the nature of development this index may overestimate the impact of rural residential housing on terrestrial species. However, we presume that once an area has been settled at densities above 1 house per 5 acres it would generally be considered a very low priority for State-funded conservation activities to protect native terrestrial biodiversity.

To map housing impact in California we used the CDF-FRAP projections of housing density by decade for 2000 and 2040, which were based on actual housing density recorded in 1990 census data and historical patterns of development (Spero 2001). Housing density was estimated in 3x3 mile (5x5 km) grid cells. For the purposes of estimating ecological impacts of rural development we assume that the impact of houses was uniformly distributed within these 9 mi² areas.
Road effects ($R$)

Roads through rural landscapes have many ecological impacts, for example, road mortality, spread of invasive species, reduced bird nesting success, altered drainage to streams and wetlands and, in colder regions impacts of road salt (Forman and Deblinger 2000, Trombulak and Frissell 2000, Carr and Fahrig 2001, Forman et al. 2002, Gibbs and Shriver 2002, Clevenger et al. 2003). Empirical studies have demonstrated that the magnitude of road effects on wildlife is a function of both traffic volume and road density (Fahrig et al. 1995, Forman and Alexander 1998).

Road density has been used as a proxy for road impacts on terrestrial and aquatic species and ecosystems, but simple road density does not account for differences in traffic volume and hydrologic effects. For example, in 1999 the average traffic volume on a stretch of California State Highway was roughly 29,000 vehicles per day compared to 0.05 vehicles per day on an average stretch of Forest Service roads (California Department of Transportation 1999). Given our focus on terrestrial biodiversity, we developed an index to estimate effects of traffic volume based on road class and local housing density calibrated based on traffic statistics from the California Department of Transportation. We assumed major roads (interstate highways, state highways, major county roads and interchanges) had the highest traffic volumes and that their impact on terrestrial biodiversity decreased from a maximum at the highway midline to zero at a distance of 500 m, taking the quadratic form (Forman and Deblinger 2000). We created an index of effects of major roads as a function of distance $d$ from the road center as:

$$R_{o}^{t} = \max(0,1 - \left( \frac{d}{500} \right)^2)$$  \hspace{1cm} (8)

We assumed that the impact of minor roads (e.g., local streets, unpaved rural roads) was a function of their traffic volume, which we estimated as a linear function of local housing density. Assuming that the impact increases linearly to a maximum when urban densities of 1 unit/acre are reached or exceeded, and the effect of minor roads extends to a maximum of 300 m, minor road impact was calculated as:

$$R_{o}^{m} = \max(0,\min(h_{o},1)-\left( \frac{d}{300} \right)^2)$$  \hspace{1cm} (9)

A composite road impact index ($R$) can be created that accounts for areas of overlap between primary and secondary road effect zones by taking the maximum value of the two scores, that is:

$$R_{o} = \max(R_{o}^{t}, R_{o}^{m})$$  \hspace{1cm} (10)

To model road impacts we used 2000 TIGER data developed by the (U.S. Census Bureau 2002). TIGER road classes 1,2,3, and 6 were considered...
major roads and road class 4 was treated as minor roads. Major and minor roads were extracted as two separate GIS coverages and a 100 m grid of distance to road was created for each coverage using 500m as the maximum distance for major roads and 300m for minor roads. Equations for $R'$ and $R''$ were applied to those grids and then $R$ was derived as described.

**Forest structure (F)**

 Logging, silviculture and wildfire have extensively modified canopy tree structure in forests and woodlands, with associated impacts and loss of habitat quality for many native plant and animal species (Franklin and Fites-Kaufmann 1996). Here we use a simple index of forest structure geared towards wildlife habitat mapping in California that is mapped and monitored by the U.S. Forest Service and California Department of Forestry and Fire Protection. The index varies from 0.33 for early seral forests (tree crowns less than 12’ diameter for conifers and 30’ for hardwoods) to 1 for mid-to-late seral forests with tree crown cover > 40% and tree crowns > 24’ for conifers and 45’ for hardwoods. Intermediate forest structures were assigned a value of 0.66 (See Table 5 in Stewart 2003). In summary:

$$F_o^t \in [0.33,1]$$ (11)

Forest structure data at 100 m resolution were obtained from CDF-FRAP (http://frap.cdf.ca.gov/data/frapgisdata/select.asp). We only applied this index to forest types where trees can attain large size, for example Sierran Mixed Conifer forest or Eastside Pine Forest. The index was not used for woodland types such as Pinyon-Juniper woodland or oak woodlands.

**A composite ecological index of land condition**

We combine the 4 indices using Boolean logic that an area in good condition for supporting native terrestrial biodiversity is not converted AND has low impact from residential development AND is not affected by roads AND if forested has good forest structure. That is:

$$S_o^t = \min\left(C_o^t, (1-H_o^t), (1-R_o^t), F_o^t\right)$$ (12)

For our case study of the Sierra Nevada we mapped $S$ at 100m resolution, although these data were ultimately integrated over 5 x 5 km sites (Figure 2). The resolution of the data used to derive the index was 100m for all variables except for the 5x5 km housing grid, which was oversampled to 100 m in order to create the composite index.

Grids were produced based on estimated housing densities (and associated road effects) for 2000 and 2040. The different between these two grids forms the basis for evaluating the distribution and severity of threat to biodiversity over a 40-year planning period (Figure 3). This presumes that new housing development and associated environmental degradation pose the most
important threat to biodiversity in the region that can be directly mitigated by conservation action. (Other scenarios of threat are certainly conceivable and could be substituted). Although we recognize that forest growth, harvest and burning will alter the pattern of forest condition over the next 40 yrs, for this exercise we assumed forest condition remained constant. We also assumed no new highway construction, although with transportation system plans it would be relatively straightforward to incorporate this information.

**Measuring the Conservation Value of Sites**

As described above, we used five objectives to prioritize areas for terrestrial biodiversity conservation. In this section we provide a brief conceptual background and specific measure for each of the five criteria.

**Objective 1. Hotspots of rare, endemic, threatened and endangered species (M₁)**

Many conservation efforts give high priority to areas that support high densities of geographically restricted, threatened and endangered species (Dobson et al. 1997, Abbitt et al. 2000, Chaplin et al. 2000). These species have special legal status and their persistence is jeopardized by additional human impacts.

We assume that there is a finite list of \( E \) species of concern. We also presume that each species’ distribution has been mapped at some level of detail, even if it is simply the presence or absence of the species in the set of sites \( i = 1 \ldots I \) in the reference region (which could be the planning region or different area used to evaluate the level of protection for the pool of species in the analysis). Occurrences can also vary in their “quality,” for example as a function of the quality of the observation, the extent of the habitat, or the size of the local population. Conservation is evaluated at the scale of the site rather than at the scale of the occurrence under the assumption that species populations could be either directly or indirectly impacted by human activities occurring throughout the site. This is probably reasonable when populations occupy all or a moderate fraction of the site but is problematic when the occurrence spans several-to-many relatively small sites or when the sites are so large that the dynamics of the species are not strongly related to the average condition of entire site. In the former case, an ensemble of sites would need to be recognized as a single occurrence and in the latter condition would have to be measured for occurrence-specific areas within the sites. While both are feasible, the implementation below assumes that occurrences in different sites are independent and that the condition of the site is relevant to its conservation value for all species of special concern that occur in that site.

The site’s hotspot value is a function of the number of species of special concern, the degree of endemism of each species based on the total area of known (or alternatively, predicted) occurrence, the extent and condition of unprotected land in the site, and the current ecological condition of all other sites where the species occurs. The calculation is similar to “endemism” as
proposed by Nott and Pimm (1997). The condition-weighted area (CWA) of site \( i \) is

\[
\Gamma_i' = \sum_{o \in i} a_o' s_o'
\]  

(13)

where \( a_o' \) is the area of observation unit \( o \) and \( s_o' \) is its condition at time \( t \). The summation “\( o \in i \)” refers to all observation units that are located within site \( i \). We use \( t=0 \) to indicate the current time period.

Letting \( \rho_o \) indicate whether observation cell \( o \) is protected (\( \rho_o = 0 \)) or unprotected (\( \rho_o = 1 \)), then the current condition-weighted area of unprotected land that is available for new conservation investments in site \( i \) is:

\[
u_i^0 = \sum_{o \in i} a_o^0 s_o^0 \rho_o
\]

(14)

Conversely, the condition-weighted area of protected land in site \( i \) is:

\[
u_i^p = \sum_{o \in i} a_o^0 s_o^0 (1- \rho_o)
\]

(15)

Finally, we require a measure of the quality of occurrence of species \( e (e = 1, \ldots, E) \) in site \( i \), which we denote \( Q_{ei}^0 \), where \( 0 \leq Q_{ei} \leq 1 \). For example, if presence-absence data are available then \( Q_{ei} \) would be 1 if a species is recorded in site \( i \) and 0 otherwise. Alternatively, element occurrence ranks that are maintained by State Heritage Programs could be recoded on a 0-1 scale to capture more information about occurrence quality in terms of population size, condition and context (Stein and Davis 2000).

The overall contribution of site \( i \) to the objective of protecting hotspots of rare, threatened and endangered species is then calculated as:

\[
M_{i,1} = \sum_{e=1}^{E} U(\sum_{i=1}^{0} Q_{ei}^0 \nu_i^0, \sum_{i=1}^{0} Q_{ei}^0 \Gamma_i^0, \sum_{i=1}^{0} Q_{ei}^0 \Gamma_i^0) = \sum_{i=1}^{E} \frac{Q_{ei}^0 \nu_i^0}{\sum_{i=1}^{E} Q_{ei}^0 \Gamma_i}
\]

(16)

\( U(\cdot) \) in equation 16 is the function defined in equation 5. We have set \( A = G \) in \( U(\cdot) \) so that there is no decrease in marginal value as the species is afforded more protection. This could be easily modified for other policy scenarios. Equation 16 states that (ignoring site cost for the moment) a site has higher conservation value for rare, threatened and endangered species if available land accounts for a large fraction of the total condition-weighted area for each of a relatively large number of RTE species. Assuming that the goal is to protect all occurrences of such species, sites are prioritized from higher to lower scoring sites and the value of conservation decreases as higher scoring sites are conserved. Notice that we are effectively assuming that all available (not currently protected) CWA area is threatened. An alternative would be to replace \( \nu_i^0 \) in the numerator with \( \nu_i^0 - \nu_i^p \), so that areas where condition is predicted to be more threatened would be given greater value, as described in Section 5. Because most special status species
are already considered globally threatened, we have made the simplifying assumption that all individual occurrences are threatened and that highest priority should be given to protecting sites that are currently in the best condition. In this case we have set the same goal for all species, but species-specific goals could also be applied to give greater weight to some species.

To demonstrate this measure, statewide data on rare, threatened and endangered species were extracted from the California Natural Diversity Data Base (Fall 2002 version), which is developed and maintained by the California Department of Fish and Game. For the purposes of this analysis we considered species with conservation ranks G1 and G2 and treated quality as a binary variable (i.e., presence/absence in the site). Data on land management in the form of the “Management Landscape v1.” 100m grid were obtained from CDF-FRAP. All lands mapped as “public” or as “private reserved” were considered protected and lands mapped as “private non-reserved” were considered non-protected.

Although the planning region is the Sierra Nevada bioregion, we included the entire State of California as the reference region for analyzing G1 and G2 species rather than the Sierra Nevada. This minimizes the effect on site scores of marginal occurrences of species that are more widely distributed in neighboring regions. Greater emphasis could be placed on conserving taxa that are rare in the Sierra Nevada region by using the bioregion as the reference region for calculating site scores.

Scores for township quadrants in the Sierra Nevada Bioregion range from 0 to 0.98 (Figure 4). Clusters of high scoring sites are scattered across the private lands of the western foothills. Many of the high scoring sites are areas with distinctive soils and associated concentrations of rare plant species. For example, the highest scoring cells in the foothills of Nevada, Placer, Amador and El Dorado Counties are locations of serpentine and gabbroic soils that support chaparral communities with rare endemic plant species such as *Calystegia stebbinsii* and *Fremontodendron californicum ssp. decumbens*. Similarly, several high scoring sites at the southern end of the region in Kern County are areas of Blue oak (*Quercus douglasii*) woodlands on adobe soils that support rare plant species such as *Mimulus pictus* and *Fritillaria striata*.

Because the majority of special-status species in the Sierra Nevada is comprised of localized plant taxa, scores are largely dictated by plant species. A map of values based solely on animal species shows a quite different pattern (Figure 5) that reflects in particular the locations of rare invertebrates that may be recorded from only one or two localities in the State. The lack of coincidence in patterns of richness for different taxonomic groups is commonly observed (Prendergast et al. 1993, Kershaw et al. 1995). This result combined with uncertainty in the knowledge of rare species distributions and the strong scale-dependence of patterns of species richness (Stoms 1994) has led some to question the value of hotspots for setting conservation priorities at regional to local scales. However, given the attention paid to hotspots by various agencies and conservation
organizations, some measure of hotspot value is needed for priority setting. It may be useful to calculate scores for the different taxonomic groups and then derive a composite hotspot score as the weighted sum of scores using weights developed based on agency mandate and/or through stakeholder processes.

**Objective 2: Underrepresented habitat types (M₂)**

For many years conservation planners have promoted the concept of “representative reserve networks” to reduce the risk of biodiversity loss due to human activities (Cocks and Baird 1989, Margules 1989, Scott et al. 1993, Davis and Stoms 1996, Davis and Stoms 1999). Expanded protection for poorly represented communities, ecosystems, or other biodiversity surrogates is viewed as an efficient way to protect many at-risk species without resorting to species-by-species conservation (Scott et al. 1993). The technique of Gap analysis is now widely used to assess the current conservation status of general vegetation types. Many state, federal and non-governmental agencies (e.g., California Parks and Recreation, the U.S. Forest Service, The Nature Conservancy) include representation as a criterion for prioritizing new areas for acquisition or special management designation. The main difficulties in implementing representative systems are choosing the appropriate ecological classification system, defining the representation targets (often a percent of current or historical extent of the element), and establishing a relationship between the level of protection for a surrogate and its likelihood of persistence. Also, current reserve systems can be so biased that a large number of vegetation types and species may fall below the conservation targets and other criteria may be needed to prioritize among them.

Denote by \( \Theta_k \) the goal (target level of conservation) expressed as condition-weighted area (CWA, equation13) for habitat type \( k \), and let the future CWA in that habitat type in the absence of any conservation action be \( \Theta_k^T \).

The value of site \( i \) to this conservation objective is measured by the difference between the conservation value summed over all habitat types in the future with and without the conservation of site \( i \). Denote by \( \Theta_{ik} \) the contribution of site \( i \) to the CWA of habitat type \( k \),

\[
\Theta_{ik} = \sum_{o \in T, o \in k} (a_o^T s_o^T - a_o^T s_o).
\]

Then the value of site \( i \) across all habitat types is given by:

\[
M_{i,2} = \sum_{k=1}^{K} U(\Theta_k^T \cdot \Theta_{ik} \cdot \Theta_k^T) \tag{17}
\]

where the function \( U(\cdot) \) is the function defined in equation 5. Note that we set the lower threshold in the utility function to zero, but other values could be substituted.

To demonstrate the method in the Sierra Nevada we measured site value for representing general wildlife habitat types as defined in the California Wildlife
Habitat Relationship (WHR) System (Mayer and Laudenslayer 1988). A current map of WHR types at 100 m was obtained from CDF-FRAP. The conservation goal was set at 100% of the current extent of the type in the Sierra Nevada bioregion. Highest marginal values were thus associated with WHR types with lowest predicted average condition in 2040 (Table 1). These included commercial conifer types such as Ponderosa pine forest and Eastside pine forest and oak woodland types such as Blue oak–Foothill pine woodland and Valley oak woodland. Township quadrants scoring the highest were those where habitat types with high marginal value and in relatively good condition occurred on threatened private lands (Figure 6). Thus high scoring sites are clustered at low-to-mid elevations on the western slope of the Sierra where rural housing density has increased in recent decades and is projected to continue increasing in the future (Duane 1996).

Objective 3: Biophysical Landscapes (M3)

Conservation planning has emphasized protecting species, communities or biophysical environment types. An alternative approach is to conserve some portion of every biophysically distinctive landscape, each of which may be viewed as somewhat unique by virtue of location and physical properties such as physiography, geology and soils. To borrow G. Evelyn Hutchinson’s metaphor of the ecological theatre and the evolutionary play (Hutchinson 1965), this conservation strategy emphasizes conservation of “the stage” rather than of “the actors.”

There are compelling reasons to pursue such a strategy. First and perhaps most important is the dynamic nature of biotic distributions, especially in a time of rapid climate change, which argues against conservation priority-setting based on today’s biological composition. A second reason is the incomplete and biased nature of data on biological distributions. Finally, the motivation for much ongoing conservation is in fact “place-based.” Local governments, conservancies, land trusts, and citizens groups tend to place high value on the habitat value and ecosystem services associated with undeveloped lands in their local planning area whether or not they support species or communities of special concern. This is especially true where a larger fraction of the landscape has been developed. Landscape-based conservation is obviously subject to the vagaries of classification and mapping, but the general principle of protecting some amount of every landscape, ideally through deliberate design, is a longstanding principle of urban and regional planning that has recently received renewed attention by landscape ecologists (Forman and Collinge 1997, Collinge and Forman 1998).

In setting priorities across a large region with many distinctive landscapes, we formulate the problem as that of “representing landscapes” and follow the same logic as described under Objective 2 above. The main difference is that the reference area for evaluating the marginal benefit of additional conservation is now the landscape rather than the entire planning region.

The shape of the marginal value function is problematic. The responses of native species populations and ecosystem processes to landscape conversion...
and fragmentation can be highly non-linear and dependent on spatial configuration (Andren 1994, Andren 1999) but are also highly process- and species-specific (Fahrig 2001). Ecosystem processes also show highly non-linear, process-specific responses to landscape development and habitat loss (Franklin and Forman 1987). In reviewing empirical studies Andren (1994) found area and/or isolation effects increased significantly when less than 20% of habitat remained in the landscape. Based on a simple spatial model with random land conversion, Forman and Collinge (1997) suggest that in the absence of spatial planning the remaining ecological value is a linear function of habitat remaining. They also suggest that conservation planning and design may be most important at intermediate levels of habitat conversion (10-40% of the landscape), before important local habitat areas in the landscape have been removed.

We assume that there are \( L \) landscapes of interest. Letting \( \Lambda_i \) denote the percentage of CWA of landscape \( l \), our approach is based on the notion of conserving some minimum proportion of the landscape (\( \bar{\Lambda} \)) below which habitat isolation effects may become extreme, and then linearly decreasing marginal return on conservation up to a point where a large proportion of the landscape is undeveloped (\( \Lambda_i \)). As with other formulations, we set conservation value based on projected future landscape condition as opposed to current landscape condition, the logic being that highest priority should go to those areas where conservation will have the greatest positive effect on the level of landscape biodiversity at the end of the planning period. Let the condition of landscape \( l \) at time \( t \) be measured as the mean area-weighted condition of all observations of land condition in the landscape:

\[
\Lambda_i^t = \frac{\sum_{o \in l} a_o S_o}{\sum_{o \in l} a_o} \quad (18)
\]

Denote by \( \lambda_i \) the change in percentage of CWA of landscape \( l \) that could be attributed to protecting site \( i \). It is given as follows:

\[
\lambda_i = \frac{\sum_{o \in l, o \neq i} a_o S_o}{\sum_{o \in l} a_o} - \frac{a_i S_i}{\sum_{o \in l} a_o} \quad (19)
\]

Then the conservation value of any given site \( i \) in landscape \( l \) is measured as follows:

\[
M_{i,3} = U(\Lambda_i^T, \lambda_i, \Delta_i, \bar{\Lambda}) \quad (20)
\]

The site score for landscape conservation ranges from zero to one.
For this analysis we adopted the ecological subsections of California as our units for landscape conservation (Goudey and Smith 1994). These are relatively large areas and are used here mainly to demonstrate the approach. The scores for township quadrants in the Sierra Bioregion are shown in Figure 7. Highest scores in the northern region are clustered in the Lower Foothill Metamorphic Belt in the foothills of Nevada, El Dorado and Calaveras Counties, and in the Upper Foothills Metamorphic Belt of Nevada, Placer and El Dorado Counties. Highest scores in the southern region are clustered in the Hardpan Terraces of Fresno and Kern Counties. These terraces form the eastern margin of the San Joaquin Valley.

**Objective 4: Wildlands for area-dependent species (M₄)**

A number of conservation scientists and organizations have promoted the protection of extensive wildland areas for large carnivores and other animals that require large areas and are sensitive to human activities ("area-dependent species") (Noss et al. 1996, Soule and Noss 1998, Noss et al. 1999, Soule and Terborgh 1999, Noss 2000). Conservation organizations may have aesthetic as well as ecological reasons for giving high priority to wildland conservation, so protecting relatively wild areas may be a conservation or restoration goal even in the absence of focal area-dependent species (Aplet 1999, Soule and Terborgh 1999). Conservation for area-dependent species entails identifying the focal species (e.g., umbrella species, flagship species, keystone species) for the region, compiling detailed autecological information on those species and modeling their viability under different conservation scenarios in order to identify important "core areas" and associated linkages between them (Noss 2000, Kautz and Cox 2001, Stoms et al. 2003).

Focal species planning requires considerable species-specific analysis and is beyond the scope of our demonstration for the Sierra Nevada, although this term in the framework provides a means of integrating such information. In the absence of species-specific analyses it may still be possible to locate sites that have characteristics normally associated with area-dependent species. Such sites would likely be in extensive contiguous areas that have low impact from roads, low levels of human activity, ample vegetation cover and low levels of habitat conversion (Beier 1995, Carroll et al. 1999, Carroll et al. 2001, Crooks 2002).

Assuming that large blocks of non-fragmented wildlands have been mapped, and again ignoring cost for the moment, highest priority would logically be given to protecting blocks where threatening processes would have the greatest impact on the future contiguous extent and condition of the area. Denote by \( \Pi_w \) the CWA of wildland block \( w \) at time \( t \). Below some minimum area, \( \Pi \), we assume that each additional unit of CWA added to the wildland block has the highest marginal value. We further assume that there are diminishing returns to additional conservation beyond that threshold up to a target CWA of \( \Pi \) (beyond which additional conservation has negligible marginal benefits).
Denote by $\Pi_{i,w}$ the change in CWA of block $w$ in future time $T$ that can be attributed to conserving site $i$, as follows:

$$\Pi_{i,w} = \sum_{o \in T} (a_o S_o^0 - a_o S_o^T)$$

Then the contribution of site $i$ toward wildland block $w$ is $U(\Pi_{w,i}, \Pi_{i,w}, \Pi, \Pi)$ and the contribution of site $i$ to all wildland blocks is:

$$M_{i,4} = \sum_{w=1}^{W} U(\Pi_{w,i}, \Pi_{i,w}, \Pi, \Pi)$$

As with measures $M_2$ and $M_3$, the marginal value diminishes linearly to zero with each increment of conservation up to the stated goal. To demonstrate the idea we developed a set of hypothetical wildland blocks for the Sierra Nevada by first smoothing the 1ha grid of the current condition index using a mean filter with a 500 m radius and then delineating patches of 1 ha cells where the filtered condition value was above 0.75 in every cell. The value 0.75 was determined by examining the distribution of condition scores within existing wilderness areas. (All wilderness areas have a mean score > 0.75 and most large wilderness areas exhibit a mean condition score of > 0.9. We set a lower threshold of 0.75 to capture sparsely settled and sparsely roaded private lands). We set a minimum patch area for consideration as a wildland block and removed all patches below that size before calculating a site’s value for wildland conservation. A range of minimum block sizes was tested from 2000 ha to 40,000 ha. Predicted condition weighted area of each patch in 2040 was calculated based on projected household density and the value of each site $i$ calculated as per equations 21-22.

In calculating $M_{i,4}$ we set $\Pi$ and $\Pi$ to 10,000 ha and 200,000 ha, respectively, and examined scores over a range of minimum patch areas for identifying wildland blocks. When all wildland blocks larger than 4000 ha are included, areas with high marginal value are concentrated in the central and southern foothills from Calaveras to Kern Counties, but also include smaller regions of the northern Sierra Nevada such as the French Creek Basin in Butte County or the Lower Cosumnes Basin in El Dorado and Amador Counties (Figure 8). After excluding all areas smaller than 40,000, regions of high value occur mainly in Tulare and Kern County in areas such as the foothills of the Tule River Basin and Kern River Basin (Figure 9).

**Objective 5: Expanding existing reserves (M_5)**

Many existing reserves may be of insufficient size to maintain viable populations of species and ecological processes if they become isolated by human-dominated land uses. Consequently, a site may have conservation value because of its location adjacent to a threatened reserve, irrespective of the site’s value for any of the other four biodiversity conservation objectives.

We consider the contribution of site $i$ to each of a total of $V$ reserves, where the land area of reserve $v$ is denoted $A_v$. We assume that the contribution of
an observation cell to an existing reserve depends on two factors. First, it will depend on the distance between the observation cell and the reserve, denoted $d_{o,v}$, for sufficiently large $d_{o,v}$, cell $o$ contributes nothing to reserve $v$. The second factor can be thought of as the “demand” of the reserve for additional area. This is consistent with the concept of the species-area relationship (Leitner and Rosenzweig 1997). This relationship states that the number of species supported by a reserve is a function of the area of the reserve as follows: $c A^z_v$ for constants $c$ and $z$. Then the marginal contribution of area to a reserve (in terms of additional species that could be supported) is $z c A^{z-1}_v$.

Assuming that the contribution is inversely related to distance, the distance-weighted contribution of cell $o$ to reserve $v$ is $\frac{z c A^{z-1}_v}{d_{o,v}}$. Summing over all reserves, the distance-weighted contribution of cell $o$ to all reserves is as follows:

$$D_o = \sum_{v=1}^{V} \frac{z c A^{z-1}_v}{d_{o,v}}$$

To calculate the overall contribution of cell $o$ to conservation between time $0$ and time $T$ we must account for threat as in the measures above. To do so, we calculate the change in condition in cell $o$ between present time $0$ and time $T$ (given no conservation): $s_o^0 - s_o^T$. This provides a measure of how conserving cell $o$ (within site $i$) will retain present condition in that cell. The overall contribution of site $i$ to enhancing existing reserves is the summation over all cells ($o$) in site $i$ as follows:

$$M_{i,5} = \sum_{o \in i} D_o (s_o^0 - s_o^T)$$

For this application we set $c$ equal to 150 and $z$ equal to 0.4. Although $z$ is expected to be lower for mainland terrestrial environments, we use a higher value such as would be expected for insular habitats.

Note that a site with cells that are in poor condition or are expected to remain in their present condition will receive a lower marginal value than a site in good condition that is likely to be degraded, given that both have equal expansion potential. Note that we do not adjust $M_{i,5}$ directly by diminishing its marginal value as conservation actions expand existing reserves towards a goal or threshold as was done with the other objectives. Rather, the diminishing marginal value concept is represented in this objective in the demand term for the reserve (i.e., the reference region demand is less for larger protected areas), which then propagates to the supply term.

To demonstrate this objective, we classified the CDF Management Landscape v1 map into “reserves” (private reserves, plus all public land except where public land use = urban) or “available” (all other categories). Contiguous
reserve cells were aggregated into reserve regions whose sizes were calculated and used to calculate demand. For practical reasons, we simplified the calculation of $D_0$ in the Sierra Nevada demonstration by limiting the contribution of a cell to its nearest reserve rather than summing over all reserves. Most reserves will be sufficiently far from a cell that this makes no difference, but this simplification will undervalue cells that could connect small reserves in close proximity. Distance of cells up to 1000 meters from the nearest reserve (and its identity and demand) was generated to determine their distance-weighted contribution. Condition of each cell in 2000 and 2040 was calculated based on equation 12, and the marginal value was calculated as per equation 24.

The distribution of scores for the Sierra Nevada is mapped in Figure 10. Clusters of high values are seen in the northern foothills where public lands tend to be in small isolated units and where private lands are in relatively good condition now but that the growth model predicts will experience increased development over the next 40 years.

**Composite utility**

The five criteria are combined in a simple, additively separable utility function with weight $w_j$ placed on objective $j$. For this demonstration, we assigned equal weights (i.e., 0.2) to all five objectives. In the stepwise iterative procedure described above, the utility of site $i$ towards all objectives is given as follows:

$$
\Delta_i = \frac{\sum_{j=1}^{5} w_j M_{i,j}}{\sum_{j=1}^{5} M_{i,j}}/\text{Cost}_i
$$

(25)

The algorithm involves choosing the site $i$ with maximal $\Delta_i$, recalculating all values, and repeating until the budget $B$ has been exhausted.

**Composite Results for the Sierra Nevada**

With the exception of $M_1$ (value for RTE species), the criteria described above are all based in part on threat. Because a single map of threat is used one might expect high correlation among the spatial patterns of scores for the Sierra Nevada. However, when the normalized scores are calculated and compared to one another the level of correlation is quite low (Table 2). RTE hotspots show the lowest correlation with the other measures ($r$ values ranging from 0.05 – 0.08). There is relatively high correlation among values for representing habitat types and conserving landscapes, mainly reflecting the relatively simple habitat classification scheme and large size of the ecological subsections. We expect the correlation would be much lower if a more detailed habitat classification system was used or if smaller landscape units were utilized.

The generally low correlation among scores illustrates how the location of conservation priorities can vary considerably depending on specific criteria and reference regions. Thus the assignment of weights is an important consideration in applying this framework. During NCEAS workshops we
applied the Analytical Hierarchy Process (Saaty 1980) and found this a very useful technique for establishing weights through group decision making. Others have had similar success using this approach (Anselin et al. 1989, Bantayan and Bishop 1998, Schmoldt and Peterson 2000) or other multi-criterion methods (Jankowski and Richard 1994, Guikema and Milke 1999, Rauscher et al. 2000). In our framework for terrestrial biodiversity, the small number of criteria (5) and explicit definition and mapping of criterion scores should make application of AHP relatively straightforward.

If all criteria are weighted equally, many township quadrants in the Sierra Bioregion show moderately high scores (Figure 11). Larger regions of high-scoring cells include central Placer County, southwestern and southeastern El Dorado County, central-western Calaveras County, but only a few units have high scores for all five criteria. For example, two large regions of high value occur in western El Dorado County, central Madera County, south-central Tulare County, and south central Kern County. Perhaps more to the point is that, based on relatively crude surrogates for biological composition, condition and threat, most areas of the foothills and lower montane zone of the Sierra Bioregion have high value for one or more criteria and at least moderate conservation value when all criteria are considered. A few areas of the eastern Sierra also appear consistently, although the scores are generally lower because of lower projected threat of development and the high percent of public ownership. Variations in costs and opportunities thus could play a significant part in determining priorities, as demonstrated below.

5. PRIORITIZING CONSERVATION INVESTMENTS BASED ON SITE COSTS AND BUDGET CONSTRAINTS

**Estimating Conservation Costs**

The goal of our framework is to maximize biodiversity conservation for a given budget. This requires spatially explicit information on the predicted cost of taking a particular conservation action over the extent of a site. To reiterate what was said in Section 5, a conservation action is an investment to remove the threat to a particular resource. If the threat takes the form of land development, the conservation action could be land acquisition or the purchase of a conservation easement, and the cost would be the fee title cost or easement cost, respectively. If instead the threat is non-sustainable resource harvest, then the action could be reduced harvest and/or implantation of other new management practices, and the cost would be incurred through stewardship agreements, incentive programs, or compensation to landowners. We recognize that new state or local land use and resource harvest policies are another means or removing threats to resources and that there are costs associated with development, adoption and implementation of those policies. Our framework is not really designed to address broader policy changes that do not involve allocation of funds to specific places.
To demonstrate the allocation model, we consider conservation of private lands by outright acquisition to remove the threat of development. Many if not most of the State’s investments of conservation funds take this form. This requires information on the geography of land values, which vary in relatively predictable patterns in response to social, spatial, and environmental factors. It was beyond the scope of our project to develop detailed land value information for California at the resolution of our sites. For demonstration purposes only in the Sierra Nevada study area, we used 2002 data from the California Chapter of the American Society of Farm Managers and Rural Appraisers [available online at http://www.calasfmra.com/landvalues/2002/index.html] for county-level estimates for land value of rangeland for Butte, Placer, Madera, Fresno (eastern half), Tulare, and Kern (eastern half) counties. We chose land values for the remaining counties that reflected the broad pattern of land use and development pressure relative to the known county values. Counties in the eastern part of the Sierra Nevada bioregion were given the lowest land values; those in the central western foothills were assigned medium land values; and those lying just east of Sacramento were given relatively high values. For this demonstration, land values ranged from $988-$2470 per hectare ($400-$1000 per acre). The total conservation cost of a site is the product of the per-hectare cost and the total area in hectares of land available for conservation in the site (total land area minus public land and converted land). In a quick comparison of these land values with prices actually paid in recent years through California bond initiatives, ours tended to correspond to the low end of the range for the county. Often the high end of the range was several times the price we used, and where there were many acquisitions, the price range in a county was extremely variable. This suggests that county-level estimates grossly oversimplify the geography of the real estate market.

**Prioritization of Sites for Conservation**

Using the estimated land values and the measure of overall marginal value for terrestrial biodiversity conservation with equal weighting between objectives, the greedy algorithm was run until an arbitrary 50 sites were selected at a predicted total acquisition cost of $44 million for approximately 25,000 hectares, or about 10% of the remaining available land in the bioregion (Fig. 12). This represents an average of $1760 per hectare, very near the $1800 per hectare average estimated price in the bioregion. This scenario should be interpreted as one possible alternative, based on an equal weighting of conservation objectives. The outcome is sensitive to our very crude estimates of land values, to the choice of reference regions and goals, and to the model of future urbanization.

Rather than focusing on the particular sites that were selected, it is more useful to examine what the allocation reveals. Figure 12 shows that the 50 sites selected occur where composite marginal value divided by land value is highest. Sites with the highest marginal value for rare species hotspots (25th site selected) and vulnerable landscapes (1st selection—this landscape
is very rare in the Sierra Nevada but larger in the San Joaquin Valley) were included in the scenario, but the highest value sites for the other objectives were not. Some sites excelled in a single objective, whereas others contributed to multiple objectives.

In general, the mean marginal value for each objective in selected sites was much greater than the mean for all sites. Forty-two of the 50 selected sites had no marginal value for at least one of the five objectives. Interestingly, the spatial pattern of selected sites is quite scattered. There was no large concentration of sites, as might occur if wildlands or landscapes were weighted more heavily than other objectives. A large fraction of the 50 sites occur in the eastern Sierra counties of Alpine, Mono, and Inyo, which were assigned the lowest estimates of land values. The composite marginal value for these eastside sites was 4 times less than those selected on the west slope of the Sierra, but the mean benefit-cost ratios were almost identical. Clearly our estimates of land values had a strong influence on the scenario, by allocating funds to more land of moderate conservation value than spending it all on relatively fewer hectares of land with the maximum marginal conservation value. This result underscores the point that making efficient and effective conservation investments requires more information than simply identifying sites with the highest biodiversity conservation value (Ando et al. 1998).

6. DISCUSSION

Integrated conservation planning frameworks are especially important given the trend in planning from top-down “command-and-control” style planning towards more collaborative processes (Klosterman 1997). Conservation usually raises conflicts between competing ideological and/or economic interests, and success may depend on achieving political agreement through informed negotiation (Pressey et al. 1996). Well-designed conservation planning frameworks have value in such negotiations by helping stakeholders articulate more explicit goals, by promoting better understanding of natural resource amenities and the threats to those amenities, and by facilitating the production and evaluation of alternative policy and management scenarios. Furthermore, because systematic conservation planning involves gathering, organizing and maintaining information on condition and conservation status of resources across the planning region, integrated frameworks facilitate ongoing “auditing” of conservation efforts (Margules and Pressey 2000).

The framework that we have developed for the California Legacy Project has not been fully vetted with the relevant State agencies or other stakeholder groups so it remains to be seen whether the ideas and methods presented here will prove useful in real planning efforts. Most of the calculations are relatively straightforward and easily implemented in ArcGIS and Access, so the framework should be widely accessible. We believe the strengths of the framework are its generality, explicitness, applicability with readily available data, flexibility for exploring alternative goals and objectives, consideration of threats and costs as well as biodiversity values, and perhaps most
importantly its ability to reveal short-term priorities and its usefulness in helping to choose among competing projects based on a formal cost-effectiveness analysis.

**FRAMEWORK LIMITATIONS AND PRIORITIES FOR TESTING AND REFINEMENT**

The framework as currently implemented is somewhat cumbersome and needs a simple user interface and software to facilitate analysis and planning. We are currently developing such a planning support environment in collaboration with NatureServe. After developing such software it will be much easier to conduct sensitivity analyses on models of development threat, different planning horizons, classification schemes, parameters and marginal value functions that are integral to estimating site conservation value.

This is a data-driven framework whose usefulness obviously depends on the quality of the data. We have deliberately limited the application to statewide data that are in wide use and whose accuracy and bias are relatively well understood. In doing so we have sacrificed biological detail for better consistency and accuracy. To test how results might vary with data of higher quality or resolution we have been compiling local data from the Sierra Nevada and other regions of the State. Thus far we have found that for analysis of private lands many of the data sets used here (e.g., FRAP land use-land cover data, FRAP land ownership data, TIGER roads data, NDDB data on rare species occurrences) are the same data that are being used for subregional and County-level analyses. However, some Sierra Counties (e.g., Placer, Nevada) have recently developed more detailed geospatial databases that can be used to test some of the statewide input data. This is a large and complex task that we will be completing over the next several months.

We have developed many novel measures and approaches for estimating condition, threat and conservation value. Although based on current conservation theory and evidence, these measures and approaches will need to be tested and refined with empirical data. For example, we are collaborating with Bill Zielinski (Redwood Sciences Lab) to test our measure of condition and wildland value against recent field surveys of fishers in the Sierra, Cascades and Klamath Regions. In Napa County we are working with NatureServe to test the framework against other conservation approaches. We hope that by disseminating our data and results we will encourage staff in The Resources Agency and other organizations to undertake their own comparisons as well.

One of our major concerns with the current framework is that it does not consider the effect that taking conservation actions will have on the ensuing distribution of development threat. We are looking into ways of updating the threat surface as part of updating calculations of conservation value. This will be especially important for applications of the framework at finer spatial scales.

Several target-based site selection algorithms are now in wide use for conservation planning, for example:
These and other tools are now seeing increasing use in conservation planning frameworks such as those discussed at the beginning of this report. Another research priority for us will be to undertake formal comparisons of the results obtained using such tools vs. those obtained using the marginal value approach that we have described here. We are currently in the initial phases of such comparisons.
7. LITERATURE CITED


California Department of Transportation. 2001. *California motor vehicle stock, travel and fuel use forecast*. Sacramento, California Department of Transportation Division of Transportation System Information.


Franklin, J. F. and J. F. Fites-Kaufmann. 1996. Assessment of late-successional forests of the Sierra Nevada. Pages 627-662 in *Sierra Nevada Ecosystem Project: Final Report to Congress, Assessments and Scientific Basis for Management Options*. Davis, University of California Centers for Water and Wildland Resources. II.


Landis, J. D. and M. Reilly. 2002. How we will grow: Baseline projections of California’s urban footprint through the year 2100. Berkeley, California, Institute of Urban and Regional Development, University of California.


Pressey, R. L. and V. S. Logan. 1998. Size of selection units for future reserves and its influence on actual vs targeted representation of


Stewart, W. 2003. Final Report on CDF Fire and Resource Assessment Program (FRAP) contract with the California Legacy Project to provide data layers and methodology to work with the data systems and decision making tools of NCEAS and the California Legacy Project. Sacramento, California, California Department of Forestry and Fire Protection Fire and Resource Assessment Program.


8. TABLES
Table 1. Hierarchy of conservation goals

<table>
<thead>
<tr>
<th>Conserve California’s Lands and Natural Resources</th>
<th>Maintain Resource Production Capacity</th>
<th>Conserve Natural Capital</th>
<th>Provide Adequate High Quality Public Open Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protect Productive Rangelands</td>
<td>Protect Productive Timberlands</td>
<td>Protect Productive Cultivated Lands</td>
<td>Conserve Aquatic and Wetland Biodiversity</td>
</tr>
</tbody>
</table>
Table 2. Current and projected extent and condition of WHR habitat types in the Sierra Nevada Bioregion based on 1 ha digital maps of vegetation and ecological condition. Types are sorted from lowest to highest predicted mean condition in 2040.

<table>
<thead>
<tr>
<th>WHR Class</th>
<th>Area</th>
<th>Current Condition</th>
<th>2040 Condition</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponderosa pine</td>
<td>240410</td>
<td>0.483</td>
<td>0.439</td>
<td>0.043</td>
</tr>
<tr>
<td>Eastside Pine</td>
<td>100084</td>
<td>0.490</td>
<td>0.483</td>
<td>0.006</td>
</tr>
<tr>
<td>Douglas Fir</td>
<td>153056</td>
<td>0.564</td>
<td>0.510</td>
<td>0.054</td>
</tr>
<tr>
<td>Jeffrey Pine</td>
<td>182540</td>
<td>0.544</td>
<td>0.539</td>
<td>0.005</td>
</tr>
<tr>
<td>Montane hardwood-conifer</td>
<td>212234</td>
<td>0.620</td>
<td>0.543</td>
<td>0.076</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>200511</td>
<td>0.556</td>
<td>0.554</td>
<td>0.002</td>
</tr>
<tr>
<td>Montane hardwood</td>
<td>538290</td>
<td>0.643</td>
<td>0.558</td>
<td>0.085</td>
</tr>
<tr>
<td>Blue oak - Foothill Pine</td>
<td>120097</td>
<td>0.721</td>
<td>0.568</td>
<td>0.153</td>
</tr>
<tr>
<td>Valley oak woodland</td>
<td>14658</td>
<td>0.717</td>
<td>0.569</td>
<td>0.148</td>
</tr>
<tr>
<td>Sierran mixed conifer</td>
<td>1103865</td>
<td>0.598</td>
<td>0.590</td>
<td>0.008</td>
</tr>
<tr>
<td>Blue Oak Woodland</td>
<td>421866</td>
<td>0.715</td>
<td>0.615</td>
<td>0.100</td>
</tr>
<tr>
<td>Annual Grassland</td>
<td>709651</td>
<td>0.697</td>
<td>0.617</td>
<td>0.080</td>
</tr>
<tr>
<td>Red fire</td>
<td>406424</td>
<td>0.647</td>
<td>0.643</td>
<td>0.004</td>
</tr>
<tr>
<td>Mixed Chaparral</td>
<td>171459</td>
<td>0.715</td>
<td>0.649</td>
<td>0.065</td>
</tr>
<tr>
<td>White fir</td>
<td>104837</td>
<td>0.659</td>
<td>0.653</td>
<td>0.006</td>
</tr>
<tr>
<td>Chamise Chaparral</td>
<td>39358</td>
<td>0.755</td>
<td>0.677</td>
<td>0.079</td>
</tr>
<tr>
<td>Alkali Desert Scrub</td>
<td>183213</td>
<td>0.794</td>
<td>0.780</td>
<td>0.014</td>
</tr>
<tr>
<td>Bitterbrush</td>
<td>19891</td>
<td>0.845</td>
<td>0.813</td>
<td>0.033</td>
</tr>
<tr>
<td>Desert Scrub</td>
<td>88641</td>
<td>0.835</td>
<td>0.832</td>
<td>0.003</td>
</tr>
<tr>
<td>Coastal oak woodland</td>
<td>1423</td>
<td>0.901</td>
<td>0.846</td>
<td>0.056</td>
</tr>
<tr>
<td>Wet meadow</td>
<td>36842</td>
<td>0.873</td>
<td>0.852</td>
<td>0.020</td>
</tr>
<tr>
<td>Sagebrush</td>
<td>539997</td>
<td>0.877</td>
<td>0.862</td>
<td>0.014</td>
</tr>
<tr>
<td>WHR Class</td>
<td>Area</td>
<td>Current Condition</td>
<td>2040 Condition</td>
<td>Change</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------</td>
<td>------------------</td>
<td>----------------</td>
<td>--------</td>
</tr>
<tr>
<td>Low sagebrush</td>
<td>12708</td>
<td>0.875</td>
<td>0.872</td>
<td>0.003</td>
</tr>
<tr>
<td>Aspen</td>
<td>12956</td>
<td>0.884</td>
<td>0.875</td>
<td>0.010</td>
</tr>
<tr>
<td>Montane chaparral</td>
<td>222152</td>
<td>0.887</td>
<td>0.877</td>
<td>0.009</td>
</tr>
<tr>
<td>Juniper</td>
<td>7442</td>
<td>0.945</td>
<td>0.944</td>
<td>0.001</td>
</tr>
<tr>
<td>Pinyon juniper</td>
<td>217291</td>
<td>0.958</td>
<td>0.949</td>
<td>0.009</td>
</tr>
<tr>
<td>Barren</td>
<td>544788</td>
<td>0.973</td>
<td>0.970</td>
<td>0.004</td>
</tr>
<tr>
<td>Alpine Dwarf Scrub</td>
<td>81472</td>
<td>0.987</td>
<td>0.987</td>
<td>0.000</td>
</tr>
<tr>
<td>Subalpine conifer</td>
<td>220893</td>
<td>0.992</td>
<td>0.992</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Table 3. Correlations among site scores for the five conservation criteria.

<table>
<thead>
<tr>
<th></th>
<th>RTE species</th>
<th>Habitats</th>
<th>Wildlands</th>
<th>Landscapes</th>
<th>Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTE species</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Habitats</td>
<td>0.08</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wildlands</td>
<td>0.07</td>
<td>0.19</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landscapes</td>
<td>0.06</td>
<td>0.80</td>
<td>0.13</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Expansion</td>
<td>0.05</td>
<td>0.62</td>
<td>0.02</td>
<td>0.57</td>
<td>1.00</td>
</tr>
</tbody>
</table>
9. FIGURE CAPTIONS

Figure 1. Utility functions and associated marginal utility functions for estimating site conservation value.

Figure 2. Calculated ecological condition based on land use, housing density, roads, and forest structure for selected forest types. Grid resolution is 1 ha. See text for description of data sources.

Figure 3. Calculated threat to current ecological condition from new housing development projected to occur between 2000 and 2040 A.D. The threat levels range from 0 to 1 and are calculated as the difference between cell condition in 2040 and 2000.

Figure 4. Hotspot value of township quadrants in the Sierra Bioregion for rare, threatened and endangered plant and animal species. Scores reflect documented distributions of all G1 and G2 species in the 2002 version of the California Natural Diversity database.

Figure 5. Hotspot value of township quadrants in the Sierra Bioregion for rare, threatened and endangered animal species. Scores reflect documented distributions of all G1 and G2 animal species in the 2002 version of the California Natural Diversity database.

Figure 6. Marginal value of township quadrants in the Sierra Bioregion for conserving wildlife habitat types.

Figure 7. Marginal value of township quadrants in the Sierra Bioregion for conserving landscapes, where landscapes are ecological subsections of the region as defined and mapped by Goudey and Smith (1994).

Figure 8. Marginal value of township quadrants in the Sierra Bioregion for conserving wildland blocks larger than 4000 ha.

Figure 9. Marginal value of township quadrants in the Sierra Bioregion for conserving wildland blocks larger than 40,000 ha.

Figure 10. Marginal value of township quadrants in the Sierra Bioregion for conserving areas that expand existing reserves.

Figure 11. Composite scores for township quadrants in the Sierra Bioregion given equal weighting among the five conservation criteria.

Figure 12. A sample run of the greedy site selection algorithm. The algorithm was run until an arbitrary 50 sites were selected at a predicted total acquisition cost of $44 million for approximately 25,000 hectares, or about 10% of the remaining available land in the bioregion.
10. FIGURES
Figure 1. Utility functions and associated marginal utility functions for estimating site conservation value: (a) a utility function for target-based conservation where utility accumulates linearly until the specified conservation target (in this case 25% of current resource amount) is reached and then remains constant; (b) marginal utility function associated with (a); (c) the utility function used here for evaluating terrestrial biodiversity in the Sierra bioregion; (d) the marginal utility function associated with (c); (e) Change in marginal value associated with a conservation action today that increases the predicted future level of the resource from $X$ to $X+x$. The total benefit of the conservation action is calculated as the area under the marginal value curve.
Figure 2. Calculated ecological condition based on land use, housing density, roads, and forest structure for selected forest types. Grid resolution is 1 ha. See text for description of data sources.
Figure 3. Calculated threat to current ecological condition from new housing development projected to occur between 2000 and 2040 A.D. The threat levels range from 0 to 1 and are calculated as the difference between cell condition in 2040 and 2000.
Figure 4. Hotspot value of township quadrants in the Sierra Bioregion for rare, threatened and endangered plant and animal species. Scores reflect documented distributions of all G1 and G2 species in the 2002 version of the California Natural Diversity database.
Figure 5. Hotspot value of township quadrants in the Sierra Bioregion for rare, threatened and endangered animal species. Scores reflect documented distributions of all G1 and G2 animal species in the 2002 version of the California Natural Diversity database.
Figure 6. Marginal value of township quadrants in the Sierra Bioregion for conserving wildlife habitat types.
Figure 7. Marginal value of township quadrants in the Sierra Bioregion for conserving landscapes, where landscapes are ecological subsections of the region as defined and mapped by Goudey and Smith (1994).
Figure 8. Marginal value of township quadrants in the Sierra Bioregion for conserving wildland blocks larger than 4000 ha.
Figure 9. Marginal value of township quadrants in the Sierra Bioregion for conserving wildland blocks larger than 40,000 ha.
Figure 10. Marginal value of township quadrants in the Sierra Bioregion for conserving areas that expand existing reserves.
Figure 11. Composite scores for township quadrants in the Sierra Bioregion given equal weighting among the five conservation criteria.
Figure 12. A sample run of the greedy site selection algorithm. The algorithm was run until an arbitrary 50 sites were selected at a predicted total acquisition cost of $44 million for approximately 25,000 hectares, or about 10% of the remaining available land in the bioregion.
11. APPENDIX

SUMMARY OF MATHEMATICAL NOTATION

Parameters:

$I$: number of sites on which conservation can occur (indexed by $i=1...I$),
$O$: number of observation units, $O\geq I$ (indexed by $o=1,...,O$),
$E$: number of RTE species in analysis (indexed by $e=1,...,E$),
$K$: number of habitat types (indexed by $k=1,...,K$),
$L$: number of landscapes (indexed by $l=1,...,L$),
$W$: number of wildland blocks (indexed by $w=1,...,W$),
$V$: number of protected areas (indexed by $v=1,...,V$),
$T$: some number of periods in the future (indexed by $t$).

Variables:

$a_{to}^t$: Area of observation unit $o$,
$s_{to}^t$: Habitat suitability of observation unit $o$ at time $t$,
$C_{to}^t$: Indicator variable indicating whether observation unit $o$ is unconverted at time $t$,
$H_{to}^t$: Residential housing impact on unit $o$ at time $t$,
$R_{to}^t$: Road effect on unit $o$ at time $t$,
$F_{to}^t$: Forest structure on unit $o$ at time $t$,
$\Gamma_{ti}^t$: Condition–weighted area (CWA) of site $i$ at time $t$,
$\rho_{to}$: Indicator variable for the protection status of observation unit $o$,
$u_{i}^0$: Currently available CWA of site $i$,
$v_{i}^0$: Currently protected CWA of site $i$,
$Q_{ei}$: Quality of occurrence of species $e$ on site $i$, $0 \leq Q_{ei} \leq 1$, 

$70$
\( \Theta_k \): CWA of habitat type \( k \) at time \( t \),

\( \theta_{ik} \): Contribution of site \( i \) to \( \Theta_k \) for habitat type \( k \).

\( \bar{\Theta}_k \): User-defined conservation goal for the area of habitat types above which marginal value is zero,

\( \Lambda_i^l \): Percentage of CWA of landscape \( l \) at time \( t \),

\( \lambda_i^l \): Contribution of site \( i \) to \( \Lambda_i^l \),

\( \Lambda_i \): User-defined minimum percentage of landscapes below which there is constant marginal utility from new conservation and above which marginal utility diminishes with each increment of conservation,

\( \bar{\Lambda}_i \): User-defined conservation goal for the percentage of landscapes above which marginal value is zero,

\( \Pi_w \): CWA of wildland block \( w \) at time \( t \),

\( \Pi_{iw} \): Contribution of site \( i \) to \( \Pi_w \),

\( \Pi \): User-defined minimum area of wildland blocks below which there is constant marginal utility from new conservation and above which marginal utility diminishes with each increment of conservation,

\( \bar{\Pi} \): User-defined conservation goal for the area of wildland blocks above which marginal value is zero,

\( A_v \): Area of protected area \( v \),

\( d_{o,v} \): Distance between observation unit \( o \) and protected area \( v \),

\( D_o \): Distance-weighted species contribution from observation unit \( o \) to all protected areas.

\( M_{i,1} \): Value of site \( i \) towards RTE species objective (objective 1)

\( M_{i,2} \): Value of site \( i \) towards habitat type objective (objective 2)

\( M_{i,3} \): Value of site \( i \) towards landscapes objective (objective 3)
\( M_{i,4} \): Value of site \( i \) towards wildland block objective (objective 4)

\( M_{i,5} \): Value of site \( i \) towards protected areas objective (objective 5)

\( \Delta_i \): Utility value of site \( i \) towards all objectives

\( Cost_i \): Cost of conserving site \( i \) (product of available area * cost per unit area in site \( i \))