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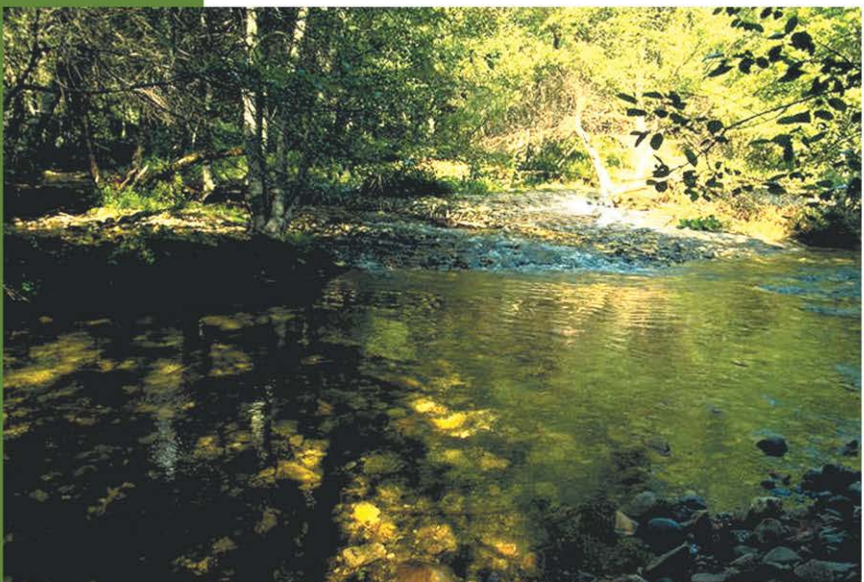
Pacific Southwest Research Station
General Technical Report

Proceedings of a Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status

January 26, 1998 **Clovis, California**



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Abstract

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Over the past couple of decades, the challenge of crafting guidelines for managing public lands in the Sierra Nevada has been hampered by a lack of credible information on many important questions. In particular, these involve timber harvest; threats of increasing intensity and extent of wildfires resulting from the heavy accumulations of surface and ladder fuels in forests of the Sierra Nevada; the use of prescribed burning to reduce fuel accumulations; the potential of management actions to lead certain native species of wildlife toward Federal listing as threatened or endangered; and the growing impacts of residential developments adjacent to public forests. The Kings River Sustainable Forest Ecosystem Project is a joint undertaking of the Sierra National Forest, the Pacific Southwest Region of the USDA Forest Service, and the Pacific Southwest Research Station to study the impacts of timber harvest and prescribed fire on many components and processes of conifer forests in a 64,000-acre study area on the Kings River District of the Sierra National Forest. The project was initiated in 1994 and is intended to continue for many years—even decades. This document, therefore, reports only the initial efforts of this project. On the management side, papers included here present methods and results of landscape-level planning, timber harvest, prescribed burning, historic fire intervals, and riparian assessments. Reports from research involve the effects of timber harvest and prescribed burning on forest ecosystem processes, soils, hypogeous fungi, spotted owls, songbirds, small mammals, and fishers.

Retrieval Terms: fisher, forest management, hypogeous fungi, prescribed burning, riparian resources, Sierra Nevada, small mammals, soils, songbirds, spotted owl.

Technical Editor

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English-to-metric conversions:

1 inch	=	2.540	centimeters
1 foot	=	0.305	meter
1 square foot	=	0.093	square meter
1 acre	=	0.405	hectare
1 mile	=	1.609	kilometers
1 square mile	=	2.590	square kilometers
1 ounce	=	28.350	grams
1 pound	=	0.454	kilogram
1 quart	=	0.946	liter

Metric-to-English conversions:

1 centimeter	=	0.394	inch
1 meter	=	3.281	feet
1 square meter	=	10.764	square feet
1 hectare	=	2.471	acres
1 kilometer	=	0.621	mile
1 square kilometer	=	0.386	square mile
1 gram	=	0.035	ounce
1 kilogram	=	2.205	pounds
1 liter	=	1.057	quarts

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Contents

Preface

Ecosystem management aligns different uses of the land with ecological parameters and goals of environmental quality. An important USDA Forest Service mission is to balance the multiple uses of its lands in an ecologically sustainable way. This objective has been particularly challenging for National Forests of the Sierra Nevada in the face of heated controversies over the effects of even-aged timber harvest on old-growth forests and their associated wildlife, such as the California spotted owl (*Strix occidentalis occidentalis*). Much of the concern stems from loss of habitat attributes—closed-canopied stands, very old trees, large snags and downed wood, and multiple structural layers—believed to be needed by the owl and other wildlife species. Several of these attributes are also believed to be vital for sustaining healthy, productive forests.

The Kings River Sustainable Forest Ecosystems Project involves a formal administrative study and associated research, with joint leadership and collaboration among line officers and staff of the Sierra National Forest, the Kings River Ranger District, and the Pacific Southwest Research Station (PSW). District personnel are implementing two landscape-level management options, at watershed scales, while researchers study the effects of those options on various forest resources and values. Persons involved with the project are optimistic that both options, with minimal "zonation" for special needs, will sustain all key resources (soil, water, vegetation, and wildlife) and functions of the ecosystems involved, while reducing risks of catastrophic fire, restoring fire as a forest ecosystem process, promoting forest health, allowing sustainable levels of commodity extraction, and supporting recreational use by the public.

On January 13, 1993, the Forest Service's Pacific Southwest Region released the Decision Notice for an Environmental Assessment (EA) that provided interim guidelines largely driven by concerns for the California spotted owl. Effective March 1, 1993, this EA amended the Land and Resource Management Plans for all National Forests of the Sierra Nevada that have spotted owls, markedly changing options for forest management in these National Forests for an interim period of 2 years, not only for the owl but also for many other resources and values as well. In response to this new direction, and with encouragement from the Pacific Southwest Region to initiate an administrative study in ecosystem management, a small group of managers and scientists from the Sierra National Forest and the Pacific Southwest Research Station's Forestry Sciences Laboratory in Fresno, California, met in mid-February, 1993, to discuss opportunities. A coordinating group with members from the Forest, the District, and laboratory was formed after this meeting. This group continued to meet over the next few weeks and soon agreed on the basic features of a study plan that eventually developed into the Kings River Sustainable Forest Ecosystems Project.

Objectives of the Project include implementation of timber harvest that will maintain key attributes of late successional forest, provide for wildlife species that are closely associated with them, and deal with the growing threats of extensive and intensive wildfires as a result of heavy accumulations of surface and ladder fuels during the past century. Planning for the Project focused on a study area encompassing 64,000 acres and two major watersheds on the Kings River District of the Sierra National Forest. A prescribed burning program was already underway in the project area; and a demographic study of the spotted owl, begun in 1990, already encompassed most of the area. The scope of this owl study was enlarged in 1994 to cover the entire project area. Other studies were initiated in 1994 and 1995, and the first vegetation treatments were initiated in 1997. Results of these efforts are beginning to come in.

These proceedings comprise an interim report on the various management actions and research studies underway in the project area. Some projects and studies have been completed, some are still in progress, and others have yet to begin. The paper by Verner and Smith provides an overview of the inception, objectives, and progress of the overall project; and Fleenor's paper describes the development of the Landscape Analysis Plan required to undertake the project. The plan and current updates can be viewed on the internet at www.r5.fs.fed.us/sierra/kras. Progress and lessons learned in the implementation of an uneven-aged strategy for forest management are described by Smith and Exline, and McCandliss reports on methods and progress in the program of prescribed burning. By September of 2001, prescribed fire had been applied to approximately 15,000 acres in the project area, including some Protected Activity Centers of the California spotted owl. Data on historic fire-return intervals within the project area are presented in the report by Phillips, and Gallegos reports on watershed analyses.

The paper by Powers details the effects of certain management activities on soil properties. Findings accumulating through this study may lead to improved soil-based standards of sustainable forestry. An experiment involving innovative methods of fuel reduction was established in 2000 as part of planned fuel break operations in mixed-conifer sawtimber on the Sierra National Forest near Shaver Lake. The aim is to evaluate alternative methods of reducing understory fuels on soil properties and the organic carbon cycle. Treatments range from a "do-nothing" control, through mechanical mastication, to incorporating masticated residues into surface soil. Experience from this helped to secure competitive grant funding to extend this study to a broader geographic base at the forest/urban interface. Two new installations have been established in northern California on Federal and private holdings, and more are planned for 2002.

The Teakettle Experiment (http://teakettle.ucdavis.edu) described by North is particularly complex and involves a rigorous experimental design. All thinning treatments were completed by August, 200l, and the prescribed burn was completed in November of 2001. All of the Teakettle studies have collected 2-3 years of pretreatment data at mapped sample points, and researchers began collecting response data in May, 2002, at these sample points to assess immediate effects of fire and thinning treatments on different ecosystem functions. The Experiment now includes 27 studies, 17 institutions, and funding from 20 different sources. Some of the new studies include the use of isotope ecology to investigate water and nutrient transfer between shrubs and trees, ground-piercing radar to investigate the influence of soil depth on vegetation composition, modeling of ecosystem energy and mass flow with water- and shade-manipulation experiments, and establishing Teakettle as a demonstration site and community outreach for information on fire and thinning efforts to reduce fuels. Several of the associated doctoral students are completing their projects, and new students and research projects have joined the experiment.

Hypogeous (underground) fungi play a key role in the establishment, nutrient uptake, and water uptake of trees in forest ecosystems. Fundamental research on their abundance and species composition, and response to fire, is described in North's paper on truffles and the paper by Bruns and his coauthors.

Three reports—by Munton and others, Steger and others, and North—describe results of various aspects of the general biology, ecology, and demography of the California spotted owl. The demographic work and studies of owl diets are continuing, with conclusions about the status of the owl population in the study area through 2001 essentially unchanged from those described here in the paper by Steger and others.

Purcell describes results of a labor-intensive study of forest songbirds in ponderosa pine (*Pinus ponderosa*), mixed-conifer, red fir (*Abies magnifica*), and lodgepole pine (*Pinus contorta*) forests. With additional years of data since the symposium, some results of this study have changed, possibly related, at least in part, to annual variation in weather.

The paper by Laudenslayer and Fargo describes a study of small mammal populations and ecology in the project area, and Boroski and others report on research on the fishers (*Martes pennanti*). The fisher population in the study area is especially important, as apparently this medium-sized furbearer has been extirpated from the Sierra Nevada north of Yosemite National Park. Although Dr. Boroski has left the USDA Forest Service, the fisher research is continuing under the direction of Dr. Kathryn Purcell.

Two key studies have been added to the Kings River Project since the symposium: the first involving the use of new development in remote sensing of vegetation, and the second involving an intended long-term study of the effects of forest management actions on stream ecosystems.

A collaborative study, "Forest Structure from Remotely Sensed Imagery," by Dr. Carolyn Hunsaker of the Pacific Southwest Research Station, Dr. JoAnn Fites of Adaptive Management Services in Nevada City, California, and scientists from the University of Michigan, the University of Maryland, and the National Aeronautics and Space Administration (NASA) began with a planning workshop in 1998. Key initial objectives include compiling structural attributes desired by ecologists and proposing actions needed to more effectively measure forest structural attributes across the entire Sierra Nevada. NASA committed to obtain radar and lidar (laser altimetry) data with flights over the Kings River Project area, the Teakettle Experimental Forest, and field study sites in the northern Sierra Nevada. The remotely sensed data will be compared with ground data from 290 1-ha plots in the southern Sierra Nevada and 300 plots in the northern Sierra Nevada to allow calibration of remote-imagery classifiers. Attributes of interest include canopy cover, life-form diversity, large-tree density, tree size distribution, vertical diversity of tree crowns, biomass, crown volume, height to live crown, tree decadence, surface dead material, and moisture content. Development of map products is expected to begin in 2002.

In 2000, under the direction of Dr. Hunsaker of the station's Forestry Sciences Laboratory in Fresno, California, the Kings River Experimental Watershed was added to the Kings River Project to address issues regarding stream systems. This well-funded project is being developed to quantify the variability in attributes of stream ecosystems and their associated watersheds in the southern Sierra Nevada and to evaluate the effects of forest management (prescribed fire and uneven-aged, small-group tree selection) on those ecosystems. Instrumentation of the eight headwater watersheds, in mixed-conifer forest at 5,000 and 7,000 feet in elevation, will be completed by 2002. The study will investigate physical attributes (upland erosion, stream flow, channel characteristics, and weather conditions), chemical characteristics (nutrients, chloride, sulfate, calcium, magnesium, potassium, sodium, pH, electrical conductivity, and acid neutralizing capacity), and biological features (stream invertebrates and possibly algae, along with some riparian and upland vegetation).

The vision of the original coordinating group for the Kings River Sustainable Forest Ecosystems Project was open-ended. Members of the group knew that the process of converting the existing, highly modified forest into an uneven-aged structure by a process of small-group selection would take many years. They also knew that studies of the effects of this conversion on certain ecosystem values and processes, on spotted owls, on fishers, and on certain other resources would take years—even decades. This will require much effort and vigilance to maintain a strong commitment by the USDA Forest Service to continue this project, to maintain adequate funding, and to assure that dedicated personnel are continuously in place.

The Kings River Sustainable Forest Ecosystems Project: Inception, Objectives, and Progress[1]

Jared Verner[2] and Mark T. Smith[3]

Abstract

The Kings River Sustainable Forest Ecosystems Project, a formal administrative study involving extensive and intensive collaboration between Forest Service managers and researchers, is a response to changes in the agency's orientation in favor of ecosystem approaches and to recent concern over issues associated with maintenance of late successional forest attributes and species that are closely associated with them, such as the California spotted owl (*Strix occidentalis occidentalis*). Planning for the project began in mid-February, 1993. A prescribed burning program was already underway in the project area then, and the first vegetation treatments were initiated in 1997. Two additional projects involving treatment of vegetation are nearing implementation. A demographic study of the spotted owl, begun in 1990, already encompassed most of the project area, and it was enlarged in 1994 to cover the entire area. Other research projects were initiated in 1994 and 1995, and results of those are beginning to come in. An appendix lists 77 technical papers, abstracts, theses, and dissertations that were completed through 1999, based on work associated with the project, and one extensive database on the distribution and habitat associations of California's plant species, which is now available on the Internet.

Ecosystem management aligns different uses of the land with ecological parameters and goals of environmental quality. An important USDA Forest Service mission is to balance the multiple uses of its lands in an ecologically sustainable way. This challenge has been significant for National Forests of the Sierra Nevada, especially with controversies over the effects of even-aged timber harvest on old-growth forests and their associated wildlife, such as California spotted owls. Much of the concern stems from loss of habitat attributes—closed-canopied stands, very old trees, large snags and downed wood, and multiple structural layers—believed to be needed by the owl and other wildlife species. Several of these attributes are also believed to be vital for sustaining healthy, productive forests.

The Kings River Sustainable Forest Ecosystems Project involves a formal administrative study and associated research, with joint leadership and collaboration among line officers and staff of the Sierra National Forest, the Kings River Ranger District, and the Pacific Southwest Research Station (PSW). District personnel are implementing two landscape-level management options, at watershed scales, while researchers study the effects of those options on various forest resources and values. Persons involved with the project are optimistic that both options, with minimal "zonation" for special needs, will sustain all key resources (soil, water, vegetation, and wildlife) and functions of

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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the ecosystems involved, while reducing risks of catastrophic fire, restoring fire as a forest ecosystem process, promoting forest health, allowing sustainable levels of commodity extraction, and supporting recreational use by the public.

Inception of the Project

On January 13, 1993, Ronald E. Stewart, Regional Forester of the Forest Service's Pacific Southwest Region, released the decision notice for an Environmental Assessment (USDA 1993) that provided interim guidelines for the California spotted owl, amending the Land and Resource Management Plans for all National Forests of the Sierra Nevada that have spotted owls. Better known as the CASPO EA (California Spotted Owl Environmental Assessment), this document markedly changed options for timber management in National Forests of the Sierra Nevada for an interim period of 2 years, effective on March 1, 1993, while longer-term plans were to be developed through a new Environmental Impact Statement covering those National Forests. It was evident from the EA that new directions were needed for managing National Forest lands in the Sierra Nevada, not just for the owl but for many other resources and values as well. In response to this new situation, and with encouragement from the Pacific Southwest Region to initiate an administrative study in ecosystem management, a small group of scientists and managers from the Sierra National Forest and PSW's Forestry Sciences Laboratory in Fresno met in mid-February, 1993, to discuss options. A coordinating group with members from the forest, the district, and PSW was formed after this meeting. This group continued to meet over the next few weeks and soon agreed on the basic features of a study plan that eventually developed into the current project.

The District has dedicated to the project two adjacent watersheds—Big Creek and Dinkey Creek—each of about 32,000 acres (*fig. 1*). The selection of these watersheds was based on their accessibility; their similarity in size; and the fact that a demographic study of the California spotted owl, begun in 1990, encompassed most of the project area. Forests in the Big Creek watershed are

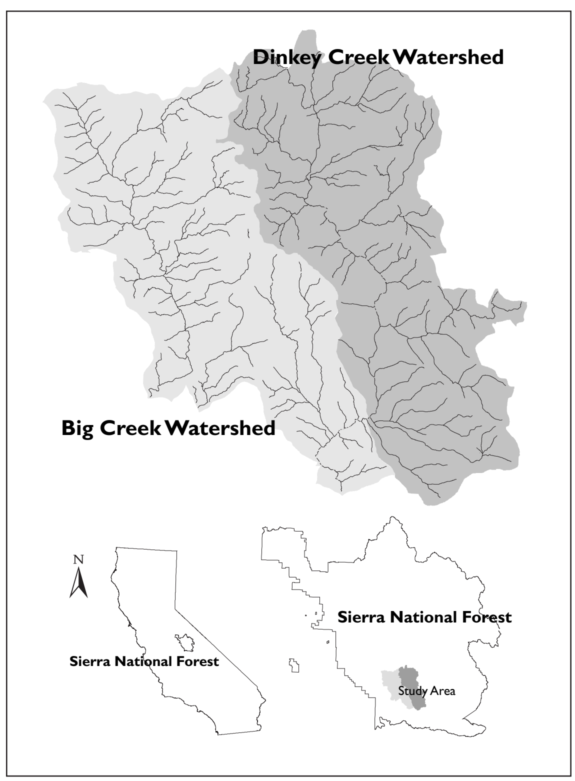

Figure 1—The Kings River administrative study area in the Sierra National Forest in central California includes the 64,000-acre Big Creek and Dinkey Creek watersheds (indicated by shading).

dominated by ponderosa pine (*Pinus ponderosa*) forest, with a small component of mixed-conifer type. Shrubs, attributable in part to natural land potential and in part to past logging and fire history, dominate much of the landscape. Proposed management in this watershed emphasizes uneven-aged, small-group selection with a 200-year rotation. An expected benefit of this strategy is reduction in the reliance on zoning to meet various resource needs and public values. Riparian values, however, will be maintained by zone-specific standards and guidelines, but the final strategy there is open to adaptation as the current debate within the Sierra Nevada Conservation Framework may point to an approach that would benefit from applied research. Fuel reduction treatments will be situated strategically to reduce the likelihood of wildfires spreading up the canyon into the community of Shaver Lake.

The Dinkey Creek watershed is dominated by mixed-conifer forests with a small component of ponderosa pine forest, and influences of past logging and fire are less extensive there than in the Big Creek watershed. The management emphasis for Dinkey Creek is to develop a three-tiered landscape with different objectives in each—a late-seral riparian area with infrequent fire and little or no timber harvest and an emphasis on habitat maintenance and/or restoration (about 20 percent of the watershed); a mid-slope transition area (about 50 percent of the watershed) with forest cover averaging at least 40 percent crown closure; and an upper-slope/ridge-top area (about 30 percent of the watershed) managed by thinning and prescribed burning to create fuelbreaks in the form of open, park-like forests of evenly spaced trees and canopy closure of about 40 percent. The management strategy for the mid-slope transition area is still pending, with approaches like uneven-aged, single-tree selection or perpetuation of a two-layered forest structure under active consideration. The Dinkey Creek watershed includes an existing furbearer management area, established in 1992 by the Sierra National Forest's Land and Resource Management Plan, which will influence the choice of an approach for sustaining the forest.

In spite of the substantial commitments of time and funding by all participating entities, it was clear from the beginning that available funds would substantially limit both the management and research activities needed to generate a worthwhile administrative study. Coincidentally, the Forest Service proposed for fiscal year 1994 a special appropriation for ecosystem research and, in March of 1993, the Washington Office issued a request for proposals from all research stations to compete for these funds, assuming that Congress would allocate them. PSW submitted a successful proposal, based on the study design developed by the coordinating group, and Congress did pass the special appropriation for ecosystem research. The result was a near doubling of PSW's operating budget available to support research in the project area. This additional funding was renewed each year through fiscal year 1998. Beginning with fiscal year 1999, it was added to the base funding for PSW's laboratory in Fresno, which provided secure funding for this research, at least for several years.

At about the same time, the Pacific Southwest Region requested proposals from all National Forests in the Sierra Nevada for support of projects in ecosystem management. Again, based on the study design being developed for the Kings River Project, the Sierra National Forest submitted a successful proposal to the Regional Office for funds to offset administrative costs of implementing its part of the collaborative study. Since that time, the forest has been successful in its yearly request for this additional funding.

Objectives

General Objectives

A primary goal of the project is to maintain nearly continuous forest cover with significant numbers of older trees, large snags, and large logs well-distributed throughout both watersheds, while restoring fire to its former role as a dominant process in these ecosystems. A second general objective, though without the rigor of classical adaptive management, is to learn something through research and monitoring from every management action. Implementing the landscape-level silvicultural treatments, with accompanying research into the effects of those treatments on various ecosystem components and functions, provides an inherent feedback system. Results from studies can be applied in the next round of management planning, leading to modifications more likely to result in desired future conditions. Thus, the two processes advance together, each complementing the other.

Specific Objectives

Specific objectives of the project include:

- Determining the feasibility of applying small-group selection as a landscape-level silvicultural treatment in ponderosa pine and mixed-conifer forests of the western Sierra Nevada of California, following the planning and implementation procedures of a typical Forest Service Ranger District.
- Comparing two promising, landscape-level alternatives for multi-objective management to ensure long-term maintenance of California spotted owls, while retaining all other resource values, improving forest health, and developing a sustainable level of land productivity.
- Determining interrelations of various forest components and their responses to small-group selection harvests and to a three-tiered forest landscape treatment of watersheds.
- Evaluating effects of these alternate strategies on multiple forest components, wildlife species, biodiversity in general, ecosystem functions, soil/plant processes needed to sustain long-term forest productivity, and on plant species likely to become locally rare.
- Demonstrating the use of distributional data sources and geographic information systems (GIS) to identify concerns about critical plant biodiversity at the landscape level.

Progress

Management

The Kings River District has established a core interdisciplinary (ID) team that includes a planner, a forester, a biologist, and a GIS specialist to develop a Landscape Analysis Plan consistent with the existing Land Management Plan for the Sierra National Forest. Other specialists are engaged in this process as needed. In 1997, the ID team released a draft Landscape Analysis Plan for review and comment, and the plan is currently in revision based on comments received. The draft plan proposed desired future conditions for both watersheds and delineated mechanisms for using feedback from implementation of the two strategies to gauge progress toward desired future conditions. To better understand effects of the treatments on various forest resources, the district is collecting data on existing vegetation (both live and dead), comparing two approaches to watershed analysis, chronicling past fire history in each watershed, and monitoring the effects of prescribed burning.

GIS mapping layers are now in place for a variety of general elements (topoquads, CALWATERSHEDS [as designated by the California Interagency Watershed Mapping Committee], soils, roads, streams, vegetation, and fire history) and special features (Ecologic Unit Inventory study plots; District vegetation sampling plots; Protected Activity Centers for California spotted owls; spotted owl nest tree locations; forest bird study plots; deer holding areas, migration routes, and winter ranges; and furbearer management zones). Other layers are being developed. These electronic files are essential for efficient evaluation of the effects of projects and for effective cumulative effects analyses over the full project area.

To date, progress is underway on three projects in both watersheds, using timber sales, prescribed fires, and mastication of shrubs and small trees to accomplish the work. In Dinkey Creek, the Indian Rock Upper Tier Project is under contract, but harvesting has not yet occurred. In the Big Creek watershed, the Bear Meadow project is currently in an advanced stage of planning, and the first stage of the 10S18 Fuel Reduction Project has been completed by using an uneven-aged, small-group selection strategy. This involved removal of commercial timber and treated approximately 1,000 acres near the upper end of the watershed. The project included extensive commercial thinnings to accentuate the existing uneven-aged structure and a large “defensible fuel-profile zone,” essentially a shaded fuel break intended to alter the behavior of wildfire moving up the canyon from below in a way that would facilitate suppression efforts. The second stage of this project—mastication of the remaining surface fuels and standing small trees that contribute to fuel ladders—began in 1998; the first 200 acres is scheduled for completion in 1999. The final stage of this project, prescribed burning of residual fuels, will occur during the year after mastication. Substantial progress has been made with prescribed burning—a total of about 7,000 acres burned to date. More details of this activity, the uneven-aged management strategy, and project planning are covered in other chapters of this volume.

Research

The project allows scientists to work closely with professionals on the Forest and District and to foster directly the application of current scientific information for developing ecologically based management strategies, maximizing the public’s investment in science, and adapting management to current information. Because the number, scope, and intensity of studies underway in the project area are limited by available funding, not all topics fundamental to a project in ecosystem research are presently under investigation. We present only a brief overview because details of the various studies form the basis of other chapters in this volume.

The largest study involves the demography of California spotted owls in the project area and in an additional 100,000 acres surrounding the 64,000-acre project area. As a further control, a demographic study of spotted owls is underway in Sequoia/Kings Canyon National Parks in unharvested forests of the same types found in the project area. These studies were initiated in 1990 and include annual efforts to locate and color band (for individual recognition in the field) all spotted owls within boundaries of the study areas. In addition, diets of the owls are sampled annually by collection and analysis of pellets (aggregations of bones, fur, feathers, etc. of captured prey, which are periodically regurgitated by the owls and can be collected from the ground beneath their roosts and nests). Productivity of the owls in relation to forest stand structure and composition, and to precipitation and temperature, are under investigation.

Other studies are investigating the abundance, nest success, and productivity of all species of forest birds; ecology and population status of small mammals; ecological relations of below-ground fungi (truffles); plant species diversity in relation to stand treatments; effects of treatments on soil structure and productivity; and distribution and relative abundance of martens and fishers. Plans are underway to initiate studies of aquatic ecology in the project area.

Coordination

The collaborative nature of the project, and the shared leadership between Forest Service research and management branches, has required continual dialogue among all parties. To facilitate this activity, representatives of the Sierra National Forest, the District's ID team and District Ranger, and one or more scientists from PSW's Forestry Sciences Laboratory in Fresno have bimonthly coordination meetings. In addition, we meet in the intervening months for "brown bag lunch" sessions with the same group and any others from these administrative units who wish to participate. These meetings have proven to be invaluable and may be a primary reason why the project has run so smoothly.

Public Involvement

Some members of the public have taken an active interest in the project and participate regularly in field trips, comment on project plans, suggest alternate management scenarios, and in other ways contribute significantly and positively to the planning and implementation of the project. In addition to the usual procedure of soliciting public comments on planning documents, we have actively sought public input through direct experience with the project area via field trips during periods when weather and road conditions permit. The first of these occurred on August 4, 1994. Since then, we have hosted 23 additional field trips involving congressional staffers; academicians; representatives from the timber industry and the environmental community; scientists with specialties in forestry, botany, wildlife biology, fire and fuels, silviculture, atmospheric pollution, hydrology, soils, and others; top line and staff officers from the Forest Service's Pacific Southwest Region and PSW; interested citizens; and even a reporter from the *Fresno Bee*, which resulted in a complimentary article in the 1 December 1997 issue of the *Bee*.

Technology Transfer

The application of new information to management planning and applications is typically a slow process. In the present case, however, relevant new information can be shared immediately among members of the team, undergo scrutiny and discussion, and be evaluated in relation to our existing plans. This is the starting point for adaptive management. Plans typically identify desired future conditions and set forth procedures for attaining those conditions. If implementation of the plans fails to produce the desired conditions, feedback of that information into later planning should result in adapting management accordingly in the hope of doing a better job the next time. In the beginning, we anticipated a marked lag between implementation of a project and any realization that we might do it better, and in what ways. Certainly this will be true for much of what we learn during the life of this project. On the other hand, we've come to realize that the field trips—when various specialists have an opportunity to walk through and directly assimilate the results of a project in relation to their special knowledge—generate lively discussions and a surprising number of concerns, insights, and constructive suggestions. Already, initial visions have undergone some changes, even without results from formal studies. These have involved such items as crown volume as a structural attribute of forests important for various wildlife species, implications of different methods for estimating canopy cover, and ways to sustain some number of trees that can become very old and decadent and eventually die as a result of some natural agent.

Even though most of the project's studies are relatively young, several technical papers have reported on results (*appendix A*), and several talks have been presented at workshops, symposia, and meetings of professional societies. The small group of persons who initially proposed the Kings River Sustainable Forest Ecosystems Project, in mid-February of 1993, envisioned a very long-term effort to get answers to some of the critical questions—on the order of 50 to 100 years! Obviously, this will outlive most or all persons presently engaged. The longer the project survives, however, the more likely it is to produce important, and unequivocal, findings. We believe this is a role that the Forest Service can serve, probably better than any other entity. This agency not only manages an extraordinarily large landbase but also has the potential to sustain individual projects well beyond the lifespan of any one person. As we move forward with an emphasis on ecosystem management and ecosystem research, the Forest Service might profitably emphasize its truly unique position to carry on large-scale, long-term projects and studies. Finally, we re-emphasize the experimental nature of the Kings River Project. It is envisioned as continuing for decades, and its directions are expected to change with time as we learn from studies along the way. The work is intentionally manipulative so that responses can be gauged and new directions crafted accordingly, in the spirit of adaptive management.

Acknowledgments

We have benefited from review comments on a draft of the manuscript by Ray Porter, Bill Laudenslayer, and Nancy Fleenor.

Reference

USDA (U.S. Department of Agriculture). 1993. **California spotted owl: Sierran Province interim guidelines. Environmental assessment.** USDA Forest Service, Pacific Southwest Region. Washington, DC: U.S. Government Printing Office; 272 p.

Appendix A

This appendix lists products resulting from research associated with the Kings River Sustainable Forest Ecosystems Project. This list is current through 1999, with citations updated for "In press" papers that were published by the end of 2001.

Publications, Papers In Press, and Papers Submitted

Bidartondo, M. I.; Kretzer, A. M.; Pine, E. M.; Bruns, T. D. [In press]. **High root concentration and uneven ectomycorrhizal diversity near *Sarcodes sanguinea* (Ericaceae): a cheater that stimulates its victims?** American Journal of Botany.

Boyle, J. R., Powers, R. F. 2000. **Editorial: forest soils and ecosystem sustainability.** Forest Ecology and Management 138:1.

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A Landscape Analysis Plan[1]

Nancy E. Fleenor[2]

Abstract

A Landscape Analysis Plan (LAP) sets out broad guidelines for project development within boundaries of the Kings River Sustainable Forest Ecosystems Project. The plan must be a dynamic, living document, subject to change as new information arises over the course of this very long-term project (several decades). Two watersheds, each of 32,000 acres, were dedicated to the effort by the Kings River Ranger District of the Sierra National Forest. Several documents were used to prepare a draft LAP in 1995. Although the plan lays out general guidelines for managing both watersheds, all land and forest treatments implemented under the LAP still require preparation of appropriate documents under the National Environmental Policy Act, which are open to public comment and appeal. Adaptive management is an overriding concept, with the basic intent being to learn from all individual projects and to adjust management directions accordingly. The existing draft LAP is presently under revision in response to new information from numerous discussions during field tours, new science presented in a report to Congress from the Sierra Nevada Ecosystem Project, and new science and management guidelines being developed by the Sierra Nevada Conservation Framework (an effort to produce an Environmental Impact Statement to guide the management of 11 National Forests in the Sierra Nevada).

Why a Landscape Analysis Plan?

A Landscape Analysis Plan (LAP) forms a link between national forest plans prepared under the National Forest Management Act (NFMA) of 1976 and specific projects that implement those plans in compliance with the National Environmental Policy Act (NEPA) of 1969. It has developed in response to the USDA Forest Service's reorientation to ecosystem management, under direction from Jack Ward Thomas, former Chief of the Forest Service. The Sierra National Forest instituted LAPs as a step to provide assessments at a landscape scale, tiering off the Pacific Southwest Region's (Region 5's) definition of a landscape as "An area of interacting ecosystems where patterns are repeated because of geology, landform, soils, climate, biota, and human influences throughout the area. The size, shape, and patterns of landscapes are determined by interacting ecosystems" (Manley and others 1995: p. 206). The LAP pertains to a land area considerably smaller than that of the National Forest but considerably larger than that of an individual project. As such, it can provide "A planning schedule that documents existing conditions, desired conditions, and projects that will achieve desired conditions" within boundaries of the defined landscape (Manley and others 1995, p. 206).

In developing the LAP, we have solicited comments from within the Forest Service and from the public. In the case of the Kings River Sustainable Forest

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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Ecosystems Project, it serves as a guide for project development. Its main objectives are:

- To blend social, physical, economic, and biological needs through ecosystem analysis and public collaboration to assure productive and healthy forest ecosystems.
- To understand forest landscapes as ecological systems.
- To assure consideration of the implications of our actions in terms of those ecological systems.
- To interpret the Sierra National Forest's Land and Resource Management Plan (LRMP) (USDA 1992) by documenting our collective vision of the desired condition of the landscape and to help communicate it to others.
- To guide us in meeting the objectives of the LRMP.

Because several decades will be needed to attain the desired condition of the watersheds in the project and some effects will be evident sooner than others, the LAP must be a living document. It will be adapted and amended as new information emerges, based on its application in the field.

Development of the Landscape Analysis Plan

Soon after the Kings River Sustainable Forest Ecosystems Project received support from the Forest Service's Region 5 and Pacific Southwest Research Station, and was formally approved by the Supervisor of the Sierra National Forest, the Kings River Ranger District established an Interdisciplinary Team of specialists—team leader, silviculturist, wildlife biologist, hydrologist, soil scientist, heritage resource specialist, recreation specialist, and fire/fuels specialist—with the task of preparing a LAP for the project area. Two major watersheds are included: Dinkey Creek, about 32,000 acres, and Big Creek, also about 32,000 acres (*fig. 1*). A draft LAP was completed in 1995, following guidelines in Region 5's draft "Ecosystem Management Guidebook," later completed under a new title (Manley and others 1995). This guidebook was our primary source for developing the LAP. The Plan had to be consistent with desired conditions for the Sierra National Forest, as described in the Forest's LRMP (USDA 1992) and as amended by the California Spotted Owl Environmental Assessment (USDA 1993) and the Standards and Guides for Grazing (USDA 1995a). Finally, input from other specialists in range, geology, fisheries, landscape architecture, botany, engineering (transportation and logging), pathology, and entomology contributed to the analysis effort on an as-needed basis, and comments were solicited from the public and from scientists at the Pacific Southwest Research Station's laboratory in Fresno.

In addition, the Interdisciplinary Team followed a process developed for watershed analysis in the Forest Service's Pacific Northwest Region (Region 6), under the President's Pacific Northwest Plan. This prescribes the following, eight-step process (Furniss and McCammon 1993):

- Identify issues, describe desired conditions, and formulate key questions.
- Identify key processes, functions, and conditions.
- Stratify the watershed.
- Assemble analytical information needed to address the key questions.
- Describe past and current conditions.
- Describe condition trends and predict effects of future land management.
- Interpret, integrate, and present findings.
- Manage information, monitor, and revise strategies (adaptive management).

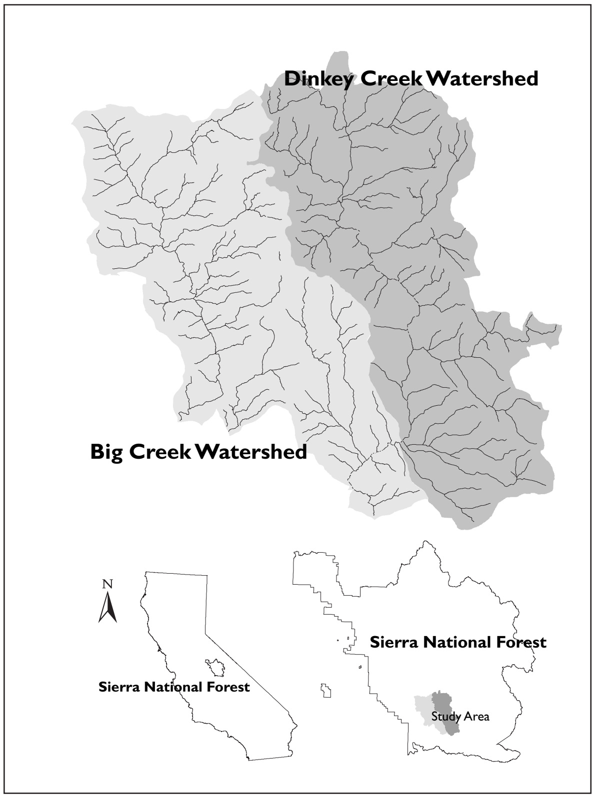

Figure 1—The Kings River administrative study area in the Sierra National Forest in central California includes the 64,000-acre Big Creek and Dinkey Creek watersheds (indicated by shading).

To attain desired conditions, the Sierra National Forest's LRMP relies heavily on zoning to allocate lands among competing resource objectives and even-aged forest management prescriptions. The two forest management systems proposed for study in the Kings River Project, however, reduce reliance on forest zoning, emphasize attainment of multi-resource objectives on more homogeneous areas in each watershed, and rely heavily on the uneven-aged management system to program vegetation treatments. Additional guidance and concepts for this approach were taken from Chapel (1990), Chapel and others (1992), Fiske and others (1993), and USDA (1994).

Although the plan lays out general guidelines for managing both watersheds (Verner and Smith, in this volume) and includes "A Landscape Management Implementation Schedule," all land and forest treatments implemented under the LAP still require the preparation of appropriate NEPA documents (Biological Evaluations, Biological Assessments, and Environmental Assessments or Environmental Impact Statements). These, of course, require full public disclosure and opportunities for public comment and appeal.

Adaptive management is an overriding concept for the Kings River Project. The basic intent, of course, is to learn from all individual projects and to adjust management directions accordingly. This is accomplished through continual interaction among management personnel of the Sierra National Forest, the Kings River Ranger District, and scientists from the Pacific Southwest Research Station's laboratory in Fresno. Scientists are studying various components and functions of the affected forest ecosystems (Verner and Smith, in this volume) to gain an understanding of the effects of treatments over the long-term (10-50 years). In addition, to discuss results to date, all of these personnel, together with members of the interested public and scientists and managers from other entities, annually participate in several field tours to treatment areas within the two watersheds. These sessions have proven to be extremely productive for the sharing of ideas and evaluating results of forest management activities intended to attain desired conditions for various resources—watersheds, forest health, wildlife habitat, fuel loading, and others. Field tours of the first two uneven-aged projects, for example, raised concerns among scientists and members of the public about tree size-class distributions and vertical diversity of the tree canopy resulting from the first applications of small-group selection (Smith and Exline, in this volume). This led to some thinking about the silvicultural prescriptions applied in the first projects and is expected to result in some revision and a different approach for some future projects. In effect, then, "adaptive management" of some sort is occurring on the ground, as we move forward.

The Current Situation

A primary objective of the LAP is that forest management in the Kings River Project area will remain dynamic as forest managers, scientists, and the public learn how to better sustain forest ecosystems. As new information comes in from the several research projects underway in the Project area (Verner and Smith, in this volume), it can be incorporated quickly into subsequent forest treatment projects. The draft LAP (USDA 1995b) is now under revision to incorporate such sources of new information. This includes input from the numerous discussions during field tours, new science presented in the report to Congress from the Sierra Nevada Ecosystem Project (SNEP 1996a, b, c, and d), and new science and management guidelines being developed by the Sierra Nevada Conservation Framework (the current effort to produce an Environmental Impact Statement to guide management of 11 National Forests in the Sierra Nevada).

Partnerships and Collaboration

The collaborative effort among researchers, interested citizens, tribal governments, forest managers, university partners, and industry representatives has developed into a synergistic approach for solving problems of natural resource management. The effort is intense and challenging as more species and ecological processes are recognized as being at risk, and the project is attracting more collaboration and partnerships.

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An Uneven-Aged Management Strategy: Lessons Learned[1]

Mark T. Smith[2] and John D. Exline[3]

Abstract

Use of an ecosystem approach at a landscape scale to program and guide accomplishments of multi-resource and social objectives has been discussed between researchers and natural resource managers for many years. Presently, great interest exists in the applicability of uneven-aged management practices for such an approach in conifer forests of the Sierra Nevada of California. The Kings River Sustainable Forest Ecosystems Project involves an administrative study by the Sierra National Forest and the Pacific Southwest Research Station that is providing an opportunity to implement and study uneven-aged management over a large landscape. The study was designed in part to answer questions about the effects and costs of implementing the group-selection form of uneven-aged management. With the implementation of several projects, some of these questions are beginning to be answered. We document some of the lessons learned, while implementing small group selections and thinning between those groups.

The Sierra National Forest Land and Resource Management Plan (LRMP) (USDA 1991), like most National Forest Plans, was based on three approaches: zoning to allocate land among competing resource objectives, primarily even-aged management, and a philosophy that the analysis and management of specific local sites would result in healthy ecosystems at a landscape scale. Since these plans were developed, some dramatic changes have occurred that eventually resulted in the current study (Verner and Smith, this volume).

Ronald E. Stewart, Regional Forester of the USDA Forest Service's Pacific Southwest Region (Region 5) from 1992 to 1994, addressed a challenge to even-aged management, especially clearcutting, by designating a committee to investigate uneven-aged group selection in the context of an ecosystem approach that would assure "continuous forest cover" and mimic the effects of small-scale, historical fires. In June 1992, Jack Ward Thomas, then Chief of the Forest Service, directed all National Forests to begin implementing ecosystem management at extensive landscape scales. Finally, in 1993 the LRMPs for all National Forests in the Sierra Nevada were amended to respond to new information about California spotted owls (*Strix occidentalis occidentalis*) (Verner and others 1992). Included in this direction was a provision for administrative studies designed to evaluate the effects of different forest management systems on owl habitat (USDA 1993).

One response to the direction for administrative studies is the 64,000-acre study area for the Kings River Sustainable Forest Ecosystems Project (*fig. 1*), located on the Kings River Ranger District of the Sierra National Forest, in the eastern portion of Fresno County, California. Vegetation types within the study area can be grouped into five categories: Chaparral, Ponderosa Pine (*Pinus ponderosa*), Mixed Conifer, Red Fir (*Abies magnifica*), and Jeffrey Pine

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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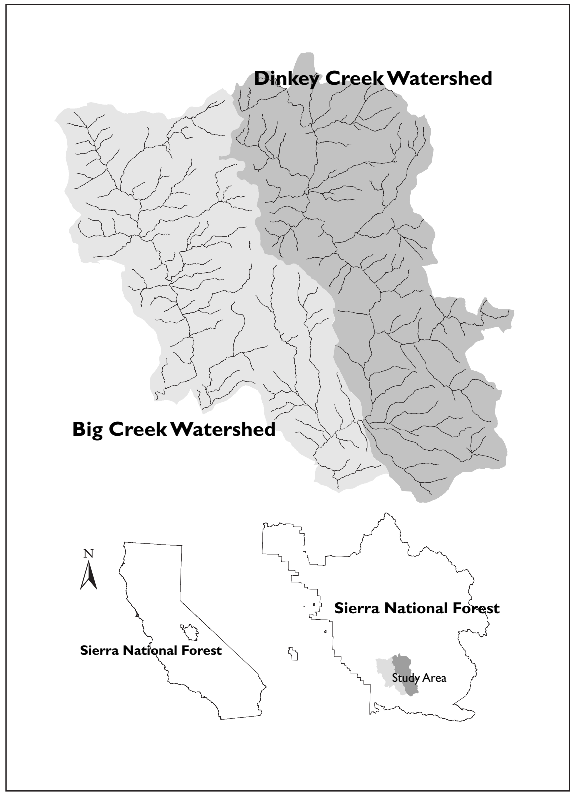

Figure 1—The Kings River administrative study area in the Sierra National Forest in central California includes the 64,000-acre Big Creek and Dinkey Creek watersheds (indicated by shading).

(*Pinus jeffreyi*) (USDA 1994). Elevations range from about 2,400 to 8,100 ft. Two large-scale projects—the 10S18 Fuels Reduction Project (10S18 FRP) and the Indian Rock Upper Tier Project (IROC)—have been implemented within the study area and are in different stages of completion. A third project—the Bear Meadow Basin Project—is still in the planning stage. The three projects cover approximately 8,000 acres of the 64,000-acre study area and fall within the Ponderosa Pine and Mixed-Conifer vegetation types. In this paper, we discuss lessons learned through the implementing of uneven-aged management in these projects.

Approach

"The term, selection system, is applied to any silvicultural program aimed at the creation or maintenance of uneven-aged stands . . . [and]. . . there is not, in the strictest sense of the term, any such thing as an uneven-aged stand. Even when a single large tree dies it is replaced, not by one new tree, but by many that appear nearly simultaneously. This is true even if the new trees are from advanced regeneration. The uneven-aged stand is an artificial entity required for the comprehension of what might otherwise be a chaos of little stands" (Smith 1962, p. 467).

One objective of the study is to develop quickly a forest of uneven-aged groups so that the effects on wildlife and the risk of large-scale wildfires become evident as soon as possible. We therefore decided to use not only the periodic creation and reforestation of small groups but also an initial thinning of the existing matrix of trees to develop an uneven-aged structure and preferred species composition. Our approach for locating reforestation groups and for thinning in the matrix led to our first lesson learned: the forest can be transformed into one with a substantially uneven-aged group structure in a few decades.

Using the J-Curve to Regulate the Stand

When the objective is to have a balanced or regulated, uneven-aged stand, a histogram depicting the diameter distribution of trees in the stand (trees per acre vs. diameter class) approximates a smooth, inverse, J-shaped curve (*fig. 2*) (Alexander and Edminster 1978). It has three key parameters: first is slope, which results from the diminution quotient (Dq—a value that, when divided into the number of trees in one size class, gives the number of trees expected in the next smaller size class); second is the largest size a tree is allowed to grow before being harvested; and third is the stocking level (basal area of trees per acre), represented by the area under the curve.

The numbers of saplings and poles needed to provide adequate growth into the large-tree classes is usually a significant influence on the beginning point of the J-curve (number of trees per acre in the smallest diameter class) and its Dq. In this study, however, two contradictory objectives influenced the beginning point. Silviculturists desired to have sufficient numbers of small trees to assure growth into the larger diameter-classes, but fuels specialists wished to minimize the contribution of seedlings, saplings, and poles to fuel ladders leading into the upper tree canopy. Analysis and discussion lead to the compromise values for reforestation groups shown in *table 1.*

We did not expect a typical acre to be fully stocked with conifers, estimating instead that 80 percent would be occupied by conifers, 10 percent by large oaks, and 10 percent by rock patches and other openings. Thus, the stocking of conifers

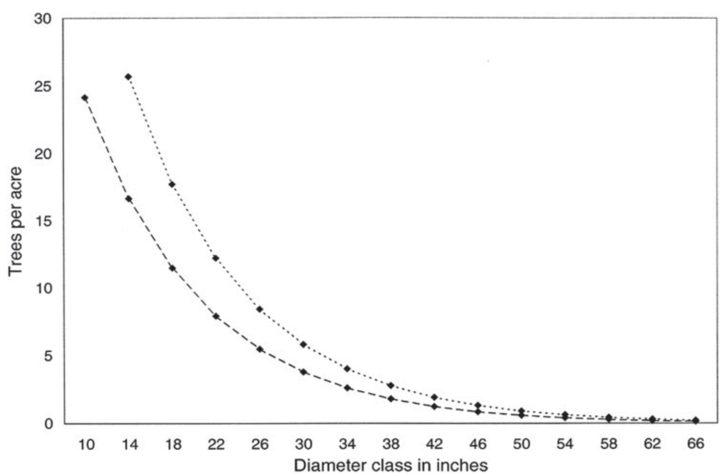

Figure 2—A typical inverse J-shaped curve; closed circles designate a moderately dense forest; closed squares designate a very dense forest.

Table 1—*Compromise numbers of seedlings and poles to be provided for adequate ingrowth into large-tree classes, based on competing silvicultural needs and desired fuel ladders*

Forest type	Site quality	Planting spacing	Resulting seedlings per acre	Estimated percent mortality	First-thin spacing	Resulting poles per acre
Ponderosa pine	Good[1]	9 x 18 ft	270	20	18 x 18 ft	135
Mixed-conifer	Good[1]	8 x 16 ft	340	20	16 x 16 ft	170

[1] Forest Survey Site Class 3.

in the smaller diameter classes (1 to 16 inches) of the J-curve should be about 110 trees per acre in ponderosa pine stands and 135 in mixed-conifer stands.

Different Dq's for a J-curve comprised of 2-inch diameter classes were tried and discarded until we identified the one that satisfied the desired number of saplings and poles. For ease of use in the field, equivalent curves were then developed by using 4- or 8-inch diameter classes.

Our approach to determining the largest size a tree would be allowed to grow before harvest was driven by a desire to maintain the presence of very large trees in the stand. Initially, we estimated the diameter at breast height (dbh) in inches, expected in 200 years, based on professional judgment and data from yield tables (Dunning and Reineke 1933, Meyers 1938). Subsequent modeling with the uneven-aged routine in the Forest Vegetation Simulator (USDA 1996) resulted in the following diameters at 200 years of age:

	Good site[1]	**Poor site**[1]	**Average site**[1]
Thin at 50 years, then every 20	58 inches	49 inches	54 inches
No thinning	39 inches	33 inches	36 inches

[1] Forest Survey Site Classes 3, 5, and 4, respectively.

Substantial public interest in assuring continuous presence of very large trees throughout the forest matrix, for wildlife and aesthetic values, led to consideration of other approaches. Analysis and discussion resulted in the study team's recommending an approach, initially suggested by the Yosemite Area Audubon Chapter, that allows the J-curve to tail off to a point that it represents only a few hundredths of a tree per acre. Summing the parts of trees in the largest diameter classes (>50 inches) suggests a total of about one such tree per acre. Thus, the practical approach to field implementation would be to leave in clumps the largest trees (those >50 inches in dbh) with desired characteristics, producing an average of about one very large, old tree per acre.

The stocking level of trees was taken from even-aged yield tables, based on the suggestions of Curtis (1978) and Foiles (1978). Commercial thinning schemes were developed both for groups of existing trees and for new groups established by reforestation by using the Forest Vegetation Simulator and professional judgment. Desired basal area per acre was set at 65 percent of full stocking (growing space 100 percent occupied) in the applicable yield table, which, according to the Simulator, would result in stands returning to 85 percent of full stocking in about 20 years (*fig. 3*).

Field Techniques

The average size and arrangement of groups of trees of the same age usually is influenced by the structure of the stand needed to provide habitat for particular species, the tolerance of the tree species to shade, and the practicality of maintaining group size and arrangement through management. The J-curve is applicable over a wide range of arrangements and group sizes, from a few acres down to openings that mimic the crown width of the largest tree desired.

Implementing the uneven-aged strategy involved primarily the identification and layout of the reforestation groups and marking for thinning in the matrix. Because the strategy was new to the sale preparation crew, we thought it would be difficult to learn and control work quality if both tasks were attempted at the same time. Initially, therefore, the crew located stand boundaries and reforestation groups so that it was evident which task was to occur in what areas of the stand. Next, the crew marked the thinning, focusing on guidelines for this

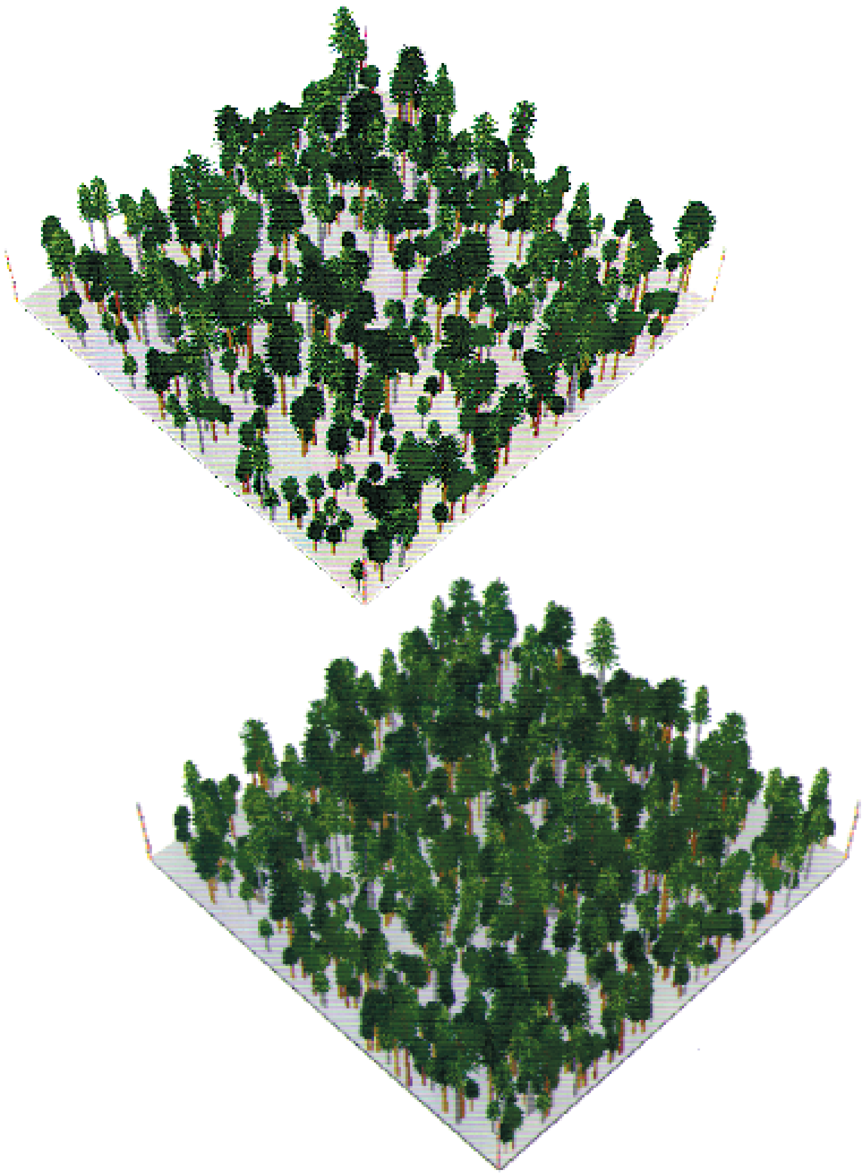

Figure 3—Simulation of a mixed-conifer forest at about 65 percent of full stocking (above) and 85 percent of full stocking (below), by the Forest Vegetation Simulator (USDA 1996).

task, without having to dwell on starting and stopping lines or the guidelines for establishing reforestation groups.

Locations of stands were determined by traditional approaches, like homogeneity of the vegetation, logging systems, and geography. Determination of stand size, however, did not follow the traditional approach. Because the intent is to develop an uneven-aged structure, stand by stand, the structure should be present at all larger scales, even in larger watersheds. The larger the stand, the easier and more efficient it was to implement the approach, resulting in stands of 75 to 150 acres.

Guidelines for locating reforestation groups focused on finding under-stocked areas within a stand that had resulted from past harvest, small fires, and insect-caused mortality. Usually under-stocked areas were evident because the majority of the area in most stands was moderately to densely stocked. Once identified by the crew walking through the stand, the boundary was located by expanding the under-stocked area until edges were located where the stand was at least moderately stocked with trees. Five acres is the largest group allowed under the guidelines (USDA 1995). The technique resulted in only 2 percent of the under-stocked areas expanding to a group larger than 5 acres.

Guidelines for thinning in the matrix focused on a desired basal area per acre where most trees to remain in an area were at least 16 inches in dbh, but on a spacing scheme where trees were mostly 15 inches in dbh and smaller. The split approach stemmed from the stark reality that small trees contribute little to stand basal area, so some other approach, like a spacing standard, is essential. The dbh split could be anywhere from 10 to 16 inches, depending on existing stand structure and the desirability of minimizing the complexity of marking guidelines.

A key to developing the uneven-aged structure and species composition by thinning in the existing matrix of trees was to look for obvious groups by large diameter classes (6 to 10 inches) and then to accentuate them by leaving as many trees as possible from the dominant diameter class in making up the desired basal area. It is important to focus on the obvious groups but not to spend time looking closely at variation in stand structure or debating the extent, boundaries, etc. Focusing on the obvious groups worked well. When groups were not evident, trees were selected to remain in the stand by thinning through all size classes present. The written marking guideline states:

> Working by 10-inch diameter classes, recognize the groups that are obviously dominated by trees in a single class, then make up as much of the desired basal area per acre as possible from favorable trees belonging to the dominant diameter class. When domination by a single class is not obvious, make up the desired basal area from favorable trees belonging to any class or crown position.

Other key marking guidelines were:

1. Disfavor the 1- to 10-inch diameter class.
2. Leave the proportion of oaks specified in the prescription, favoring black oak (*Quercus kelloggii*) over live oak (*Q. wislizenii*). Of the oaks to be removed, cut half and girdle half. Select the half to cut from those surrounded by pole-sized and larger ponderosa pine and incense-cedar (*Calocedrus decurrens*).
3. Select leave trees with at least 30 percent live-crown ratio that are free of damage and have mistletoe ratings of 1 to 2 or less, whenever possible.
4. Favor ponderosa pine over white fir (*Abies concolor*) and incense-cedar.

Implementation

One of the administrative study's tasks is to determine whether a typical Ranger District can implement this uneven-aged management strategy with its existing work force and typical management procedures. Although the first few projects are not yet completed, the answer to this question is becoming apparent. Because the major phases of implementation are sale preparation and sale administration, we focus on these. Two other areas, sale planning and post-sale treatments (reforestation, timber stand improvement, fuels reduction work, etc.) also play roles in implementation but are premature to discussion here. The planning phase has been documented in the Landscape Analysis Plan (USDA 1995) prepared for the study. Because post-sale stand treatments have just begun, we cannot evaluate performance in this area.

Timber sale preparation involves layout (establishing unit/stand boundaries on the ground), marking, and cruising (designating the trees to be cut or left and measuring the amount of wood that will be removed) in accordance with silvicultural prescriptions and other sale planning documents. It also involves appraising the timber (what it will cost to harvest the sale, and setting the asking price) and putting together the timber sale contract (legal document under which the sale operates), along with a prospectus (document describing the sale) and advertisement. Timber sale administration takes over once the sale has been sold and awarded. The sale administration team is responsible for seeing that the contract is followed and executed by the purchaser and that the Federal Government's interests are protected.

Lessons Learned From Sale Preparation

The Need to Test Marking Guidelines

One of the most important lessons learned was the value of practicing and testing the various marking guidelines. Small representative areas of individual stands were set aside as practice areas to test the marking guidelines developed by the silviculturist and the sale preparation forester. They were tested using key members of the marking crew and resource specialists. Results were reviewed on the ground by the silviculturist, timber and resource management personnel, and interested publics. Through this procedure, adjustments were made to the marking guidelines to achieve the desired silvicultural outcomes, while making the guidelines as simple as possible for the marking crew to follow. Practice made a substantial difference.

Supervision is Critical for Quality and Work Efficiency

We learned that the "art" along with the science of applying the silvicultural prescriptions under this uneven-aged management strategy is more important than is true for more traditional, even-aged prescriptions. To facilitate this, we used a coaching technique when marking stands. More experienced sale preparation personnel walked behind the crew and served as observers. They checked basal area and spacing standards, helped identify existing dominant groups of a single size-class, and helped direct the crew in making choices between trees when needed. This paid off and allowed the use of large marking crews. We were able to split crews into groups of three to five markers with a supervisor for each. Careful supervision of the marking helped to identify problems quickly and assist crews in looking for dominant groups, which clearly improved the marking production and resulted in higher quality work. Crew composition and size needed to mark and cruise are important factors to consider. More people were needed to mark and cruise for these uneven-aged prescriptions than would be typical for even-aged prescriptions. A crew-to-supervisor ratio of about 1 to 4 was ideal.

Traverse Regeneration Groups Using a Global Positioning System

Whether to traverse the regeneration groups within the stands was debated due to costs and time constraints. Given the relative ease and low costs of doing traverses with a global positioning system (GPS) device, however, we opted to do so. Consequently, we were able to keep better track of our regeneration acres and accurately map the locations of these groups for our records. Already this has proven to be worthwhile in following up with post-sale treatment work within these groups.

Plan Marking Strategies

We compared marking strategies, either marking "cut" trees (painting a narrow ring around trees to be cut) or "leave" trees (painting trees that are to remain after the sale). Aho (1983) recommended marking leave trees when dealing with fir, based on comparisons of the two marking methods from the standpoint of residual stand damage. We found, however, that additional factors needed consideration (*table 2*).

Stands need to be examined carefully before determining whether to mark them as a leave-tree unit or as a cut-tree unit. Also, applying both systems in different units may be advantageous, although mixing strategies requires vigilance by the sale administrator and the logger to avoid confusion about the marks. We found that cut-tree designation had a higher cost, but this may be offset by higher cruise costs for leave-tree marking. Smaller acreages definitely favor cut-tree marking. Dense stands of small trees favor a leave-tree mark. A cut-tree designation with a 3P cruise (probability proportional to prediction, a modification of variable probability sampling in which the chances of a tree's being selected to measure in the sample varies directly with the size of the tree) offers the best way to control the coefficient of variation (CV) of the cruise, if meeting sampling error standards is a problem.

Table 2—*A comparison of the relative advantages and disadvantages of "cut-tree" vs. "leave-tree" marking for thinnings*

Cut-tree marking	Leave-tree marking
Need clearly designated boundaries.	Need clearly designated boundaries.
If the number of cut trees/acre is less than about 1.5 times the number of leave trees/acre, cut-tree marking is more efficient and economical.	If few leave trees/acre to mark, leave-tree marking is efficient. Leave-tree marking tends to be slightly slower.
Because every tree must be marked, apply a tree-based cruise such as the 3P method.[1] Using a 3P cruise can minimize the coeffficient of variation (CV) of the cruise and result in efficient measurement costs.	Leave-tree marking favors an area-based cruise for measuring the harvest trees. It does not require that all cut trees be visited.
For small acreages, cut-tree marking is more and economical.	Area-based (plot) cruise methods generally have high coefficients of variation (>70 pct) and require many plots. The number of plots is a function of the CV, not acres. Need to have a large acreage to avoid overlapping plots.
Does not require the unit to be traversed.	Requires the unit to be traversed.
Need only one preparation entry into the unit.	Need three preparation entries (mark, cruise, traverse).
Little risk of not meeting the sampling statistics for the cruise if insurance trees are measured (3P).	More plots needed if cruise misses the sampling error percentages allowed.
Skips in mark simply leave more trees in the unit.	Skips in mark may understock the stand from prescribed levels.

[1] The 3P (probability proportional to prediction) method is a sampling method in which the chance of a tree's selection in the sample varies directly with the relative size (volume) of the tree being measured.

Lessons Learned from Sale Administration

Mark Sale Boundaries Unambiguously

Administration of the timber sales affirmed principles that we already knew. It pays to put effort, time, and money into sale preparation because it reduces headaches encountered during sale administration. One of the few sale problems we encountered during preparation for the 10S18 FRP contract involved boundary designations. As pointed out by Fiske and others (1993), marking of boundary trees is important to prevent theft and to maintain accountability with group-selection harvesting. Although these were not issues in our case, the fact that we marked boundaries of units (stands) and regeneration groups (group selection) with paint of the same color caused some confusion for the logger and the sale administrator, especially when regeneration groups were located near a unit boundary. This could have resulted in theft and accountability problems, except that we mapped each unit and regeneration group with GPS, providing a good map for each unit and an accurate location of each regeneration group. The sale was sold as a "scaled" sale (trees measured and paid for after they were cut into logs and hauled to a designated scaling location) rather than as a "tree measurement" sale (trees measured prior to sale and paid for before cutting). Each method has pluses and minuses, of course, but our experience with group-selection harvesting indicated that a scaled sale presents fewer problems when administering the contract and less temptation to cut undesignated trees.

A Need for Flexibility

Flexibility was found to be a key ingredient for accomplishing the work on the ground. Given the mix of timber sizes (dbh ranging from about 10 inches to over 70 inches), species, and topography (slopes to 75 percent), we tended to be more open to suggestions from the timber sale contractor about the types of log-skidding and processing equipment and methods that he wanted to use. So far, these have included conventional tractor skidding and hand falling, mechanical harvesters, in-woods processors, delimbers and processors at the landings (slopes <35 percent), helicopter yarding (slopes >60 percent), and skyline yarding (slopes 40-60 percent). Only by using this mix of different technologies and methods were we able to get some of the results that we desired at an economical price.

Some significant lessons were learned from working with mechanical harvesters. They have better control on directing and placing cut trees and are able to process small timber faster and more efficiently than conventional falling methods on slopes <35 percent. On the other hand, we experienced a slightly greater chance of cutting undesignated trees because of the "dog hair" thickets of pine and incense-cedar within stands. Also, we found that chances of damage to designated leave trees increased with the simultaneous operation of more than one piece of machinery in the woods. Most tractor-based units on these sales required at least two entries, one with mechanical equipment (such as a feller buncher) and another with conventional falling (chainsaws) and skidding, due to the various sizes of the trees to be removed.

More Inspection Time Required Than With Even-aged Harvests

We found that the logger covered more land at a time than during traditional timber sales because of the low volumes per acre. As predicted by Fiske and others (1993) this required more time walking more ground than on other timber sales, so timely inspections could be made and problems identified early. Also, it paid off to have our sale preparation personnel and other resource specialists spend some time with the sale administrator during harvesting activities. Experiencing first hand what works and what does not with the various types of equipment often leads to significant improvements in the marking, layout practices, and resource protection measures. Good communication is a key with everyone involved in the sale, including the contractor, resource specialists, and researchers.

Involve Sale Administrators Upfront

The key lesson learned is that sale administration personnel need to be involved in the planning and preparation phases of the project. They are responsible for carrying out the intended actions of the project, so the more they know about the project the better. Sale administrators can also provide valuable input into the design of the project, including legal aspects of a timber sale contract and the practical aspects, such as logging capabilities, practicality of certain practices, and various ways to accomplish a desired condition.

Costs

A major and continuing question for the study involves the cost of timber sales when implementing uneven-aged management. The cost includes creating small group selections and thinning between the groups to accentuate the existing uneven-aged structure of the overall stand. Sale preparation costs that are being tracked include salaries, vehicle costs, paint, and miscellaneous supplies needed (flagging, signs, etc.). Sale administration costs include administration and clerical salaries, vehicle costs, and miscellaneous supplies needed.

We assumed at the start that implementing uneven-aged prescriptions would entail a higher cost than even-aged prescriptions. Sale preparation costs were higher for uneven-aged prescriptions, using 1996 as the base year and a 4 percent discount rate for cost calculations (*fig. 4*): 10S18 FRP at $9.33 per thousand board feet; IROC at $11.25; and other (average for even-aged, sanitation, and typical thinning sales) at $8.09. Although the costs were higher, the difference was not as high as many of us expected. Factors such as the complexity associated with these sales, the lower timber volumes harvested per acre, and the amount of ground that needed to be covered all tended to inflate costs. We expect costs to decrease, however, as our experience with these sales increases.

Estimates of the sale administration costs were $5.83 per thousand board feet for the 10S18 FRP, $6.49 per thousand for IROC, and $5.55 per thousand for the other sales types (*fig. 4*). These estimates are preliminary, with the exception of the "other" costs shown, because the 10S18 FRP and IROC sales are still being harvested. Sale administration costs may increase for these two sales because of the complexity of the ground yet to be harvested and the fact that helicopter and skyline yarding remain to be used. Based on past experience with these harvesting systems, we expect sale administration costs to increase.

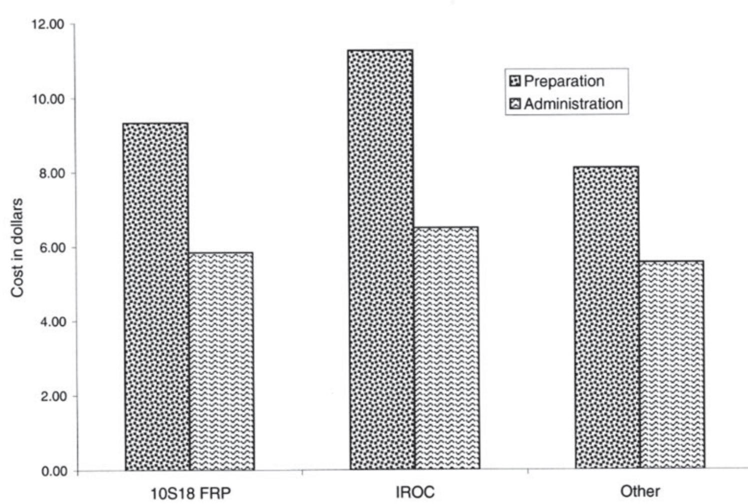

Figure 4—Costs in dollars per 1,000 board feet (MBF) for sale preparation and administration: 10S18 Fuels Reduction and Indian Rock Upper Tier projects are applying uneven-aged management strategies; "other" includes even-aged, sanitation, and typical thinning sales.

Administration costs have typically ranged from $5.30 per thousand board feet for an easy tractor-yarding operation up to $10.00 per thousand for helicopter yarding operations, where steep terrain makes all tasks more time-consuming.

The two sales sold to date have been cost-effective. Both had at least two prospective bidders and both sold for more than their appraised rate. Generally speaking, we have received few complaints by purchasers on the way these sales were packaged. Continued attention to sale economics, along with resource objectives, needs to be emphasized for all projects if one expects them to be successful.

Summary and Recommendations

The willingness to try new ideas, a major principle behind adaptive management, is probably the most important factor in our success with these projects. This principle is sometimes hard to accommodate, especially in a bureaucratic setting. Support from management and being open minded are effective in bringing about a willingness to try new ideas. It is important to be willing to listen and to discuss ideas from a wide variety of sources, including the public, academic community, and management, then to build on the ideas that work and learn from the ones that fail.

The more complicated and varied the expected outcomes or desires, the harder it will be to implement the project, especially through a timber sale in which market forces typically play a critical role. Other avenues to accomplish multiple resource objectives, such as those described by Ringgold (1998) in his paper on stewardship contracting, need to be considered and tried. Economic viability is a key to successful implementation of any package involving the market for services or commodites.

What have we learned so far, and what still needs to be explored? Preliminary results from the 10S18 Fuels Reduction Project have shown that we can successfully implement the desired silvicultural prescriptions. On the units logged with a tractor, the desired basal areas per acre have been attained, and canopy covers meet the minimum of 40 percent for spotted owl foraging habitat. Vertical structure within the groups became less diverse, however, tending to become single storied with little to no understory, especially after post-sale treatments. Thinning of the forest matrix between regeneration groups accentuated their existing group structure, as planned, so stands are conspicuously more patchy and uneven-aged than before thinning. What effect, if any, the stands with little or no understory, but more diversity in horizontal structure, will have on spotted owls and other wildlife species remains to be determined.

Although it cost more to implement uneven-aged prescriptions than is typical for even-aged prescriptions, the difference was less than expected. Spreadsheets developed for the costs of sale preparation and administration need to be expanded to capture time spent in the office and to more accurately track overhead costs. Time and funding permitted, production time and cost studies would add much to our assessments of costs from an operations standpoint.

The project has given us the opportunity to test implementation of an uneven-aged management strategy at a landscape scale. Although the study is still in an early stage, we are already gaining important insights. For example, we now know that a typical Ranger District probably can implement the uneven-aged management strategy across a large landscape, and at costs comparable to traditional even-aged management.

Acknowledgments

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Fire-Return Intervals in Mixed-Conifer Forests of the Kings River Sustainable Forest Ecosystems Project Area[1]

Catherine Phillips[2]

Abstract

Fire-return intervals were studied on six 1.4-ha plots in a 2,070-ha study area in the Dinkey Creek watershed. Stumps in mixed-conifer forest were examined for fire scars created from 1771 to 1994, with 1873 chosen as the end of the pre-Euro-American settlement period because the rate of fire events decreased on most plots after about that year. Mean intervals from 1771 to 1873 ranged from 3.19 to 5.44 years, maximum intervals ranged from 6 to 12 years, and minimum intervals ranged from 1 to 2 years. Differences between plot means were not significant during that period, and the data showed no influence of aspect, elevation, or slope position on return intervals. Plot means were shorter than those reported in other mixed-conifer areas of the central Sierra Nevada. Archived fire records for the study area, on file at the Sierra National Forest, revealed a high rate of lightning-caused fires—an average of one fire requiring suppression every 1.36 years between 1911 and 1965. This contrasts with an average of only one lightning-caused fire requiring suppression every 9 years during a similar period in mixed-conifer forests at Redwood Mountain and Bearskin Creek, 40-50 km south of Dinkey Creek, suggesting that local factors strongly influence fire events.

The Sierra National Forest, in collaboration with the Pacific Southwest Research Station, established the Kings River Administrative Project Area for study of sustainable forestry under two contrasting, landscape-scale ecological approaches (USDA 1994). The Dinkey Creek watershed was selected for application of a three-tiered landscape, assuming that pre-Euro-American fire-return intervals in the Dinkey Creek watershed were similar to those recorded by other researchers in central Sierra Nevada mixed-conifer forests (Caprio and Swetnam 1995, Kilgore and Taylor 1979, Swetnam 1993). It also assumed that the density of trees varies across a watershed in relation to landscape position and that vegetation is most dense in drainage bottoms, grading into a relatively open condition on ridges. Fire is thought to be one causal agent for this gradient because it is believed to be more common and has shorter return intervals on ridges than in valleys.

Fire intervals had not been studied previously in the Dinkey Creek watershed. The goals of this study were to determine the mean fire-return interval and to explore relations between fire interval and landscape position in the mixed-conifer forest. The study was intended to provide land managers with site-specific information about the role of fire-return intervals in determining vegetation density. Results reported here came from a two-part effort that included the ponderosa pine forest type in the Big Creek watershed, which adjoins the Dinkey Creek watershed immediately to the west. Because results from Big Creek were inconclusive, they are not included here.

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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Study Area

The study area covered 2,070 ha of the Dinkey Creek watershed (37°1'N, 119°7'W) in the Sierra National Forest. Dinkey Creek, a tributary of the North Fork of the Kings River, occupies a southerly trending canyon in the southern Sierra Nevada. Elevation in the study area ranges from 1,450 to 1,950 m. Climate is Mediterranean, with warm dry summers and cool wet winters. Precipitation in the form of rain and snow falls mainly from November to April. Lightning is common in the study area.

Mixed-conifer forests of the study area are characterized by white fir (*Abies concolor* [Gordon & Glend.] Lindley) in codominance with at least two of the following species: sugar pine (*Pinus lambertiana* Douglas), incense cedar (*Calocedrus decurrens* [Torrey] Florin), ponderosa pine (*P. ponderosa* Laws.), or Jeffrey pine (*P. jeffreyi* Grev. & Balf.). Understory species typical for the sites are bearclover (*Chamaebatia foliosa* Benth.), Mariposa manzanita (*Arctostaphylos viscida* ssp. *mariposa* [Dudley] P.Wells), Sierra gooseberry (*Ribes roezlii* Regel), deer brush (*Ceanothus integerrimus* Hook. & Arn.), and little leaf ceanothus (*C. parvifolius* [S. Watson] Trel.). Scientific names of plants follow Hickman (1993).

Methods

The study area was stratified into three tiers—upper (ridge top), middle, and lower (riparian)—using geomorphologic designations of landscape processes. Upper areas were experiencing some fluvial erosion, primarily classified as eroding hillslopes. Middle slopes were dominated by fluvial and mass-wasting processes and experiencing some colluvation and debris sliding. The lower tier was generally an area of deposition. Two 1.4-ha study plots were located in each tier in mixed-conifer forest with known harvest dates within the last 11 years. Selected sites were examined for evidence of fire by using methods described in Arno and Sneck (1977). Sample plots had at least six relatively fresh stumps from trees more than 200 years old. All sampled stumps were located with a global positioning system (GPS) and labeled with metal tags. No attempt was made to control for plot elevation or aspect.

I selected an average of 7.7 stumps from each plot for a total of 46 stumps and, with a chain saw, removed a slab from the top of each stump exhibiting a continuous fire record in the form of open cat faces or fire scars (Drumm 1999). Slabs were sanded with 500-grit sand paper and examined under 10x and 20x magnification. Dates of fires were determined by counting annual growth rings backwards in time from the known year of harvest. Correlation of ring sequences into a single chronology was done for each plot by using methods described in Arno and Sneck (1977). Missing rings, often associated with fire events, may have resulted in some error in the data, so dates associated with a single fire event were interpreted accordingly.

Results and Discussion

Fire dates ranged from the mid-1500's to 1943. The clearest fire records came from sugar pines and generally dated from about 1770. Numbers of fire events per year declined in 1871, after what appeared to be a fairly active and widespread fire period. Thirty-two of the 46 stumps sampled recorded fire events in 1871, but only six recorded fire events in 1873. Caprio and Swetnam (1995) sampled in the Kaweah River drainage, 55 km south of my study sites; Wagener (1961) sampled further north, at various locations in the central Sierra Nevada; and Kilgore and Taylor (1979) sampled 40-50 km to the south. All documented a similar period of high fire activity in the early 1870s, followed by a decline, suggesting a regional influence on fire activity in the early 1870s. Kilgore and Taylor (1979) cited two sources that document a period of drought between 1869 and 1871 and drew a relationship between the drought and a "larger, higher-intensity fire" that occurred in 1871. Swetnam (1993) found a similar correlation between low-rainfall years and widespread fire events along 160-km transects in the southern Sierra Nevada. However, the lack of correlation between the 1862-1864 event listed in Kilgore and Taylor (1979) and large numbers of fire scars in the Dinkey Creek watershed imply that local conditions vary and may play an overriding role in local fire behavior.

Mean fire-return intervals from 1770 to 1871 ranged from 3.19 to 5.44 years (*table 1*), a range generally shorter than reported in other studies. Comparable sites sampled by Caprio and Swetnam (1995) had mean return intervals of 6.58 and 7.82 years, and return intervals at similar elevations were 14 to 17 years, mainly from giant sequoia groves (Kilgore and Taylor 1979).

The apparent shorter return intervals in the Dinkey Creek area may be a result of high lightning activity. Known lightning "hot spots" exist in three locations near the study area—Bear Mountain, Cabin Meadow, and Dinkey Station (*fig. 1*). According to Sierra National Forest fire atlases, 39 lightning fires occurred within the study area between 1911 and 1964, a rate of one every 1.36 years. None of these fires was allowed to burn more than 2.5 ha, but we can probably assume that lightning activity in this area has not changed appreciably since the mid-1700's. This level of lightning activity is significantly higher than that reported by Kilgore and Taylor (1979) in their giant sequoia study sites to the east of Dinkey Creek. They reported two fires in the area of Redwood Mountain and three in the Bearskin Creek area from 1921 to 1972, or an average of only one every 9 years.

Caprio and Swetnam (1995) reported an inverse relation between elevation and the number of lightning-ignited fires, speculating that sites at lower elevations are more flammable because they support more understory vegetation and, hence, generate more fuels. Although the high number of lightning ignitions in the Dinkey Creek study area is consistent with the findings of Caprio and Swetnam, I did not find a significant relation between elevation and return intervals in the Dinkey area, possibly because of a relatively small sample size.

Plot location did not significantly influence fire-return intervals, though some influence of aspect is suggested by the data. More fire scars were found per tree on sites with northerly aspects, even though such sites showed trends toward slightly lower fire frequencies. The apparent greater continuity of scar

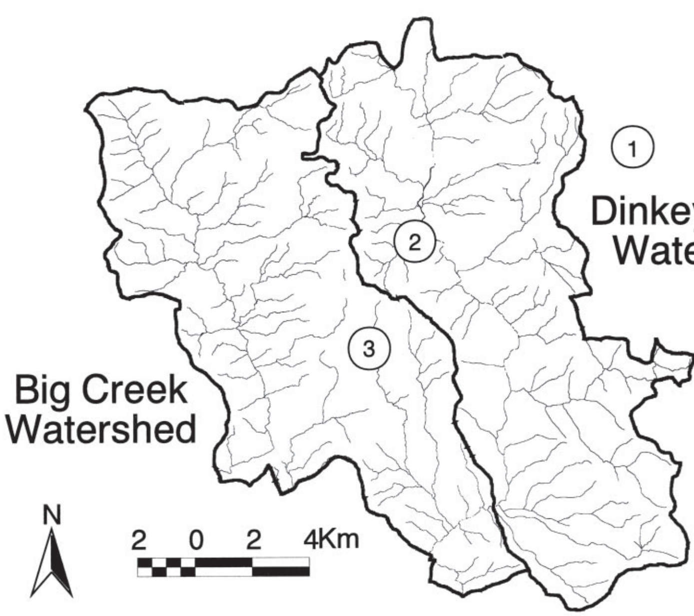

Figure 1—Areas in or near the Dinkey Creek watershed that experienced high lightning activity from 1911 to 1964: 1–Bear mountain; 2–Cabin Meadow; 3–Dinkey Station.

Table 1—*Fire-return intervals (years) in the Dinkey Creek watershed, Sierra National Forest, 1770-1871*

Plot number and tier[1]	Aspect	Elevation (meters)	Mean fire-return interval ± SD	Min.– max. fire-return interval	Number of years[2]	Tree stumps sampled	Number of fire events
P1, lower	S	1,707	4.45 ± 2.2	2-11	99	8	21
P2, lower	N	1,463	3.96 ± 2.3	1-10	96	6	24
P3, middle	NNE	1,634	5.44 ± 2.2	2-9	99	7	18
P4, middle	SW	1,798	3.19 ± 1.4	1-6	100	8	33
P5, upper	SSW	1,902	3.64 ± 1.8	1-10	103	10	28
P6, upper	N	1,780	4.33 ± 2.4	2-12	102	7	20

[1] Lower tier = the riparian management zone; upper tier = about 30 percent of the watershed, from the ridge top down; middle tier = remaining side slope between the lower and middle tiers, comprising about 50 percent of the watershed.

[2] Duration of the interval sampled.

data suggests that cooler (more mesic) conditions on northerly aspects reduce the number of missing rings a tree may exhibit after fires, or that the cooler conditions may limit fire-scar formation to events that burn hotter and presumably cover a larger area. It is clear, however, that additional work is needed to fully understand the effects of landscape position on fire-return intervals.

The maximum period between fire events in the study area ranged from 6 to 12 years (*table 1*), but the distribution of return intervals on all plots was weighted toward shorter intervals of 2 and 3 years (*fig. 2*). Short fire-return intervals have implications for land managers in supporting the fine-grained model proposed by Swetnam (1994) and Chang (1996). According to these sources, a system under short fire-return intervals would have a fine-grained appearance of patches in the landscape. In fact, the landscape would be in a steady state of disequilibrium, one constantly changing at a small scale, but one that remains in a fairly stable condition, overall. Biodiversity may be high because many different light and structural conditions are represented over a relatively small area.

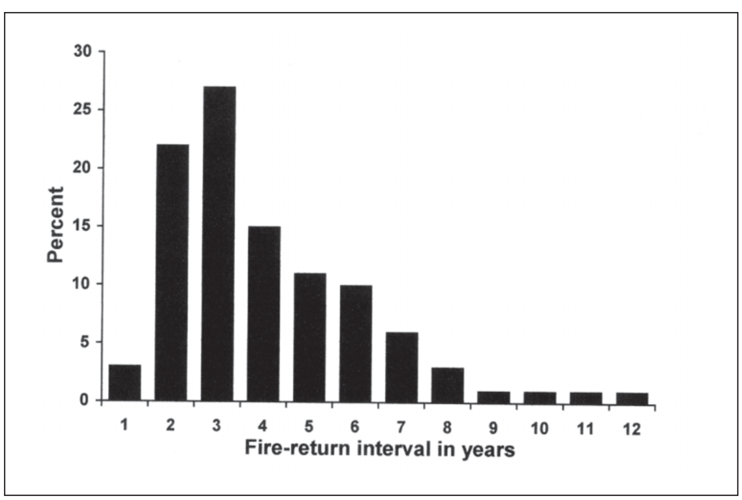

Figure 2—Frequency distribution of fire-return intervals in the Dinkey Creek study area, 1770 to 1871.

Conditions today have changed enormously, and stand conditions have become more homogeneous at a small scale but less homogeneous at a large scale. Minnich (1983) and Swetnam (1994) discussed this phenomenon. Historic logging practices, which removed the large-tree component in much of the Sierra Nevada and targeted specific desirable species like sugar pine, have also contributed (McKelvey and Johnston 1992).

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Mary Drumm's assistance with the field work was indispensable. Neil Sugihara, Forest Service Regional Fire Ecologist, was responsible for initiating the project, and Mark Smith, silviculturist on the Sierra National Forest, obtained funding from the Sierra National Forest. Don Potter and Jared Verner provided helpful review comments. To all I express my deep appreciation.

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Prescribed Burning in the Kings River Ecosystems Project Area: Lessons Learned[1]

David S. McCandliss[2]

Abstract

The prescribed fire program on the Sierra National Forest is in its infancy. Prescription burning was initiated in 1994 in two 32,000-acre watersheds in the Kings River District of the Sierra National Forest. Primary objectives are to return fire to a more historical role in forest ecosystems and to provide opportunities for scientists from the Pacific Southwest Research Station, and elsewhere to study various effects of these fires. Approximately 11,900 acres of prescription burns were completed by the end of 1999, and documents required by the National Environmental Policy Act have been completed for burning on about 23,000 additional acres. A Draft Landscape Analysis Plan has been prepared and reviewed, and a final draft is presently in preparation. Two fuels-reduction projects are nearly completed, using small-group selection, thinning of conifers, conversion of brush patches to conifer stands, and prescribed burning. A second fuels-reduction project is currently being planned. Many lessons have been learned that relate to needed equipment, crew size, lighter experience, and ignition methods; indicators of appropriate times and places to burn; weather patterns; indicators of desirable flame lengths and fire intensities; indicators of the effects of burns on fuels, duff layer, and soil; and measures of the extent of brush, surface fuels, and ladder fuels removed by burns differing in intensity.

Past efforts to underburn with prescribed fire on the Kings River Ranger District of the Sierra National Forest consisted of isolated, 100- to 1,000-acre projects spread over the district during the 1970's. The main objective was to improve summer forage for mule deer (*Odocoileus hemionus*) of the North Kings herd (Eaton 1978). These projects were single-entry burns done mainly during fall in mixed-conifer and red fir (*Abies magnifica*) vegetation types, although some burning in the ponderosa pine (*Pinus ponderosa*) type occurred during spring months. Opinions varied about whether these burns were successful forest management practices. Some evidence indicated improved forage for deer (Bertram and others 1978), although several fire-salvage timber harvests were done in the area immediately after the prescribed burns in the 1980s. We have no records of underburning between 1980 and 1989.

With the exception of a 60-acre underburn in 1990 in the area covered by the Kings River Sustainable Forest Ecosystems Project, the current underburning program began in 1994. We presently have 23,000 acres of underburning covered by National Environmental Policy Act (NEPA) documents for the Kings River District, and all but 3,000 of those acres are within boundaries of the Kings River Project (*fig. 1*). Prescribed burning has been completed on 11,900 acres during the past 6 years, 3,900 acres of which are second-entry burns (that is, burned twice). Most of the prescribed burns are routinely accomplished without thinning or other mechanical pretreatment of fuels. Much of the landbase has not seen fire of any type for over 100 years.

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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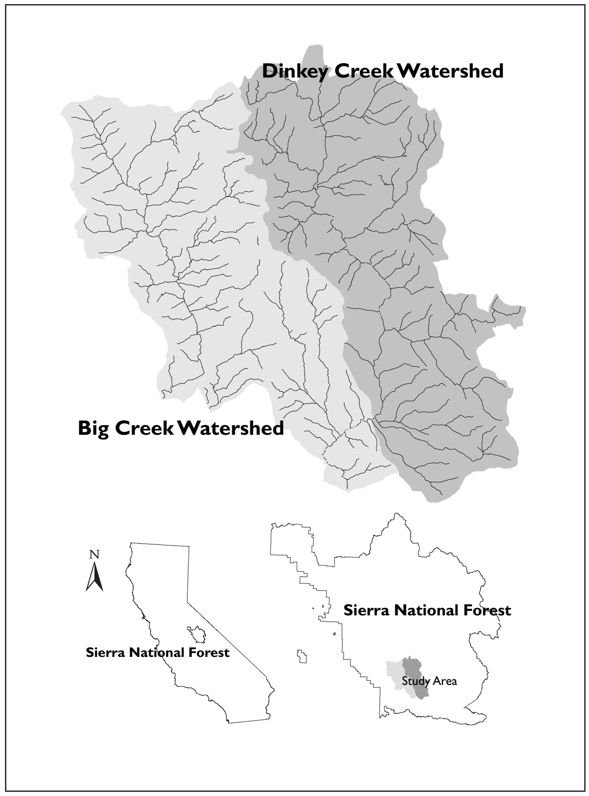

Figure 1—The Kings River administrative study area in the Sierra National Forest in Central California includes the 64,000-acre Big Creek and Dinkey Creek watersheds (indicated by shading).

Objectives

Initial underburning was tied to Environmental Assessments for helicopter salvage sales, and objectives were to remove activity fuels and natural fuels to protect wildlife habitat, mainly for California spotted owls (*Strix occidentalis occidentalis*) using funds from Knudtson-Vandenburg (KV-natural fuels, KV-wildlife) and brush disposal (BD) collections from timber sales. In an effort to reduce dead-and-downed fuels remaining, sale administrators attempted to yard whole trees killed by insects. This effort failed, however, because most of the trees were brittle from dessication and fractured during felling operations.

New NEPA documents later changed objectives to include restoration of fire as a functional part of forest ecosystems and to minimize the damaging effects of wildfire; a sense of urgency was associated with these objectives. Brush species comprise a large part of the understory in the ponderosa pine and mixed-conifer forests in the area. During wildfires, increased fuel loads from brush, litter, logging slash, and conifer reproduction add fuel, increasing fire intensity and damaging the overstory. Brush is generally easy to kill with fire and, considering the short fire-return interval in the area (an average of one fire every 5-10 years; Drumm 1999), probably did not exist historically in its current volume and arrangement. In recent years, patterns of wildfire in the Sierra Nevada pointed to increasing damage to forest environments from unhistorically high fire intensities.

Our burning philosophy is based on the concepts of Biswell (1989), which call for light underburns twice within 5 years. This reduces brush competition in the understory, especially from species that are obligate seeders. Thereafter, maintenance involves reentry with fire every 5-10 years.

General Methods

Two underburning projects were developed for 16,000 acres in the Dinkey Creek, Big Creek, and Rush Creek drainages. Large-scale (1,000-2,000 continuous acres) fuels-reduction projects were planned that combined treatments of thinning from below, mastication, pile and burn, herbicide, and underburning in ponderosa pine and mixed-conifer vegetation types. The main objectives were to reduce the fire hazard and reintroduce a historic fire regime. Defensive fuel profiles zones (DFPZs) were established to reduce the effects of potential wildfires on key resource values and/or urban areas. Following NEPA regulations, Environmental Assessments were developed for these projects, and they were categorically excluded from further analysis under Category 31.2(6).

Three portable, automated weather stations on the District are used to monitor and collect hourly weather data from burn sites. These are tied into the daily fire-danger weather reporting system, and they can be accessed from the District office via computer with radio and/or phone hookups. The stations are queried daily at 6:00 a.m., and the weather for the past 24 hrs is waiting for the burn bosses when they get to work. The outputs are faxed to the National Weather Service, where a Spot Fire Weather Forecast and a Smoke Dispersal Forecast specific to the burn site is produced.

Most control points on the burns are roads and running streams. Firelines are constructed around private property where we lack agreements with landowners. Both handlines and dozer lines are constructed. In addition to roads and streams, control points in the winter and early spring months consist of snow banks, north slopes, and brushfields. The pure chaparral stands on the District do not burn well outside of fire season because grass is the main carrier of fire, and this is green or damp and beaten down then. Burning during fire season requires that control lines be constructed to wildfire standards.

Burns ranging in size from 130 to 1,500+ acres are planned for all aspects at elevations from 3,000 to 7,000 ft. Most burn units are adjacent to other units. In several areas on the District, continuous burn units now cover several thousand acres. Under suitable burning conditions, several areas may be grouped together as one unit and ignited aerially. Units are ignited to burn down from their upper elevations. Backing fire downhill in this way tends to result in lower flame lengths, lower fire intensities, and slower rates of spread. Such a fire is easier to control than those that run uphill.

Burning takes place when burn units come into prescription. This may occur at any time of the year, often even during dry spells in the winter. The 10-hr-lag-time, fuel-moisture stick has proven to be the best indicator of when a unit's fuelbed is in prescription and how it will burn. These sticks are produced to set standards, using wood with known attributes for absorbing and evaporating water. The stick "index" is based on the percentage of its weight comprised of water, so a "stick of 8" is 8 percent water. Large areas covered for burning by NEPA documents provide considerable flexibility. With many acres covered on different aspects and elevations, usually one or more can be selected and burned when conditions are appropriate.

We generally do not apply cut-off dates for burning, as weather patterns fluctuate widely from year to year. For example, burning in 1997 was curtailed by mid-May because conditions were too dry but, in 1998, we could not begin burning until June because of a wet spring, and burning continued into August that year.

Restricting burning to seasons that are thought to have been "historical burning seasons" (summer-fall) has several disadvantages, particularly high smoke emissions and potentially severe fire effects. Because of the heavy fuel loads in the southern Sierra Nevada, burning in the summer and fall months, when fuel moistures are low, can cause unacceptable resource damage. Flame lengths are apt to be longer and scorch heights higher in the trees than desired. Complete consumption of snags and downed logs is more probable. Soils are more likely to be adversely affected over a larger area. The chance of spot fires, which can turn a controlled burn into an uncontrolled wildfire, is higher at that time of year. In addition, often the Sierra National Forest's fire suppression resources are at minimum levels (draw down) due to fire suppression activities in other areas of California.

Members of the burn crew are instructed to not attempt ignition over every square foot of the burn. For example, wildlife logs and snags are not intentionally ignited. Ignition does not occur in riparian areas, although fire is allowed to back through them on its own, within prescription. To maintain roadside screening for wildlife, burns are generally not brought down to roads, but they are allowed to back down and go out naturally. Unburned patches are left throughout a burn. If an area will not burn for whatever reason, burners do not waste time trying to ignite it. These patches may burn out eventually when burning is done during a drying trend. To assure no risk of escape, burns must be patrolled until smoke has not been noted for several days. The patrolling phase of a burn may last longer than the ignition and holding phases.

Underburns are done with as few fire-fighting resources as possible. Maintaining unneeded personnel and equipment on standby at a burn, to serve as a security blanket, is costly. Moreover, too many firefighters carrying torches on a burn may lead to rapid ignition and undesirable fire effects. The burn plan calls for a minimum staffing level, leaving it up to the burn boss to add forces as needed. This does not mean that burns are understaffed, as we have experienced no escapes of any consequence. We have learned, however, that fewer lighters improve the quality of burns, as the fires are often just tended. Add more lighters to lengthen the fire line but not to speed ignition.

In January, it is not uncommon to have two or three burns active with two or three people and maybe a patrol truck on each burn. In May or June, however, two or three fully staffed wildland engines and patrols stay out until after sundown on each burn. Depending on wildfire activity and the Forest's ability to maintain an aggressive initial attack force, several burns may be active simultaneously. The bottom line is simply common sense: burns are staffed adequately in direct relation to fire and weather conditions.

Strategy and Tactics

The San Joaquin Valley, which is downslope from the Sierra National Forest, is in nonattainment regarding the Clean Air Act, with mid-August to mid-November being the worst period for air pollution in the valley (Guerra, pers. comm.; Martinez, pers. comm.). Acceptable burning periods do occur during the summer and fall months, but they are typically too short to implement slow underburning in conifer forest types, where only about 50 acres of underburning can be completed in a day. However, burn windows then are adequate for short-duration burns in chaparral, where it is possible to complete a 1,000- to 2,000-acre burn in one day. Moreover, we have learned that chaparral on the District does not burn well, if at all, in any season except summer and fall. A complete cycle of two cool-weather burn entries, or a mechanical treatment coupled with a cool-weather burn, needs to be done before it is feasible to ask the Air Regulators to accept long-duration underburning in the summer or fall.

Burn plans typically call for meeting resource management objectives with multiple entries. It is not necessarily the intent of the prescribed fire program to meet all objectives in one entry. Repeated burns allow burning at cooler prescriptions, consuming a little more of the fuel profile each time and increasing the distance between the ground and tree crowns. This is safer, results in fewer escapes, requires fewer firefighters, and costs less. Lower burn intensities allow ecosystems to change over a longer period of time and have less impact on wildlife, allowing them to move easily out of the way of slow-moving fires. Multiple entries reduce fuel loads over a longer period of time, producing less smoke per burn entry. Finally, repeated entries allow more time to monitor the effects of the burns so that managers are better able to learn from their experience.

Once a burn has been completed on a unit, it is scheduled for reentry in 3 to 5 years. This not only kills freshly sprouted shrubs (Biswell 1989) but also reduces the fire-caused accumulation of dead woody fuel from the first burn entry (Mutch and Parsons 1998). It is clearly a waste of time, money, and effort to burn once and not come back to reburn at an appropriate interval.

Burning in winter and early spring months is an on-again-off-again proposition. Careful monitoring of weather stations, consultation with meteorologists and air regulators, and frequent visits to the burn site are needed to assure that burn windows are not missed. As the drying trend begins in spring, burn windows become more consistent, and possibilities develop to burn on cooler aspects and at higher elevations. As one unit goes out of prescription because of dryness, another on a different aspect or at a different elevation comes into prescription.

Ideally, underburns have slow rates of spread. On first-entry burns, it is common to burn only 10-50 acres per day. Second-entry burns will burn two to three times faster because the reduced canopy cover allows more sunlight on the forest floor, resulting in drier ground fuels and higher fuel temperatures.

Strip-head ignition patterns are used when a fire will not back downhill by itself (*fig. 2*). This creates small uphill runs of 50-100 ft, depending on strip width, but long uphill runs do not occur because the fire is constantly burning either into a control line or into a previously burned strip. Fire intensity and flame length are controlled by the width of the strip. If the fire spreads downhill, we allow it to do so and make additional ignitions only along control lines. Often the best burn results occur when a fire burns downhill on its own, with little or no additional igniting from the burners. This is more typical with second- or third-entry burns (*fig. 3*), when fuel loads are considerably reduced (*fig. 4*).

Not all fire managers accept this style of burning. The thought of having a fire burn through the woods for several weeks at a time is unsettling to them, especially when a burn window occurs during fire season. Consequently, we believe that confidence, patience, and experience with underburns are significant traits to look for in burn bosses and lighters. The success of a burn is in the hands of the drip-torch operators, just as the success of a silvicultural prescription is in the hands of the tree markers (Hurley, pers. comm.)

Figure 2—First-entry burn on the west-facing slope of Patterson Mountain, Dinkey Creek Watershed, January 1998. The burn was aerially ignited using a strip-head ignition pattern, starting below the snow line and proceeding downhill. Snowfall on the third day suppressed the burn.

Figure 3—Second-entry burn on Patterson Mountain, Dinkey Creek Watershed, December 1999. This burn was aerially ignited at the top of the unit and allowed to burn downhill on its own. Some hand ignition was done to maintain a straight line of fire across the slope. This ignition pattern, together with the reduced fuel loads left after the first burn, helped control fire intensities. This burn was suppressed by precipitation on 15 January 2000.

Figure 4—Results after the second-entry burn on Patterson Mountain, Dinkey Creek Watershed, photographed in May 2000. A third-entry burn is planned for sometime between 2008 and 2012.

Results: Lessons Learned and Some Indicators

From 1994 through 2000, we were able to burn substantial acreages during January in 4 years—200 acres in 1994, 200 acres in 1997, 1,400 acres in 1998, and 2,500 acres in 2000. Obviously this burning is low intensity. It occurs on south- and west-facing slopes and usually at elevations below 5,000 ft. Pine needles and bear clover (*Chamaebatia foliolosa*) burn, as do the 1- and 10-hr time-lag fuels. These fuels create enough heat to break the bark on whiteleaf manzanita (*Arctostaphylos viscida*), which successfully kills the stem. Flame lengths are typically 18 inches or less. Duff, medium to large logs, and snags are rarely totally consumed, although large stumps will completely burn out. Readers need to keep in mind the location of the Kings River Ranger District, its climate, and its vegetation types, as some of our results are not likely to apply everywhere.

Our burns have cost about $70 per acre. The few burns that escaped cost twice that amount. One project in January, involving a helicopter equipped with a chemical ignition device (CID) and five personnel, underburned 1,400 acres in 2 days and cost $6.50 per acre. Ignition occurred 2 days before a predicted storm, which arrived on time. By burning during the moist seasons, little to no mop up is needed, resulting in a significant cost savings.

For our first underburn in 1994, we used a fuel-moisture stick index of 8 as too dry to burn safely. With more experience, however, we learned that acceptable burning can be accomplished at readings of 7 and even 6. In mixed-conifer forest, the prescription on the dry end now allows for a stick of 6 on south and west aspects. A prescription using a stick of 8 was validated to help protect white fir (*Abies concolor*) stands that are predominantly on north- and east-facing aspects, because white fir is less fire tolerant than the pine found on hotter aspects. Prescription burns are not feasible with fuel-stick values of 12 or 13—conditions are simply too wet. Lighting a strip at the top of a burn area when the fuel-stick value was 8 allowed us to get a fire to back downhill by itself through bear clover and pine needles. When sticks get to 6, watch the burn like a hawk and consider putting it out if it goes below 6 for much of the day. This will probably occur in late spring or early summer and last for a day or two. It may be prudent not to conduct ignitions at this time and to patrol for a few days until the weather changes. It is possible to get fuel-stick readings of 6 or below in the winter months of some years.

Flame length is the key indicator of fire effects above the ground on trees and brush. Our prescriptions allow for flame lengths of about 4 ft. Combined with other prescription parameters, this equates to scorch heights at about 20 ft, meaning that it is acceptable to kill everything below 20 ft. This occurs at the hot end of the prescription, but underburns are seldom ignited at this end. Usually the hot end is reached, if at all, only after several weeks of burning, and most of the burning occurs at the lower intensities. It is common to have flame lengths of 18 inches or less over the majority of a burn. Higher flame lengths occur in patches of slash and insect kill, where the intent is to have 4-ft flame lengths and 20-ft scorch heights so that those patches will be consumed. If the unit is burning with consistent flame lengths of 4 ft, however, it is probably too intense and needs to be put out or the ignition pattern altered.

An inventory of the brush on the Barnes Mountain Underburn showed that 33 percent of the area was covered in brush before the burn. The initial underburn left only 16 percent of the area still covered by brush (*table 1*) (Ballard 1998).

The desired condition for vegetation taller than 6 ft ranges from 5 to 20 percent of the area covered, which is intended to provide hiding cover and forage for wildlife, minimize fuel ladders, and maintain growth of seedlings and saplings. *Table 1* may suggest that the desired condition has been met with the first burn entry, but it is important to understand that the vegetation described in

Table 1—*Percent cover and height of various species of shrubs before and after prescribed underburning in the Kings River Sustainable Forest Ecosystems Project Area*

Species	Percent cover		Mean height (feet)	
	Preburn	Postburn	Preburn	Postburn
Arctostaphylos mariposa	26.89	10.55	10.60	10.80
Arctostaphylos mewukka	0.14	0.14[a]	5.80	([1])
Ceanothus cuneatus	3.66	3.45	8.10	8.10
Cercocarpus betuloides	1.93	1.21	10.30	9.90
Ceanothus integerrimus	0.38	0.17	9.10	9.00
Rhamnus californica	0.13	0.10	6.70	6.30
Totals	33.13	15.62	8.40	8.76

[1] Fire top-killed the shrubs; all resprouted.

the desired condition includes all vegetation, not just brush. A second fire entry is needed to kill off new obligate seeders and to avoid an over-abundance of brush by the third entry. At some point in the near future, conifers should begin to fill space now occupied by brush.

The color and amount of ash are indicators of fire effects on the soil and root systems. The Sierra National Forest's Land and Resource Management Plan specifies that most of these burn units should retain 50 percent ground cover. In the present case, we defined ground cover as any vegetative material (duff, dead limbs, trees, burned stems, etc.) that will break the fall of a rain drop before it hits the dirt. Commonly lower portions of the duff layer are retained after an underburn, but this depends to a large extent on the season of the burn, which influences the moisture content of the duff layer. Burning in January removes the litter layer but retains most or all of the duff layer. A fire then usually makes one run over the area, barely penetrating the duff layer. On the other hand, when the duff layer is in a drying trend, as in May and June, burns will make an initial pass over the area and smolder in a log or in the duff until the duff has dried out sufficiently to allow the fire to smolder through the area again, and again, until remaining fuel is insufficient to carry the fire another time. This process has been repeated up to three times on some burns in early summer. Because it can cause holding problems if the burn is not patrolled properly, this problem should be anticipated.

If the fire quickly passes through each time, the ash will be black, indicating low-intensity, short-residence time, and resulting in little if any damage to the soil or tree roots. If the fire smolders through the area, burning from the top of the duff to the soil, the ash will be white and the soil will be reddish brown and powdery. The soil may have been damaged and feeder roots on large trees may have been killed (Sackett, pers. comm.). Deep white ash is an indicator of high heat areas. This occurs on many burns, especially as the drying trend continues and/or in areas where large fuel accumulations burn out. This should be expected and monitored to determine whether the burn is meeting management objectives.

Postscript

The prescribed fire component of the Kings River Sustainable Forest Ecosystems Project is moving ahead rapidly and yielding much useful information. Although we are experiencing some resistance to the program as a result of Air Pollution Control Standards, our working relations with the local Board have been excellent, and the public has generally supported our efforts. This is a result of regular, open communication among groups and a growing realization by the public that unnatural levels of fuels have accumulated in Sierran forests and need to be reduced. Indeed, we expect the full scope of the management proposed for the Kings River Project to benefit all resources—water and watersheds, wildlife, air quality, recreation, timber supply, and so on. We must continue efforts to inform and educate the public about the need to strike a balance between full fire suppression and fuels management if we expect to attain our ultimate objectives.

Acknowledgments

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The Teakettle Experiment[1]

Malcolm P. North[2]

Abstract

A critical question in the Sierra Nevada concerns how to use disturbance effectively to restore forest ecosystems after nearly a century of fire suppression. With increases in stem densities and ladder fuels, many forests require a combination of stand thinning and controlled burning to mimic natural fire intensity. In spite of their widespread use, the different effects of fire and thinning on fundamental ecological processes have never been studied in mixed-conifer forests of the Sierra Nevada. The Teakettle Ecosystem Experiment is designed to compare these effects in an old-growth, experimental forest by applying fire and thinning manipulations in a factorial design. By using integrated sampling methods, coordinated studies will follow vegetation, soil, microclimate, invertebrate, and tree response variables before and after treatments on replicated plots. These five component studies will provide a core understanding of changes in ecosystem allocations of energy, water, and nutrients among plants and first-order consumers. Responses of these baseline processes should provide important metrics of fundamental changes in ecosystem conditions throughout higher trophic levels. This experiment can provide an important contrast of how the type and intensity of disturbance affect forest functions and succession.

A fundamental question concerning forest management in the Sierra Nevada of California involves the degree to which selective timber harvesting mimics the ecological effects of the natural fire-disturbance regime. If thinning differs from burning, what ecosystem functions and processes are being altered, what are the consequences of these changes, and how might the effects be mitigated?

In the Sierra Nevada, fire historically has been the disturbance dynamic driving forest ecosystem structure, function, and composition. If forest management is to conserve biodiversity and maintain ecosystem functions, the effects of silvicultural treatments should approximate the disturbance regime by which the flora and fauna of the Sierra have evolved. In the summary section of critical findings, the report from the recent Sierra Nevada Ecosystem Project (SNEP 1996, summary p. 4-5) emphasized that this essential information was absent:

> Although silvicultural treatments can mimic the effects of fire on structural patterns of woody vegetation, virtually no data exist on the ability to mimic ecological functions of natural fire. Silvicultural treatments can create patterns of woody vegetation that appear similar to those that fire would create, but the consequence for nutrient cycling, hydrology, seed scarification, nonwoody vegetation response, plant diversity, disease and insect infestation, and genetic diversity are mostly unknown.

Accordingly, the Teakettle Ecosystem Experiment has been designed to compare the impacts of fire and timber harvest on key ecosystem functions in old-growth, mixed-conifer forest of the Sierra Nevada.

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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Teakettle's Role in the Kings River Administrative Study

Landscape-level research, such as that in the Kings River Sustainable Forest Ecosystems Project (KR Project), is ideal for studying within a watershed such large-scale processes as hydrology, geomorphology, large animal movements and habitat requirements, and management effects on forest fragmentation. All of these processes, however, build on fundamental ecosystem dynamics, many of which operate at a much finer scale. Changes in an ecosystem are often the cumulative effect of many site-specific alterations in the exchange of energy, nutrients, and interactions within the food web. Changes in these stand-level processes can cascade through higher trophic levels, fundamentally altering a watershed's ecological dynamics.

The Teakettle Experimental Forest (Teakettle), located on the southeastern edge of the KR Project area (*fig. 1*), is typical of mixed-conifer forests in this area. Teakettle is 1,300 ha of old-growth, mixed-conifer and red fir (*Abies magnifica*) ranging in elevation from 1,980 m along the southern boundary to 2,590 m at the top of Patterson Mountain, along the northern boundary. Annual precipitation averages 110 cm at 2,100 m, falling mostly as snow between November and May. Mean, maximum, and minimum July temperatures are 17°C, 30°C, and 3°C (Berg 1990). Teakettle grades from a mix of white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), incense-cedar (*Calocedrus decurrens*), Jeffrey pine (*Pinus jeffreyi*), and red fir at the lower elevations to red fir, lodgepole pine (*Pinus contorta*), and western white pine (*Pinus monticola*) at higher elevations. Soils are generally Xerumbrepts and Xeropsamments typical of the southwestern slopes of the Sierra Nevada (Anonymous 1993).

Research Design

Ecological research requires a robust experimental design to assure that treatment responses can be detected amongst the variability inherent in complex, interactive

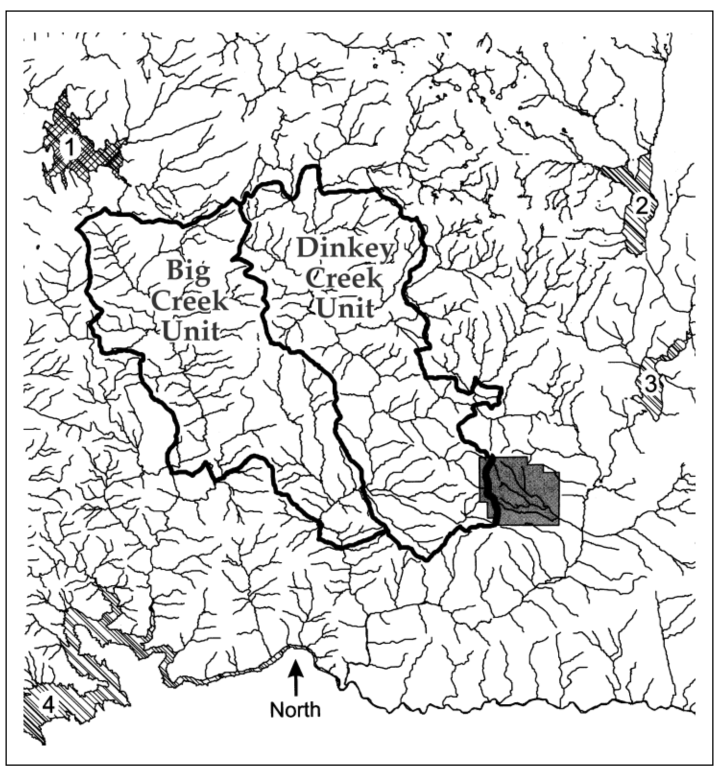

Figure 1—Teakettle Experimental Forest (shaded) abuts the southeastern edge of the Kings River Sustainable Forest Ecosystems Project area. Major water bodies are numbered: 1–Shaver Lake; 2–Courtright Reservoir; 3–Wishon Reservoir; 4–Pine Flat Reservoir.

processes. The Teakettle experiment is a controlled, replicated, manipulation study. Baseline data on ecosystem functions will be collected for 2 years on replicated treatment and control sites, followed by treatments and 4 years of data collection on responses. This design has advantages over chronosequence or comparison studies, where often little control is possible over replication or treatment effects. Furthermore, conducting multiple studies on the same sites will enable scientists to examine the interaction effects among different ecosystem components.

Selecting a plot size and identifying replicated sites can be difficult in mixed-conifer because of its variability. The size of a representative unit or stand of Sierra mixed-conifer forest has never been identified. In a new approach, this problem was addressed following a three-step process using two data sets collected during the 1997 field season.

In the first step, a field crew established a reference grid 100 by 100 m throughout the 1,300 ha of Teakettle using a surveyor's total station, permanently marking each point with Cartesian coordinates, and sampling vegetation. These data were analyzed with cluster analysis, and all mixed-conifer association points were mapped. In the second step, soils within the mixed-conifer areas were surveyed using soil pits and augur extraction. The most common soil was a well-drained, mixed, frigid Dystric Xeropsamments, formed from decomposed granite typical of many southern Sierra forests (Anonymous 1993). Mixed-conifer areas with other soil types were eliminated from further consideration.

In the final step, a grid 50 by 50 m was established within the selected areas, and vegetation was intensively surveyed (20 percent sample of the area). We used two methods to determine plot size and how to replicate mixed-conifer's heterogeneity. Plot size was determined by calculating the distance from a fixed point required to incorporate the full range of variability in the vegetation data. Basal-area-by-species data were converted to linear, univariate values using eigenvalue scores from a principal components analyses. A variogram analysis (Anonymous 1991) indicated that 58 percent of the data's variability was present even in adjacent points (the relative nugget effect) and that points 180 m apart were spatially independent (the sill value) (Bailey and Gatrell 1995). The large nugget effect implied that an effort to use a small plot to replicate vegetation would be difficult. By using the sill value as a guide, a plot size of 200 by 200 m was selected as large enough to include the range of variability within Teakettle's mixed-conifer forest.

In the second method, vegetation data were analyzed with cluster analysis and all 50-by-50-m points were mapped as one of the four identified clusters. The relative percentages of each cluster type were calculated (for example 11 percent of all points were type 1) and plot windows of 200 by 200 m were moved over the grid points until the enclosed set of points contained a representative ratio of the four cluster types. Tree density, basal area, and species composition were compared with one way ANOVA and 18 plots were selected with no significant difference ($P > 0.05$).

Treatments

In forests, many structural components such as litter depth, tree size, shrub cover, and snag and log volumes covary. Covariance can make it difficult to isolate and identify processes, and multicollinearity among measured variables can significantly weaken data analysis (North and Reynolds 1996). Although it is with reservation that the experiment proposes manipulating old growth, some perturbation is required to tease apart the covariation of components in a forest ecosystem.

Six stand conditions will be determined by combinations of fire and tree removal (*table 1*). Each of these six conditions will be replicated three times on 4-ha plots. Burn treatments will have two levels: no burn and a ground fire. The burn is designed to mimic the historical disturbance regime by containing the

Table 1—*Full factorial design of the Teakettle Experiment*

Thinning level	No burn	Understory burn
None	Control	Burn only
From below	Light thin/No burn	Light thin/Burn
Shelterwood	Heavy thin/No burn	Heavy thin/Burn

flames to a ground fire and avoiding overstory crown ignition (Skinner and Chang 1996). Ladder fuels—understory trees with tops within 5 m of overstory tree crown bases—will be felled and left on the ground prior to burning.

Thinning treatments will contrast three levels of tree removal: no removal (present forest conditions), removal of the understory (thinning from below), and removal of the overstory (shelterwood harvest). Understory thinning removes all trees with a diameter at breast height (dbh) ≤76 cm, and overstory thinning removes all stems >30 cm in dbh, except 15-18 of the largest trees per ha.

Understory thinning mimics stem reduction patterns noted in post-wildfire studies in the Sierra Nevada, where mortality is associated with a tree's size and canopy position (McKelvey and Johnston 1992, Weatherspoon 1996). Many smaller trees are shade-tolerant species with thin bark and a low crown base, so they ignite easily. While understory thinning may mimic the tree structure produced by a ground fire, the removal of stem wood and increase in litter and shrub cover will produce a significantly different effect on carbon pools and flows. Sierra National Forest personnel will mark and administer the thinning, following current guidelines outlined in the California Spotted Owl (CASPO) Report (Verner and others 1992).

Overstory thinning removes most of the stand's large structures, leaving 15-18 widely spaced, dominant trees per ha and regenerating trees with a dbh <30 cm. This method is used to mimic stand structure 40 years after an intense wildfire in which small-diameter regeneration is filling in the gaps between a few widely spaced, "legacy" trees (Skinner and Chang 1996, Stephenson and others 1991). Although a less frequent disturbance historically, these types of fire may have provided the large openings required for pine regeneration and be important for creating mixed-conifer's combination of shade-tolerant and intolerant species. Overstory thinning will produce a distinct tree structure, composition, and distribution from ground fire or understory thinning treatments.

Research Studies

Multiple-study or "pulse" research at a common site allows scientific collaboration across disciplines and can provide insights into ecosystem interactions often hidden from single-study experiments. The Teakettle Experiment focuses on elemental pathways in a forest ecosystem—nutrients, moisture, energy, and food—and their allotment among soil, plants, invertebrates, and "higher" animals (*fig. 2*).

In each study, conditions will be monitored for 2 years before and 4 years after treatments (*table 2*). Detailed information on sampling protocol is available at the Teakettle Experiment website (http://teakettle.ucdavis.edu).

Post-treatment analyses will examine both treatment-induced changes in the pathways, in kind and magnitude, and the dynamic relations among the components as the system responds to disturbance. This allows for revision of a model's hypothesized pathways developed from the pretreatment analysis, as well as exploration of temporal feedbacks arising from the different disturbances.

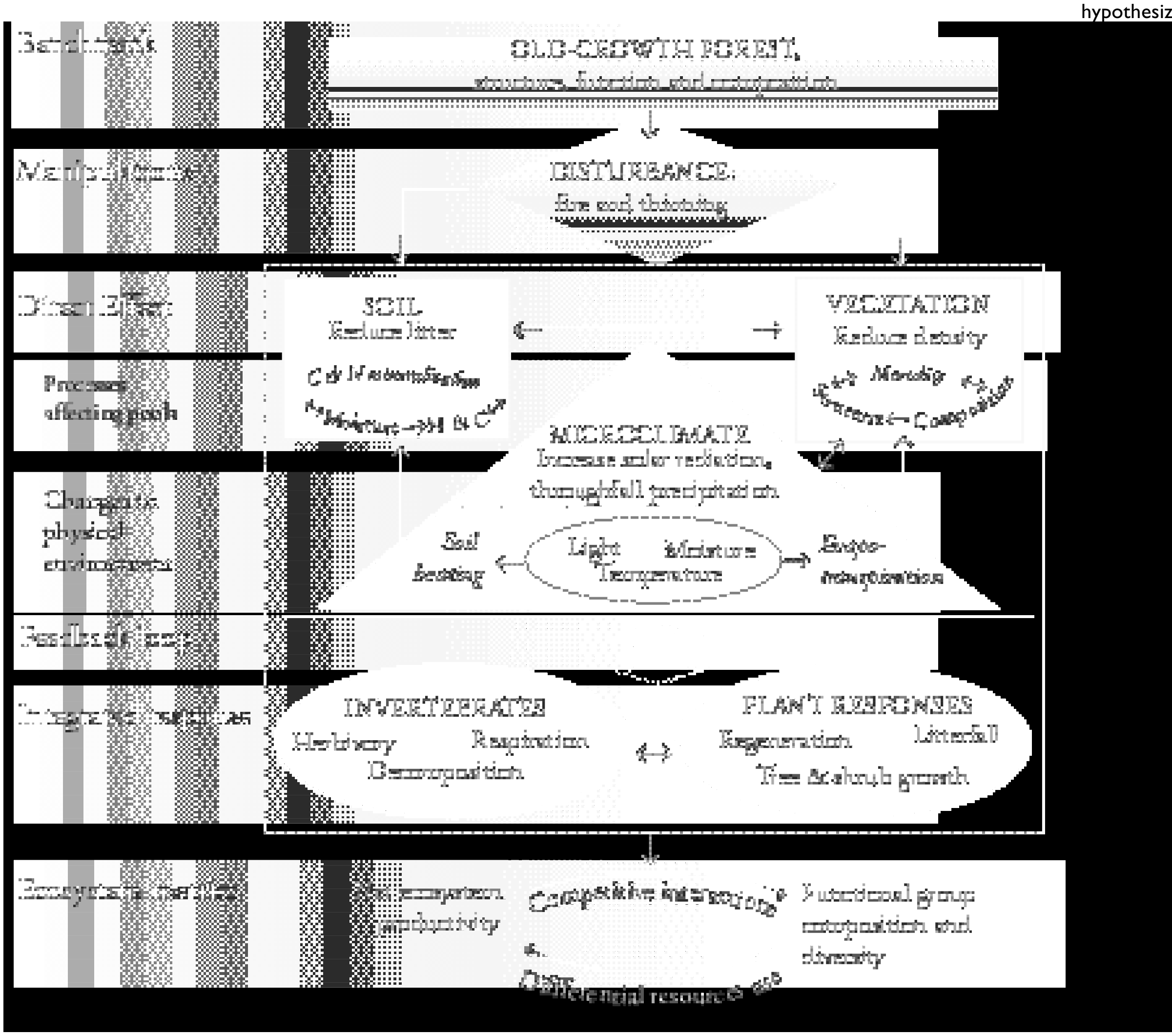

Figure 2—Schematic of the hypothesized interactions of ...mponent studies ...ettle Experiment. ...s in the ... are: the five ... studies; ...interactions that ...hways within the ...erall ecosystem ...hich is shown at ... *C* = carbon, *N* =

Project Coordination and Data Integration

A common sampling design was developed with the project's statistician to ensure that component studies collect data at the same mapped sample points. The goal of this design is to measure plot-level differences among the six treatments as well as to assess spatial variation within a treatment. Mixed-conifer forests are highly heterogeneous, and we expect data values within a plot to vary in response to small-scale changes in forest conditions, such as canopy cover, stem density, and litter depth. To address this variability, one replicate of each of the six treatments will be sampled intensively on a seven-by-seven grid (points spaced 25 m apart, including a 25-m buffer to the plot boundary). These 49 within-plot samples serve to determine the scale at which data points for a particular measure become independent, using variogram analysis. To interpolate among the discrete sample points, a response surface for each plot will be calculated using kriging analysis. A three-by-three grid with points spaced 50 m apart will be used at the two other replicate plots in each treatment. Data from these points will be averaged to calculate a mean plot response. Mean plot values from both sampling schemes will allow tests for significant differences among replicates.

We will convert data from the mapped grid locations to layers in a geographic information system (GIS), using ARC/INFO and linked to S-Plus, allowing the use of spatial statistics. Pretreatment analyses will be static examinations across space to detect the kinds of pathways and their magnitudes between specific components. GIS layers will be examined for patterns of spatial concordance among different variables. For example, soil sites with abundant invertebrates also may have high nitrogen levels or ceanothus shrubs. Robust data visualization tools, and bivariate Ripley's K analysis will be used (Diggle 1983) to test for significant associations among component measures within treatment plots. Associations involving nonspatial component measures will be investigated using multi-dimensional scaling, canonical correlation analysis, and regression techniques appropriate to each data set (Jongman and others 1995). Associations will be used to develop hypothetical models of ecosystem pathways.

Table 2—*Research studies, scientists, and their institutional affiliation cooperating in the Teakettle Experiment*

Study	Principle Investigator	Institution
Tree pathogens	Tom Smith, Dave Rizzo	University of California, Davis
Fire history and stand reconstruction	Jim Bouldin, Michael Barbour	University of California, Davis
Small mammal diets, movement, and demography	Marc Meyers and Douglas Kelt	University of California, Davis
Fire history	Robert Figener, Michael Barbour, and Malcolm North[1]	University of California, Davis
Epiphyte diversity and response	Thomas Rambo, Malcolm North[1], and Michael Barbour	University of California, Davis
Decomposition	Martin Jurgensen	Michigan Tech. University, Houghton
Microclimate, soil respiration, and NEP[2]	Siyan Ma and Jiquan Chan	Michigan Tech. University, Houghton
Canopy and shrub invertebrates	Timothy Schowalter	Oregon State University, Corvallis
Tree regeneration and soil moisture	Andrew Gray	USDA Forest Service, Inventory and Monitoring Program, Portland, OR
Soil and CWD[3] invertebrates	Jim Marra and Robert Edmonds	University of Washington, Seattle
Ceanothus, nitrogen, and *Frankia* response	Brian Oakley, Jerry Franklin, and Malcolm North[1]	University of Washington, Seattle
Mycorrhizal diversity and response	Antonio Innez and Thomas Bruns	University of California, Berkeley
Soil nutrients	Heather Erickson	Universidad Metropolitan, SanJuan, PR
Tree/shrub growth, mortality, and distribution	Malcolm North[1]	USDA Forest Service, PSW ResearchStation, Fresno, CA
Truffle abundance and diversity	Malcolm North[1]	USDA Forest Service, PSW ResearchStation, Fresno, CA
Herb diversity and response	Malcolm North[1]	USDA Forest Service, PSW ResearchStation, Fresno, CA

[1] Project Coordinator, USDA Forest Service, Pacific Southwest Research Station, Fresno, California.

[2] Net Ecosystem Productivity

[3] Coarse Woody Debris

Importance to Long-term Research and Management Issues in the Sierra Nevada

For millennia, fire has shaped the forests of the Sierra Nevada. The ecological linkages among plants, animals, soil, and climate were forged long before modern management practices commenced. The last several decades of selectively harvesting large pines and suppressing fires does not have a historical precedent. Under this condition of deflected succession, ecosystem processes may have moved outside their historical range, reducing any options for managers to allow the forest to heal itself. Many forests are now thickets of fir and incense cedar, which can "ladder" fires into the crowns of the old-growth overstory canopy. These stands will eventually suffer catastrophic fire in which all trees will be killed and much of the soil will be sterilized. Research should help facilitate proactive ecosystem management of the Sierra Nevada by providing information on the impacts of forest practices on ecological functions. The central question of the Teakettle Ecosystem Experiment is, therefore, one of fundamental importance to management in the Sierra Nevada: "How can foresters responsibly mimic the natural fire regime?"

Acknowledgments

This project has been an interdisciplinary effort with significant assistance from the scientists listed in *table 2*, as well as many Sierra National Forest personnel who have been invaluable in planning the treatments for the experiment. Joel Reynolds and Bill Laudenslayer provided helpful comments on the draft manuscript.

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Watershed Analysis[1]

Alan Gallegos[2]

Abstract

Watershed analyses and assessments for the Kings River Sustainable Forest Ecosystems Project were done on about 33,000 acres of the 45,500-acre Big Creek watershed and 32,000 acres of the 85,100-acre Dinkey Creek watershed. Following procedures developed for analysis of cumulative watershed effects (CWE) in the Pacific Northwest Region of the USDA Forest Service, the present project is comparing the Equivalent Roaded Area (ERA) method used widely in the Pacific Southwest Region of the Forest Service, a method that has several inherent weaknesses. Selected stream reaches have been described in terms of Rosgen channel types, Phankuch stream stability, and V-star ratings. Preliminary results from the ERA method indicate that 4 of 15 subwatersheds in the Big Creek watershed and 7 of 33 subwatersheds in the Dinkey Creek watershed are at or above the threshold of concern. Results from the ERA method indicate that several subwatersheds, but no stream reaches, are of concern. By contrast, results from more specific stream surveys, an inventory of fish habitat conditions, and data on sediment delivery attributable to roads indicate concern for several stream reaches as well.

The Kings River Sustainable Forest Ecosystems Project area is located in Fresno County, approximately 32 air miles northeast of Clovis, California (*fig. 1*). About 33,000 acres of the 45,500-acre Big Creek watershed and 32,000 acres of the 85,100-acre Dinkey Creek watershed are included within the Project's boundaries. Both watersheds drain into the Kings River above Pine Flat Reservoir. Most of the two watersheds are within the Sierra National Forest, although 6,896 acres are on private land.

The Big Creek watershed ranges in elevation from about 1,000 to 6,400 ft, and the Dinkey Creek watershed ranges from about 1,250 to 10,000 ft. Each watershed is subdivided into several subwatersheds—15 for Big Creek and 33 for Dinkey Creek—within the Project's boundaries. These subwatersheds range in size from about 190 to 2,760 acres and average about 1,500 acres. Precipitation, mostly during fall, winter, and spring, ranges from 20 to 80 inches, occurring primarily as snow above 6,000 ft. Rain on snow is common. Summers are dry with low humidity. Air temperature averages from 42 to 60^{o} F. Vegetation types are mixed chaparral, ponderosa pine (*Pinus ponderosa*) forest, mixed-conifer forest, and red fir (*Abies magnifica*) forest.

Cumulative watershed effects (CWEs) are impacts to the environment resulting from the incremental accumulation of impacts of actions, past, present, and in the foreseeable future, regardless of what agency (Federal or nonfederal) or person undertakes these actions. CWEs can result from individually minor but collectively significant actions occuring over a period of time.

The current model used to analyze CWEs—the Equivalent Roaded Area (ERA) method (McGurk and Fong 1995, USDA 1988)—has several inherent

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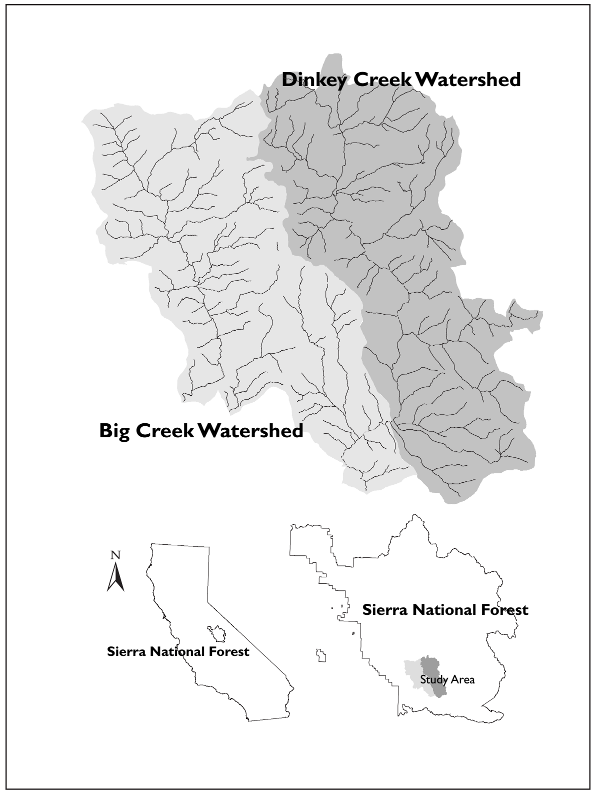

Figure 1—The Kings River administrative study area in the Sierra National Forest in central California includes the 64,000-acre Big Creek and Dinkey Creek watersheds (indicated by shading).

weaknesses, including equal coefficients for disturbances regardless of their distance from stream channels, a lack of sensitivity to sediment yields, and the scale at which the model applies. Current USDA Forest Service direction for ecosystem management requires the development of better methods and models for assessing cumulative watershed effects.

The various processes and interactions occurring within a watershed are integral to any project that endeavors to apply science-based concepts of ecosystem managment at a watershed scale. The watershed analysis briefly described here was undertaken to help understand these processes and interactions in the two watersheds in the Project area. Additional objectives are to characterize current watershed conditions and to develop and test an improved method or model to assess cumulative effects of management activities on watersheds.

Methods

Selected stream reaches can be described in terms of Rosgen channel types (Rosgen 1994), Phankuch stream stability (Phankuch 1975), and V-star ratings. Together, these data sources can be combined to describe stream channels as aquatic ecological units. The Rosgen stream channel classification divides stream reaches into seven major types that differ in entrenchment, gradient, ratio of width to depth, and sinuosity. Each major stream type is further described by dominant channel material along a continuum from bedrock to silt/clay.

Determination of Phankuch stream stability is a procedure to systematize measurements and describe the resistive capacity of mountain stream channels to the detachment of bed and bank materials and to provide information about the capacity of streams to adjust and recover from potential changes in flow, increases in sediment production, or both.

The V-star rating provides a cross-sectional sample of the depth of fine sediment at the bottom of a stream. It is obtained by pushing a slender, steel bar vertically through the sediment to bedrock or bed load at regular intervals perpendicular to the stream's course and recording the depth of sediment at each point. These data then permit estimation of the fraction of a pool's volume that is filled with fine sediment—an index of sediment supply, water quality, and stream habitat (Lisle and Hilton 1992) (*fig. 2*).

The watershed analysis identified several issues, the most important being CWEs. These can be evaluated in part by determining the sources of high sediment loads in Big Creek and the condition of aquatic habitat in both watersheds. Ecological indicators selected to establish baseline conditions and monitor watershed conditions are ground cover, rates of erosion and sediment delivery, and landslide frequency. ERA is the indicator of CWEs for the ERA method. V-star ratings and the number of benthic macro-invertebrates have been selected as indicators of the quality of fish habitat.

All subwatersheds in both watersheds were mapped and delineated in 1991 to ensure consistent analysis of CWEs. Watershed analyses followed procedures developed for use in the Forest Service's Pacific Northwest Region, as described by Furniss and McCammon (1993):

- Identify issues, describe desired conditions, and formulate key questions.
- Identify key process, functions, and conditions
- Stratify the watershed.
- Assemble analytic information needed to address the key questions.
- Describe past and current conditions.
- Describe condition trends and predict effects of future land management.
- Integrate, interpret, and present findings.
- Manage information, monitor, and revise.

CWE analyses were done for Big Creek and Dinkey Creek using the ERA model, a decision-based model that attempts to equate impacts of projects to the impacts of a given acreage of road disturbance. The ERA model has three steps:

1. Determine the threshold of concern (TOC)
2. Determine existing and potential ERAs
3. Determine the potential for CWEs.

Step 1—Determine the Threshold of Concern

The TOC is determined for each subwatershed, based on its natural sensitivity. Subwatersheds have higher TOCs when they have high percentages of sensitive landforms (steep ground, landslide potential), highly erodible soils, and highly

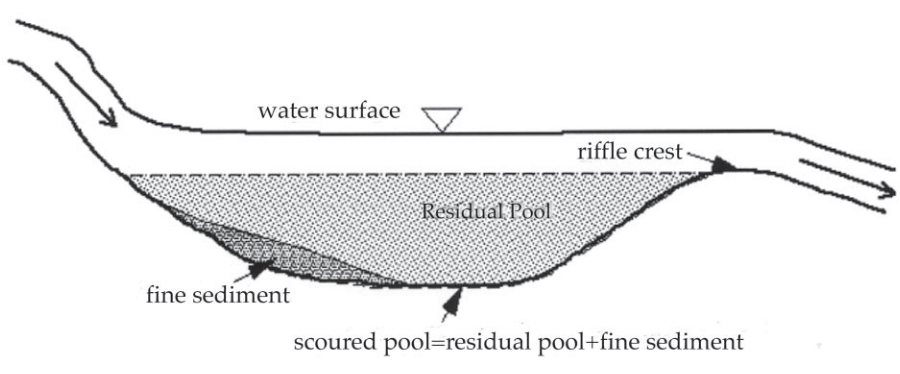

Figure 2—Schematic cross section of a pool along its longitudinal profile, showing fine sediment and residual pool.

bifurcated networks of stream channels. The Sierra National Forest uses low, moderate, and high sensitivity levels, ranging from 3.5 to 6.0 ERAs, to reflect TOCs. These values have been corroborated with field data: watersheds with sensitive landforms, highly erodible soils, and a high bifurcation ratio responded to disturbance with compacted soils, high amounts of sediment in stream channels, and less than optimum fish habitat.

Step 2—Determine Existing and Potential ERAs

The management history of affected subwatersheds is determined, and each ground disturbance is rated and assigned an ERA coefficient according to the nature and age of the disturbance. Hydrologic recover is considered when determining the ERA for any given disturbance, assuming that a disturbance could recover to an ERA value of nearly zero if enough time has passed. Values for various existing disturbance areas are then summed to estimate the total existing percent ERA value for the subwatershed. Values for proposed activities are then assigned an ERA coefficient using those established for the Sierra National Forest, and these are summed with the existing ERA values to estimate a total ERA value for the subwatershed if the activities were to occur.

Step 3—Determine Potential for CWEs

If the total ERA for a given subwatershed exceeds the TOC, it is determined to have a higher risk for CWEs. In addition, qualitative field data may be collected to determine whether CWEs are occurring. These field data could include stream condition inventories, soil quality, and condition of fish habitat. In some cases, activities have been postponed to allow natural recover, or watershed restoration has been undertaken to speed recover. In other cases, the proposed activity was implemented after site investigations found healthy soils and streams.

A Model for Watershed Condition

The model for assessing watershed condition is a process-based model that can be applied at several scales and considers natural disturbances to determine whether a watershed is degraded. The model evaluates conditions and interrelations of upland watershed areas and riparian areas. It can be used for any of the aforementioned ecological indicators (for example, ground cover and sediment delivery rates). The model has five steps that can be done concurrently or consecutively. I use rates of erosion and sediment delivery as examples to describe the model.

Step 1—Stratify the Watershed

Watersheds in the Kings River Project area were stratified using data from the Forest Service's existing Ecological Unit Inventory (EUI), which can be used to classify and delineate areas of similar ecological form and function (*fig. 3*). Components of an ecological unit include bedrock or unconsolidated deposits, geomorphic processes and landform, soil type, and potential natural vegetation.

Step 2—Describe the Reference ("Normal") Variability for Rates of Erosion and Sediment Delivery

Earlier studies estimated mean rates of sediment delivery at 110 tons/mi^2/year for the North Fork of the Kings River (Breazeale 1972) and 43 tons/mi^2/year for small basins in the Teakettle Experimental Watershed (Dunne and Reid 1985). These estimates are mean, long-term rates for watersheds with heterogeneous geology, geomorphology, soils, and vegetation. The studies did not consider natural disturbance regimes or the range of variation among areas as they recovered from disturbances.

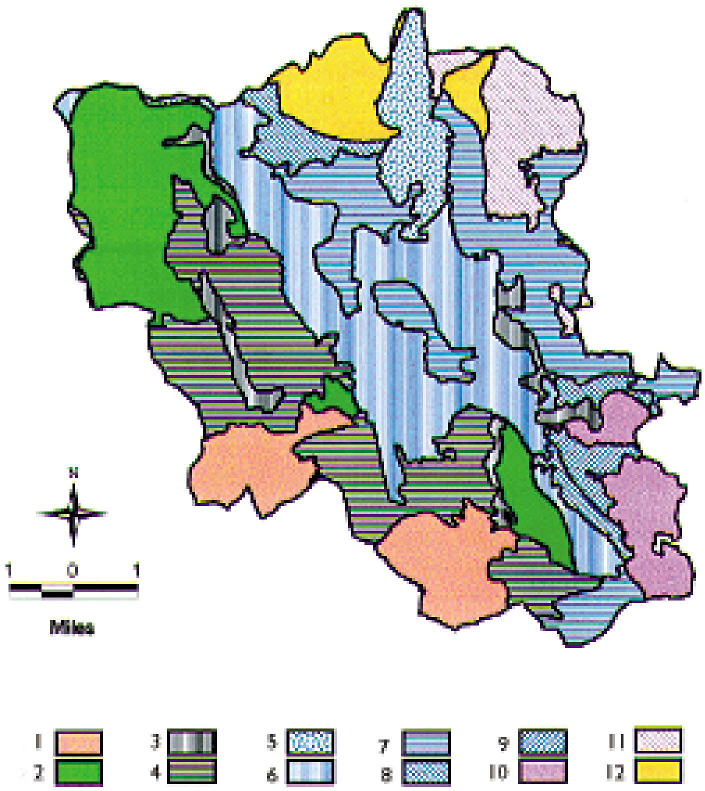

Figure 3—Ecological landscape units stratifying the Kings River Project area by geology, soils, geomorphology, and potential vegetation: 1 = Granodiorite; deep to moderately deep thermic (Auberry-Ahwahnee, Tollhouse complex); mass wasting, fluvial; chaparral. 2 = Granodiorite; deep mesic (Holland-Shaver complex); fluvial, mass wasting; ponderosa pine. 3 = Granodiorite; shallow, mesic (Chawanakee-Tollhouse complex); mass wasting, fluvial erosion; ponderosa pine. 4 = Granodiorite; deep mesic (Holland family); fluvial erosion, mass wasting; ponderosa pine. 5 = Glacial deposits, Granodioarite; deep, frigid (Sirretta family; mass wasting, fluvial, relic glacial depositional; mixed conifer. 6 = Granodiorite; deep, mesic (Shaver-Holland complex); fluvial, mass wasting; mixed conifer. 7 = Granodiorite; moderately deep to deep, frigid (Ledford-Gerle-Cannel-Cagwin complex); fluvial; mixed conifer. 8 = Granodiorite; moderately deep, frigid (Cagwin family); mass wasting, fluvial; mixed conifer. 9 = Metamorphic; deep, frigid (Ledford-Gerle complex); fluvial; mixed conifer. 10 = Metasedimentary; moderately deep to deep, frigid (Cagwin-Cannel complex); fluvial; red fir. 11 = Mixed lithology; moderately deep to deep, frigid (Cagwin-Sirretta complex); fluvial, relic glacial; red fir. 12 = Granodiorite; moderately deep to shallow, frigid (Cagwin-Rock Outcrop complex); fluvial, mass wasting; Jeffrey pine.

The reference variability for rates of erosion and sediment delivery, in tons/mi^2/year for each major ecological map unit of the two watersheds, will be determined by modeling fire and high precipitation events as the major disturbances. For example, rates of erosion and sediment delivery are at their highest in the first year after a fire, decreasing over time as vegetation recovers. Eventually these rates would be expected to fluctuate mainly in response to variation in precipitation events, then characterizing the "reference variability."

Step 3—Describe Existing Rates of Erosion and Sediment Delivery

Most erosion and sediment delivery in the Sierra Nevada are assumed to be a result of roads and stream channels. Landslides are not believed to be a major source of sediment. Data have been collected from 50 mi of roads in the Project area to use in the Watershed Erosion Prediction Project (WEPP) model (Elliot and Hall 1997). This is a process-based model with several output options including runoff, soil erosion, and sediment delivery. These data will quantify rates of erosion and sediment delivery for different types of roads (native surface, aggregate surfaced, asphalt surfaced) in different ecological units (major strata).

Step 4—Describe the Conditions of the Aquatic System

Existing data allow description of selected stream reaches in terms of Rosgen stream channel types, Phankuch stream stability, and V-star ratings. Initial

Figure 4—Section of Big Creek showing desired condition of a cobble/gravel-controlled, pool-riffle reach. Notice lack of fine sediment.

analysis of 33 V-star reaches showed that 30 percent had high sediment loads (*fig. 4*). It is not clear, however, whether this has resulted from management disturbances, from natural events, or both. Quantifying sediment sources and estimating rates of sediment transport should help to answer this question.

Step 5—Synthesize Available Data

Synthesis of available data should establish whether rates of erosion and sediment delivery are within the reference variability. If not, then channel reaches that have high sediment loads and degraded conditions will be assessed to determine which subwatersheds are the sources of sediment. These sources could include native-surfaced roads, other disturbances (for example, gullies) on highly sensitive soils, and extensively in-sloped roads adjacent to channel and road crossings.

Final Step—Identify Opportunities for Watershed Improvement

Opportunities for watershed improvement could include surfacing native-surfaced roads with gravel or asphalt, redesigning roads from an in-sloped to an out-sloped road prism, obliterating roads in highly sensitive areas, tilling highly compacted soils, and stabilizing gully systems that have developed from past management.

Preliminary Results

A strategy to collect additional data and address the key questions identified in the watershed analysis has been approved and is being implemented. Results of our efforts to develop the conceptual model have resulted in completion of Step 1 and some progress with the remaining steps. A more detailed, landtype-level (1:24,000) EUI has been completed to stratify the watershed by geology, soils, land-forming processes, and potential natural vegetation. Interpretations have been made to describe sensitive landforms, erodible soils, and potential wildlife habitat. This inventory aided in the delineation of boundaries for riparian management zones in the Big Creek watershed, where those boundaries are set according to guidelines in the Sierra National Forest's Land Management Plan. Some data have been collected and analyzed to determine the reference variability for erosion and sediment delivery rates. These data are being compared with data from other areas in the Sierra Nevada to establish long-term rates for erosion and sediment delivery. Preliminary work has been done to develop a landscape model using these data. Some of this work includes erosion and fire-spread modeling. The next phase is to integrate results from these models.

More than 50 miles of road data have been collected, including road design (width, insloped with ditch or outsloped, slope gradient), surface type, soil type, rill and gully erosion, and percent vegetation on the road cut and fill. These data are being analyzed to determine mean rates of erosion and sediment delivery for road types that occur in unique ecological units.

Stream-condition surveys, including Rosgen Channel typing, have been completed on several of the main tributaries to Dinkey Creek and the main stem of Big Creek. Macroinvertebrate data have been collected from 16 first- and second-order streams in the two watersheds. A final determination about watershed health, however, will not be made until all data are collected and an improved model is developed to analyze watershed condition.

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Effects of Soil Disturbance on the Fundamental, Sustainable Productivity of Managed Forests[1]

Robert F. Powers[2]

Abstract

Environmental policies in the United States and abroad are reducing timber harvests while wood demand is mounting. Reduced harvesting on public lands means that privately owned lands will be managed with greater intensity in the United States and that wood will be imported from other nations lacking strong environmental safeguards. It is imperative, therefore, that both public and private forest lands be managed to sustain their productivity, and many nations are seeking effective monitoring methods. Central to this is our ability to estimate a site's fundamental capacity for growing vegetation, and to detect changes in this capacity caused by management. Because soil is the factor of a site modified most easily and profoundly by management, and because soil largely is independent of the current condition of vegetation, soil-based variables offer our most effective and practicable indices of sustainable productivity. The North American Long-Term Soil Productivity cooperative research program (LTSP) is the world's most extensive coordinated effort to address questions of sustainable productivity in managed forests. Early findings from the 12 LTSP sites in California illustrate the physical importance of organic soil cover in reducing soil erosion and maintaining favorable soil temperature and moisture relations during summer drought. Findings also show that the biological significance of soil compaction depends on soil texture. Moderate compaction degrades vegetative growth on fine-textured soils but can enhance growth on coarse-textured soils where drought is a factor. Impacts of soil compaction on tree growth often are masked by effects of competing vegetation. Measurements taken under operational conditions show that compaction associated with mechanized thinning can reduce soil rooting volume by as much as one-half. Subsoiling seems to mitigate the effect. Root damage caused by subsoiling did not adversely affect the growth of residual trees. Results are providing practicable field methods for monitoring management impacts on sustainable productivity.

Forests offer many values and commodities beyond wood production. Concerned that forests have suffered from overemphasis on timber, environmentalists call for more conservative forest management practices that reduce wood harvest and preserve or restore other ecological values (Drengson and Taylor 1997). On many public lands of the western United States—historically a major source of domestic timber—harvesting continues, but at a rate less than one-third that of the last decade (USDA Committee of Scientists 1999). Pressure to de-emphasize wood production here and abroad comes while the land area formerly available for production forestry is shrinking at an annual rate of 0.4 percent (FAO 1997).

Paralleling the trend on public lands of the United States, a "green advocacy" has gained momentum and has spawned an expansive international industry to certify what is, and is not, "sustainable forestry" (Hammond and Hammond 1997, Journal of Forestry 1995). In general, leading forest scientists

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agree that timber harvesting, if conducted so as to preserve potential site productivity, need not compromise other ecosystem values (Attiwill 1994, Kimmins 1996). Many in North America's private forestry sector are skeptical of third-party "green certification" where criteria may be based more on speculation than on science (Berg and Olszewski 1995). Yet, ignoring green certification could limit markets for industrial wood.

Progress has been made toward developing more uniform and objective standards for green certification. The central international body is the Forest Stewardship Council with two affiliates in the United States—SmartWood and Scientific Certification Systems (Mater and others 1999). Green certification aims at protecting multiple forest values and long-term site productivity, but advocates often seem naïve and myopic. If all the world's forests were managed under green certification standards of the Forest Stewardship Council, harvests would average 0.7 m^3 ha^{-1} annually (Binkley 1997). Unfortunately, this average would require a one-third increase (1.1 billion ha) in global forest area just to meet the current wood demand of the world's population. Kimmins (1996) points out that popular standards for green certification often are so stringent that harvested yields are lowered by more than if the sites had been severely degraded by exploitative management. Implications of mandating unnecessarily low harvests are serious. World population and demand for wood products are rising at similar rates (FAO 1997). This demand permeates all societies (FAO 1997) and increases by 70 to 80 million m^3 annually—a volume equivalent to British Columbia's entire allowable cut in 1993 (Kimmins 1996).

Reduced wood production from green-certified nations creates a strong incentive for other countries to accelerate forest harvesting beyond sustainable levels to reap the rewards of global demand (Kimmins 1996). A scarcity in domestic wood supply will raise wood prices, stimulating consumer preference for nonrenewable substitutes. Recent studies show that with each 1 percent rise in the price of softwood lumber, the use of cement rises by 0.15 percent, structural steel by 0.3 percent, and brick by 0.65 percent (Binkley 1997). Sustaining the productivity of United States forests, regardless of ownership, is in our national interest.

Currently, a simple definition of "sustainable forestry" lacks international consensus (Nambiar and Brown 1997, Sullivan 1994). No one in good conscience can support management practices that degrade forest productivity. The problem is how to produce more wood from less area without impairing the land's potential to provide other social benefits now or in the future. Clearly, the need for a closer linkage between management and research in the forest planning process has never been stronger (USDA Committee of Scientists 1999).

This paper describes the genesis of the North American Long-Term Soil Productivity (LTSP) cooperative research program and summarizes results from the various component studies done to date in the Sierra Nevada and Cascades of California.

Developing Indices of Sustainable Forestry

An International Movement

The United Nations Conference on Environment and Development of 1992 ("The Earth Summit") led to a nonbinding agreement to establish principles for sustainable forest management (United Nations 1992). As a result, international committees have formed to develop criteria and indicators for the conservation and sustainable management of forests of the world. One such committee met informally in Montreal, Canada, in 1993. Deliberations of what has come to be called "The Montreal Process" culminated in a 1995 meeting in Santiago, Chile. There, in the "Santiago Declaration," representatives from Argentina, Australia, Canada, Chile, China, Japan, Republic of Korea, Mexico, New Zealand, Russian Federation, Uruguay, and the United States agreed to develop, implement, and continually update nonbinding criteria and indicators for the sustainable management of temperate and boreal forests (Canadian Forest Service 1995). A first step is to find an unambiguous, effective, and objective way to monitor the land's health that covers all levels of management intensity.

Monitoring Productivity Directly

The fundamental indicator of a forest's well-being is the rate at which atmospheric carbon is captured photosynthetically and accumulated as organic matter. This rate is termed "net primary productivity" (NPP). In turn, NPP is the common basis for most fundamental ecosystem processes that produce the characteristics of forests valued by society. Accordingly, degrading a site's NPP potential also degrades its potential for producing flora, fauna, habitat, clean and abundant water, and recovery from disturbance. Monitoring the departures in NPP from baseline conditions would give us a sensitive measure of the health of a forest ecosystem and whether it is agrading, degrading, or stable. Unfortunately, NPP is extremely difficult to measure. Current rates are affected not only by site quality, but also by the present age, stocking, and structure of the forest. Therefore, they may not indicate the site's true potential at full stocking, or "leaf area carrying capacity" (Grier and others 1989, Powers 1999b, Waring and Running 1998). And even at full stocking, it is almost impossible to measure NPP accurately in forests of irregular structure. An unbiased surrogate for NPP is needed that is independent of the current condition of the vegetation.

The Soil Quality Approach

Soil can be a strong and independent surrogate for measures of potential NPP. Together with climate and biotic potential of vegetation, soil forms the foundation for forest production. As recognized in the Montreal Process and Santiago Agreement, soil-based indicators of sustainable forestry must include measures of erosion, organic matter, compaction, nutrient cycling, and pollution (Ramakrishna and Davidson 1999). The USDA Forest Service recognized this requirement well in advance of the Montreal Process. The National Forest Management Act of 1976 mandates that the USDA Forest Service must manage public forest lands without impairing their permanent productivity. Accordingly, and in consultation with Forest Service Research, the Watershed and Air Management Staff of the USDA Forest Service adopted a program for monitoring the effects of management practices that is based on the following logic: management practices create soil disturbances; soil disturbances affect soil and site processes; and soil and site processes control forest productivity.

Monitoring soil and site processes is not feasible at an operational scale. Therefore, USDA Forest Service monitoring strategy centers on measurable soil variables, which, if altered beyond a threshold, indicate that potential productivity has been degraded. These thresholds of soil quality are based partly on research, but largely on professional judgment. Threshold standards for the USDA Forest Service Regions of the United States have been summarized by Powers and others (1998). Current standards for the Pacific Southwest Region are shown in *table 1*. Although these standards represent a progressive step, they are not universally accepted.

The LTSP Program

Guidelines suggested by the Montreal Process are vague and too general to be useful in operational monitoring. The USDA Forest Service's standards for monitoring soil quality (*table 1)* are much more specific but still based on conclusions drawn largely from scattered, anecdotal—and sometimes contradictory—research. This creates problems. Because the standards have not

Table 1—*Current standards of soil quality adopted by the Pacific Southwest Region, USDA Forest Service (Powers and others 1999b). Standards indicate thresholds for significant soil degradation.*

Variable	Quality standard
Operational area	Standards extend to all land capable of growing vegetation
Erosion	Not to exceed rate of soil formation, or about 2 Mg ha^{-1} yr^{-1}.
Soil cover	Forest floor covers less than 50 percent of area.
Organic matter	Litter and duff cover less than 50 percent of area. Fewer than 12 decomposing logs ha^{-1} at least 30 cm in diameter and 3 m in length.
Infiltration	Reduced to ratings of 6 or 8, as defined by Regional Erosion Hazard ratings. Extent depends on cumulative watershed effects analysis.
Compaction	Total soil porosity reduced more than 10 percent, depending on soil type, over an area large enough to reduce productive potential.
Displacement	Soil organic matter in upper 30 cm reduced more than 15 percent from natural conditions. Affects enough area that productive potential is reduced.

been calibrated against true measures of potential productivity, they may be too restrictive in some cases and too lenient in others. Without convincing evidence that such standards are accurate, forest managers in the private sector are not apt to take them seriously.

In the late 1980s, I arranged a series of small group meetings among key USDA Forest Service scientists and leaders in National Forest System to explore prospects for a definitive study national in scope. We agreed that guidelines for detecting changes in fundamental productivity were cumbersome and inconclusive. After an exhaustive review of the world's literature, our core group agreed on the following principles for guiding such a study. (1) Within the constraints set by climate and relief, the productive potential of a site depends on soil resources. (2) Management practices cause soil disturbances that affect soil properties and processes. In turn, these processes govern potential productivity. (3) The main soil processes controlling potential productivity involve physical, chemical, and biological interactions between soil porosity and site organic matter.

The third principle provides a framework for research. Recognizing that it is unlikely that any simple response would apply to all climates, soils, and forest types, our core group agreed on a common experimental design that would be applied consistently to a spectrum of benchmark sites across the United States. Following discussion among international scientific peers, a study plan was drafted and reviewed nationally by silviculturists and soil scientists in both research and management arms of the USDA Forest Service. In 1989, the final plan for a Long-Term Soil Productivity (LTSP) cooperative study was approved by the Deputy Chiefs for Forest Service Research and National Forest System. Simultaneously, our rationale and proposal were presented at a major international conference, reviewed technically, and published in the proceedings (Powers and others 1990). Along with their counterparts from the National Forest System, principal investigators from USDA Forest Service Research began implementing the LTSP experiment in 1989. Funding for the installation phase came from the Washington Office through excess timber sale receipts (approximately $9 million between 1989 and 1998).

The four main objectives of the LTSP program are to: (1) determine how site carrying capacity for NPP is affected by pulse changes in soil porosity and site organic matter; (2) develop a fundamental understanding of the controlling processes; (3) produce practicable, soil-based indicators for monitoring changes in site carrying capacity; and (4) develop generalized estimation models for site carrying capacity, as conditioned by soil and climatic variables.

The effort is hypothesis driven and involves manipulation designed to stress the soil's capacity for NPP. It focuses on major forest types of the United States within the component classified as commercial forest land. LTSP centers on closed-canopy, young-mature forests growing near the culmination of mean annual increment. It is chartered to run to at least the culmination of mean annual increment on each site (a rotation, or planning horizon). Details of this remarkably successful, North American-wide program are described by Powers (1999a).

Within a climatic region and forest type, National Forests are solicited for sites that represent an array of the major soil types along a productivity gradient. Candidate sites are examined carefully for variation in soil and stocking. If satisfactory, and with concurrence of National Forest and Ranger District personnel, each forest stand is inventoried and at least 30 trees are felled and sampled to estimate the biomass and nutrient contents of their boles and crowns (Powers and Fiddler 1997). The understory, forest floor (all organic detritus above the mineral soil), and mineral soil to 100 cm in depth also are sampled for mass and nutrient content. Regression methods are used to expand sample data to an areal basis. This process characterizes the mass and chemical state of the forest immediately prior to treatment (*table 2*).

Once sites have been characterized, all trees are felled and nine core treatments are assigned randomly to 0.4-ha plots. These treatments consist of three levels of organic matter removal/retention (commercial bole removed/

Table 2—*Approximate biomass and nitrogen (N) content of ecosystem before and after removing various components at the Challenge LTSP site (Powers and Fiddler 1997)*

Ecosystem component	Biomass in component	N content of component	Cumulative ecosystem N content	Cumulative-proportion of ecosystem N	Ecosystem N remaining after removal
	$Mg\ ha^{-1}$	$kg\ ha^{-1}$	$kg\ ha^{-1}$	percent	percent
Tree layer					
Boles	425.3	440.3	440.3	5.1	94.9
Crowns	48.0	164.6	604.9	7.0	93.0
Understory layer					
Shrubs	0.4	3.1	608.0	7.0	93.0
Herbs	0.2	1.4	609.4	7.1	92.9
Forest floor layer					
Woody debris	9.6	29.7	639.1	7.5	92.5
Litter	49.0	425.4	1,064.5	12.3	87.7
Mineral soil (1 m)	—	7,630.0	8,694.5	100.0	00.0

crown, understory and forest floor retained; all living vegetation removed/ forest floor retained; all vegetation and the forest floor removed/mineral soil exposed), crossed factorially with three levels of soil compaction (nil, intermediate, extreme) (*fig. 1*). Additional plots representing best management practices, as well as mitigation treatments (subsoiling, fertilization), are included if space is available. Plots are reforested with tree species native to the site.

Following the reforestation phase, treatment plots are divided into two 0.2-ha subplots. Native understory flora is allowed to develop naturally on one subplot. The other is kept only in trees by applied herbicides. These treatments of site organic matter and soil porosity produce a factorial, split-plot matrix encompassing the soil disturbances common to almost any operational harvesting practice. The vegetation control treatments permit complex and simple plant communities to develop side-by-side. With time, each plot and subplot provides a distinct measure of NPP as affected by pulse disturbance. Plots are sufficiently large that vegetative performance will not be confounded by edge effects from the surrounding forest. Measurement protocols have been standardized throughout the country (Powers and Fiddler 1997, Powers and others 1990).

The first LTSP installation was completed on the Palustris Experimental Forest in Louisiana in 1990. The second was at Challenge Experimental Forest in California in 1991. By 1996, the LTSP concept had spread to the Canadian Provinces of British Columbia and Ontario. Soon the program expanded to complementary studies by collaborators in academia and the forest industry. Today, the network includes 62 core LTSP installations and 40 affiliated installations, making it the world's largest and best-coordinated network of studies examining how soil disturbance impacts potential site productivity (*fig. 2*). Of the 62 core installations, 12 are in the mixed-conifer forest type of the western Sierra Nevada of California (*table 3*).

The oldest California installations have completed only twelve growing seasons, and the youngest only six. Intensive measurements are taken at 5-year intervals, partly because of restricted research funds, and partly because initial perturbations are not likely to indicate long-term trends. LTSP scientists agree that the first reliable indicators of long-term trends are not apt to appear until crowns have closed on all treatments at a site. All of the California installations have achieved their 5-year measurements, but none has reached crown closure on all treatments.

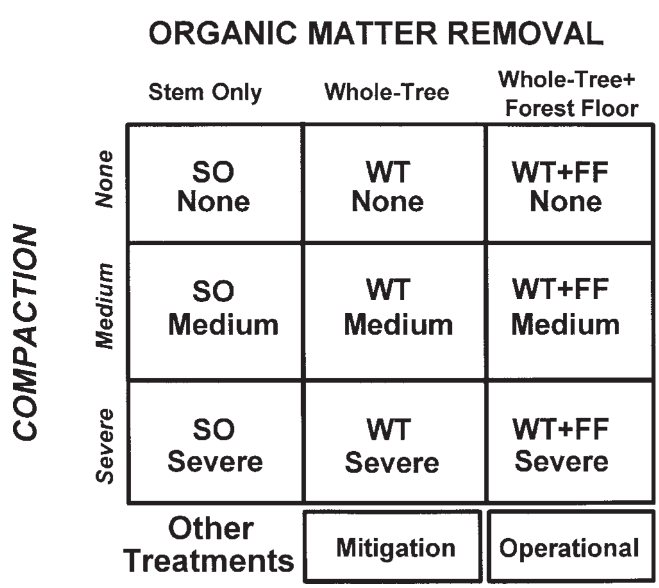

Figure 1—Standardized field design of the factorial core treatments in the LTSP experiment. Each treatment cell measures 0.4 ha and is regenerated to the principal forest trees of the region. Regional vegetation is excluded on one half of each cell and allowed to develop on the other.

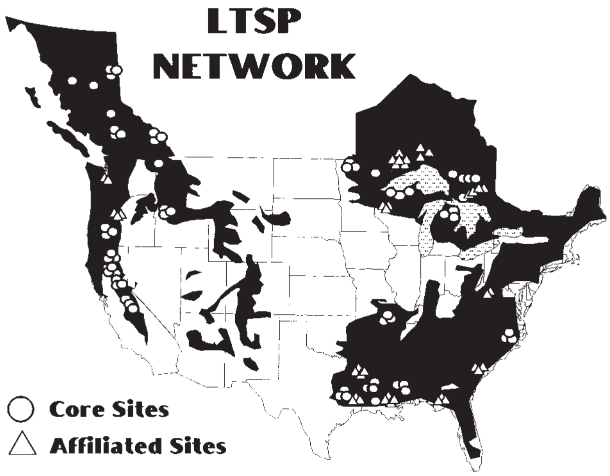

Figure 2—Distribution of core and affiliated experiments of the North American Long-Term Soil Productivity cooperative research program. Commercial forest area is shaded.

Early findings have been presented at conferences as progress reports and are summarized in the following section, along with my interpretations. Most of the NPP data are still being analyzed, and growth data reported here reflect volume measures, not NPP, although trends between volume increment and NPP will track closely. Until all installations reach crown closure, these findings are simply a nest of case studies that should not (and generally *cannot*) be examined by inferential statistics. Early trends are not offered as long-term projections. Collectively, however, they show progress and provide important preliminary findings.

Table 3—*General characteristics of 12 LTSP sites in California (Powers and Fiddler 1997)*

Place name	Year established	Parent material	Relative drought	Site quality	Forest	Ranger District or other
Challenge	1991	Metabasalt	Low	High	Plumas	Feather River
Wallace	1993	Volcanic ash	Low	Mod.	Eldorado	Georgetown
Central Camp	1993	Granodiorite	High	Mod.	Sierra	Minarets
Owl	1993	Granodiorite	High	Mod.	Sierra	Minarets
Vista	1993	Granodiorite	High	Mod.	Sierra	Mariposa
Blodgett	1994	Basalt	Low	High	Blodgett	U. of Calif.
Brady City	1995	Basalt	Low	High	Tahoe	Downieville
Lowell Hill	1995	Basalt	Low	High	Tahoe	Navada City
Rogers	1996	Granodiorite	Mod.	High	Plumas	Feather River
Aspen	1997	Volcanic ash	Mod.	Low	Lassen	Eagle Lake
Bunchgrass	1997	Volcanic ash	Mod.	Low	Lassen	Hat Creek
Cone	1997	Volcanic ash	Mod.	Low	Lassen	Eagle Lake

Early Results from LTSP

Infiltration and Erosion

Several important findings—albeit preliminary—have emerged from the California LTSP study. Troncoso (1997), working with granitic soils from the three Sierra National Forest sites, found that severe compaction reduced water infiltation by 72 percent in surface soils. Lessened infiltration can lead to surface runoff during intensive rainfall and to reduced soil water recharge. Although soil water recharge may not be a problem if precipitation occurs as low intensity rain or snow, soil erosion is another matter. Surface erosion occurs when hydraulic forces exceed the binding strengths of soil aggregates, a relatively stable assemblage of organic material and mineral particles. Materials such as organic detritus on the soil surface will break the impact of raindrops. Therefore, erosion rates will be high if the soil surface lacks cover by organic matter and if the stability of soil aggregates is low. A simple way to measure soil erosion is to drive thin pins deeply into the soil, leaving a portion exposed above the soil line. Monitoring changes in soil elevation on the pins over time provides an index of the rate soil erosion.

Sandy Inceptisols with low organic matter content, such as the Dome soil series on the three Sierra National Forest sites, lack much profile development, and soil aggregate stability is very low. Therefore, soil particles are easily detached by raindrop impact and surface water flow if infiltration rate is too low. Although erosion pins were installed at the Sierra LTSP sites, funding limitations have precluded any measurements. Casual observations, however, indicate that erosion rates there are relatively high where soil surfaces were bared and severely compacted.

Only at the Challenge site, the first California installation, have we taken measurements on erosion pins. There, soil elevations were measured after 3 years on all plots. Using changes on the Control plot as a standard, relative erosion rates increased as much as sevenfold (*table 4*). Slope variation among plots precluded a smooth response surface across treatments, but some points do seem clear. First, soil compaction *per se* had no obvious influence on relative erosion rate. In fact, in three of four cases where soil was protected with slash or forest floor, relative erosion rates on compacted plots were lower than for the control plot. Second, the soil cover effect was profound. Regardless of compaction level, erosion always was much greater where the surface organic layer was gone. Soil aggregation is much stronger on the clay-textured soil at Challenge than on the sandy textures of the Sierra National Forest sites. Presumably, if rainfall intensity were as great at the Sierra sites as at Challenge, soil erosion rates would be far greater than noted. A solid conclusion is that surface organic cover comprises the first line of defense against the erosion of surface soil.

Table 4—*Relative rate of soil loss over 3 years at the Challenge LTSP site (control = 100, Powers and Fiddler 1997)*

Compaction level	Relative rate of erosion when residual ground cover was:		
	Logging slash	Forest floor	Bare soil
	----- percent -----		
None	100	187	416
Moderate	66	270	812
Severe	84	43	330

Table 5—*Effects of presence or absence of forest floor on mean monthly temperature and moisture at 20-cm depth of noncompacted soil, Challenge LTSP site (Powers 1999b)*

Month	Soil temperature (°C)			Percent soil moisture		
	Present	Absent	Difference	Present	Absent	Difference
April	12.8	13.3	0.5	34	34	0
May	17.8	21.5	3.7	26	14	-12
June	19.0	22.8	3.8	21	13	-8
July	20.2	24.6	4.4	25	18	-7
August	18.5	23.7	5.2	20	13	-7
September	17.5	21.0	3.5	15	12	-3

Significance of Surface Organic Residues

Organic residues that protect the soil surface from raindrop impact and runoff also insulate against high summer temperatures and evaporative moisture loss. From June through August at Challenge, bare soils averaged 23.7°C at 15 cm in depth—4.5°C warmer than soils covered by forest floor (*table 5*). Also, bare soils were essentially dry by May, whereas presence of a forest floor kept soils relatively moist into August. On the sandy soils of the Sierra National Forest sites, Troncoso (1997) found that surface soils were depleted of plant-available moisture by August, but moisture was available throughout the dry summer where logging slash had been retained (*fig. 3*). Studies a year later on these same soils (Swearingen 1999) showed that the mulching effect extends deep into the soil profile. Where logging slash had been retained, soil moisture at a depth of 75 cm remained well above the wilting coefficient (about 8 percent moisture content) throughout the summer, but soils were dry by mid-July where surfaces were bare. Obviously, a condition that extends the period of plant-available moisture favors plant growth under the conditions of a Mediterranean climate. Surface organic residues do that by acting as mulch against solar heat and evaporative losses.

As soils dry, strength mounts between soil particles, regardless of the level of compaction. Increased soil strength means increased resistance to root elongation. Root stress increases greatly above 2 MPa (1 MPa = 10 atmospheres of pressure, or 10.3 kg cm^{-2}) and growth essentially ceases at 3 MPa (Sands and others 1979). At Challenge, soil strength measurements taken in July of the third year showed that strengths averaged 2 MPa or less throughout the upper 40 cm where a forest floor was present but a full MPa greater where it was absent (Powers and Fiddler 1997). Thus, surface organic residues affect root behavior in dimensions beyond simple water availability.

A progressive view of the worth of surface residues is that their direct effect on soil moisture is important but ephemeral. The mulch value of a forest floor should dissipate as canopies close and transpiration dominates evaporation. However, organic residues are a major component of the carbon cycle that supplies an energy substrate to soil organisms that dominate soil processes. In turn, these processes control the storage and biological availability of soil water and nutrients. The nutritional significance of the forest floor is far greater than indicated by its biomass. For example, the mass of the forest floor before harvest at the Challenge LTSP site was only 11 percent of the total biomass above ground (*table 2*), but the forest floor contained 43 percent of above-ground nitrogen—nearly three times that in the tree crowns that either are exported or retained as logging slash. Therefore, loss of the forest floor may

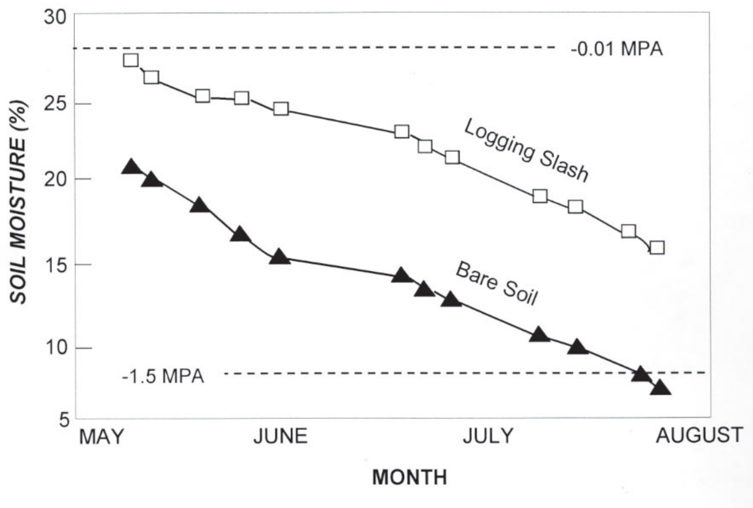

Figure 3—Soil moisture trends at a depth of 15 cm as affected by presence or absence of surface organic residues. Sierra National Forest LTSP sites, third year. Dashed lines indicate moisture content at field capacity (upper) and at wilting coefficient (lower) (Troncoso 1997).

eventually have a profound effect on soil fertility on sites less fertile than at Challenge. Its importance probably exceeds that of the crown material in logging slash.

The physical value of surface residues is conditioned by climate. At higher latitudes or at elevations where soil temperatures approach the cryic temperature regime, anything reducing soil temperature reduces primary productivity. In the frigid and cryic temperature zones, surface residues accumulate and insulate the soil, lowering soil temperature and diurnal flux (Fleming and others 1994). Moist sites remain wet and aeration may be impaired. On better-drained sites, water stress can develop because water viscosity increases rapidly as temperatures approach freezing (viscosity is 16 percent greater at 5°C than at 10°C). The same insulating properties of surface residues that reduce primary productivity in cold forests become beneficial in warm, dry regions such as found in the mixed-conifer and pine forests of California (*table 5, fig. 3*).

Significance of Compaction

Effects of soil compaction on soil moisture go beyond simple infiltration, but certain principles must be understood to interpret LTSP findings that, at first glance, may seem contradictory. Compaction alters soil pore size and volume—variables that influence the availability of soil water to plants. Soil pores are divided by convention into two size classes, based on water-retention properties (Childs and others 1989, Taylor and Ashcroft 1972). "Micropores" are voids so small that they remain filled with capillary water when gravitational water has drained and the soil is at field capacity. Much of this micropore water is held at tensions between 0.01 and 3.1 MPa (the lowest tension of hygroscopic water), meaning that not all of the water in micropores (that held at tensions > 1.5 MPa) is available to plant roots. "Macropores" are soil voids sufficiently large (> 14 µm radius) that capillary water will not bridge their diameters following gravitational drainage. Loosely held water (0.01 to 1.5 MPa tension) is retained as a cohesive film on the surfaces of particles bordering macropores, and the remaining void is filled with air. This low-tension film is the principal source of water for plant uptake and accounts for roughly half of the total water-holding capacity of an uncompacted soil (a higher proportion for sands, a lower proportion for clays). As low-tension water is depleted from macropores by transpiration or evaporation, films become thinner. As films thin, a tension gradient develops and macropores are recharged partially by water held in micropores. Eventually, water films in all soil pores thin to such high tension (by convention, >1.5 MPa) that the soil is said to have dried to "wilting coefficient." When soil pore radii are less that 0.1 µm, the affinity between water molecules

Table 6—*Effects of soil compaction (NC = not compacted, C = compacted) and understory vegetation on plant and soil properties for soils of contrasting textures (severe compaction on the clay, moderate compaction on the sand) (Powers 1999b)*

Variable	Understory vegetation absent				Understory vegetation present			
	Clay		Sand		Clay		Sand	
	NC	C	NC	C	NC	C	NC	C
Relative growth (pct)								
Abies concolor	100	56	100	167	22	33	67	100
Pinus ponderosa	100	60	100	169	33	47	94	125
Vegetative cover (pct)	Trace	Trace	Trace	Trace	91	56	55	68
Soil bulk density (Mg m^{-3})	0.88	1.13	1.06	1.14	0.88	1.13	1.06	1.14
Total soil porosity (pct)	67	57	60	57	67	57	60	57
Change in AWC (pct)	0	-24	0	+65	0	-24	0	+65
Predawn ψ_p (MPa)								
Abies concolor	-0.54	-0.63	-1.13	-0.93	-1.74	-1.15	-2.37	-3.47
Pinus ponderosa	-0.60	-0.66	-1.05	-1.14	-0.88	-0.87	-1.61	-2.05

and pore surfaces is so great that water is said to be unavailable to plants.

Soil macropores also are essential to infiltration of precipitation and exchange of oxygen and respiratory gases between the atmosphere and the root. A macropore volume of at least 10 percent of total soil volume is needed for proper root respiration by terrestrial plants (Grable and Siemer 1968, Vomocil and Flocker 1961). Soils with too few macropores may become anaerobic; those with too many may be excessively drained and droughty. Unfortunately, the distribution of soil pore sizes is difficult to measure and essentially impossible to measure in the field.

Working with sandy soils on the Sierra National Forest LTSP sites, Swearingen (1999) showed that, at a depth of 15 cm, compacted soils retained plant-available water through late June, but noncompacted soils were depleted by mid-May. At a depth of 75 cm, the wilting coefficient was reached by late June on noncompacted soils and mid-July on compacted soils. Thus, a certain amount of compaction seemed to favor the storage of low-tension soil water. But is this effect universal? And how does it affect vegetative growth?

To study these questions, the Challenge and Vista LTSP sites were chosen for more intensive study because they represent extremes in soil texture. Work centered on plots with complete organic matter removal and either no or severe compaction. As might be expected for a fine-textured soil, both tree growth and vegetative cover were suppressed (about 40 percent) by compacting the clayey soil at Challenge (*table 6*). Soil bulk density increased by 28 percent, equating to a reduction in total porosity of 15 percent. Such a reduction seems small, except that it comes at the expense of aeration porosity (macropores are the first to be deformed by compaction). Clay micelles (flat particles less than 0.002 mm in size) compact into a hard, platy structure. Although particle surface area is high, macroporosity is relatively low in clays. Measurements made in the laboratory with intact soil columns from treated plots at Challenge show a loss in plant-available water (AWC) of 24 percent. Therefore, compaction reduced both the soil's aeration and its capacity to store available water. Lowered soil AWC measured in the laboratory is not simply academic. It is reflected by field measurements of predawn xylem water potentials (ψ_p) taken in August at the peak of drought. Predawn water potentials were 17 percent lower in white fir and 10 percent lower in ponderosa pine following compaction (*table 6*), meaning that trees on compacted plots were not rehydrating fully at night when stomata were closed. Lowered AWC translates to plant drought under Mediterranean climatic conditions, helping explain why both tree growth and ground cover were suppressed by compaction on the clayey soil.

Different results were found on the sandy soil at Vista, where both trees and understory vegetation grew appreciably better on moderately compacted plots (*table 6*). Soil bulk density also was increased by moderate compaction, but only by 8 percent. Because sand grains are large, angular particles (0.05 to 2.0 mm), they have less surface area per unit volume than clay particles. Total soil porosity generally is lower in sands than in clays and is weighted heavily to macropores. Consequently, sandy soils drain quickly and, because their microporosity and specific surface area are low, retain little water. Compacting the sandy soil moderately at Vista increased AWC by 65 percent (*table 6*). Apparently, this difference reflects a rearrangement of sand grains and a reduction of pore sizes. As a consequence, white fir ψ_p in August improved an average of 18 percent. Xylem water potentials were lower (trees were drier) after compaction in ponderosa pine—possibly because the pines were about five times larger than the firs. Larger trees mean greater crown surface area and greater transpiration rates. Presumably, larger trees on compacted soil depleted soil water more rapidly throughout the summer. From this I conclude that compaction effects on plant growth depend upon soil texture, the degree of compaction, and whether or not AWC is a limiting factor.

Improved growth from compaction also occurred for aspen on droughty sands in Michigan (Stone and others 1999) and for ponderosa pine on the sandy soil at Rogers (Gomez and others 2002). Recent measurements at Central Camp and Owl LTSP sites on the Sierra National Forest show that growth was reduced by more severe compaction. Differing responses to compaction among sandy-textured soils on sites classified as the same soil series probably trace to subtle differences in distributions of pore size and/or particle size, which is fertile ground for further investigation. A contract was completed recently for detailed classification and textural analyses of the soils at all LTSP installations.

Other recent LTSP measurements of ponderosa pine growth illustrate how this concept might extend to a variety of soil textures. Severely compacting a clay-textured soil (Challenge) can lower tree growth by nearly half (*fig. 4*). The effect was much less on a loam (Blodgett) or sandy loam (volcanic ash at Wallace) and even promoted growth on a moderately compacted sand (Vista). Work underway by University of California graduate students is quantifying how compaction affects pore size distribution, water availability, and tree growth on these and other LTSP soils.

Confounding from Competing Vegetation

Compacting the clayey soil at Challenge clearly reduced AWC and conifer growth rates (*table 6*). It also increased soil strength by about 1.5 MPa throughout the upper 40 cm (Powers and Fiddler 1997). In all, the soil's productive potential was reduced substantially by compaction. Yet, this effect was apparent only when trees were free of competition from understory vegetation. Where vegetation was *not* controlled, trees were appreciably larger and their ψ_p equal or greater on *compacted* plots (*table 6*), although their absolute growth was 40 to 67 percent less than on noncompacted plots where vegetation had been controlled (Powers and Fiddler 1997). This is because the density of understory vegetation was nearly twice as great on noncompacted plots (91 percent cover vs. 56 percent cover). Understory seedlings germinating from seed could recolonize noncompacted, clayey soil much more easily than compacted soil. Less

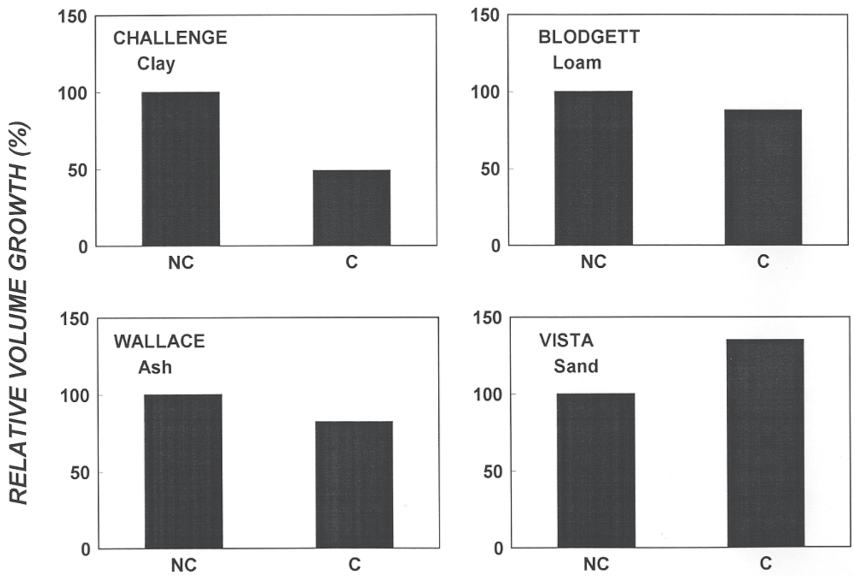

Figure 4—Effects of soil compaction on relative volume growth of ponderosa pine at four LTSP sites of differing soil texture. Symbols: not compacted (NC), compacted (C).

understory competition for water and nutrients meant that trees planted in holes augered into compacted soil could perform better than trees under greater competition in noncompacted soil, at least in the short term.

Where compaction *improved* soil water availability (the sandy soil at Vista), both trees and understory species grew faster (*table 6*). For white fir (which were smaller than ponderosa pine, and have weak stomatal control), predawn ψ_p was greater on compacted soil if understory vegetation was absent. Where understory was present, however, the higher vegetative cover on compacted soil overcame increased soil water availability and created greater competition for soil water, leading to lower ψ_p in both fir and pine (*table 6*). Furthermore, the low specific area of sand grains compared with clay micelles (Taylor and Ashcroft 1972), coupled with low precipitation at the Vista site means that the soil's storage of water there is lower than at Challenge. Therefore—and regardless of improved soil water holding capacity from compaction—soil water would be depleted very quickly if both trees and understory vegetation are present.

These findings suggest that, under certain conditions, the true effect of soil compaction can be masked completely—and seemingly reversed—by the confounding effect of competing vegetation. On sandy soils, available water-holding capacity may be improved somewhat by compaction. Because absolute soil water storage still is low, however, effects of competing vegetation will be particularly severe. Without accounting for the significance of understory vegetation, the true effect of soil compaction is not always recognized.

Extending LTSP Findings to Operational Practices

Soil Compaction

Stanislaus Thinning Study

Field monitoring methods developed from LTSP were applied to an operational-scale study established in 1994 on the Mi-Wuk Ranger District of the Stanislaus National Forest. The study was designed to evaluate the soil and stand impacts of alternative methods of mechanized thinning. The Wrights Creek Burn site had been salvage-logged in the mid-1950s following destruction of a mixed-conifer forest by wildfire. Slash and brush were piled into windrows by crawler tractor, thereby ensuring a legacy of soil disturbance that included soil compaction. In 1959 the site was planted with ponderosa pine, and the ensuing stand was thinned by using ground-based equipment during the spring and summer of

1994, while soils were fairly moist. Harvesting was done both by whole-tree removal using a Timbco feller-buncher[3] with shear and grapple skidder (FB), and by the cut-to-length (CTL) system using an FMG Timberjack harvester and forwarder that removed boles and retained slash. Unthinned areas were set aside as controls. Each system operated on plots of 2.5 ha and larger, with two replicates of each treatment.

Because the FB had to drive to each harvested tree to shear it, traffic covered much of the plot. Traffic was funneled onto well-defined trails, however, transporting whole trees to the landing and leaving minimal slash on the plots. In contrast, CTL operations proceeded linearly through the woods with the felling head reaching about 10 m laterally. Limbs and foliage were stripped by the processing head in front of the harvester, and the lengths of cut timber were passed back to the forwarder for transport to the landing. Consequently, both harvester and forwarder drove atop a bed of freshly cut slash.

After harvesting, the FB plots were split. Using a winged subsoiler drawn by crawler tractor, skid trails were tilled to a depth of about 0.5 m on half of the plots in the spring of 1996. The other half remained untilled. Preliminary findings from transects taken in each unit revealed that both types of mechanized thinning produced similar amounts of surface disturbance in traffic lanes, but the FB treatment had higher soil bulk densities beneath traffic lanes and twice as much general disturbance in the remaining area (Powers and others 1999).

Soil strengths measured in April, when soils were near field capacity and strengths were lowest, were high beneath both FB skid trails and CTL traffic lanes (*fig. 5*) and exceeded 2 MPa in the 10-20 cm depth zone. Despite the similarity of soil strengths beneath traffic lanes in both treatments, however, strengths on the CTL plots were appreciably lower in all other disturbance categories (*fig. 5A*). For the minor disturbance class, 2 MPa strengths were reached at 13 cm in the FB treatment, but not until 25 cm in the CTL treatment.

Tillage reduced soil strength in FB skid trails to less than that for the undisturbed class (*fig. 5B*), suggesting that compaction that occurred during salvage and site preparation decades earlier may have been mitigated. Roots of trees bordering the trails were severed during tilling operations. Analysis of diameter growth of about 80 trees bordering tilled and nontilled skid trails, however, gives no indication that tillage of the skid trails had any effect on tree growth in the 3 years since tillage (Powers and others 1999). Net growth was neither depressed from root damage nor enhanced by reducing the high soil strengths in the compacted trails. Whether this trend persists remains to be seen.

[3] Mention of trade names or products is for information only and does not imply endorsement by the U.S. Department of Agriculture.

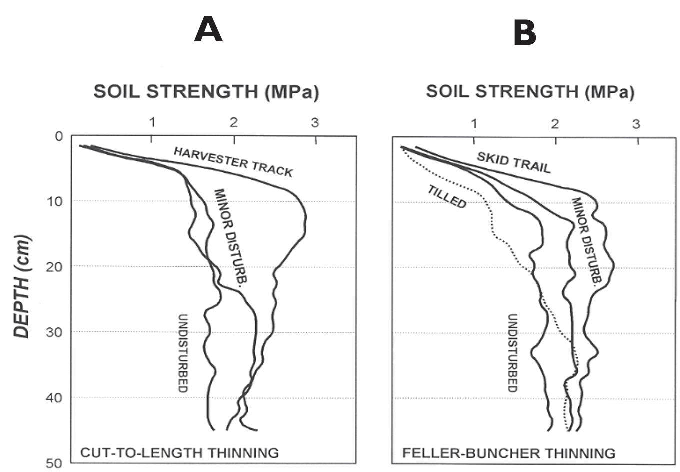

Figure 5—Soil-strength profiles for varying degrees of soil compaction following mechanized thinning at the Wrights Creek plantation. (A) Strengths were high beneath harvester/forwarder tracks following cut-to-length thinning, but not for the remainder of the unit. (B) Feller-buncher operations had a greater impact throughout the unit. Tillage (broken line) reduced soil strength in skid trails (Powers and others 1999).

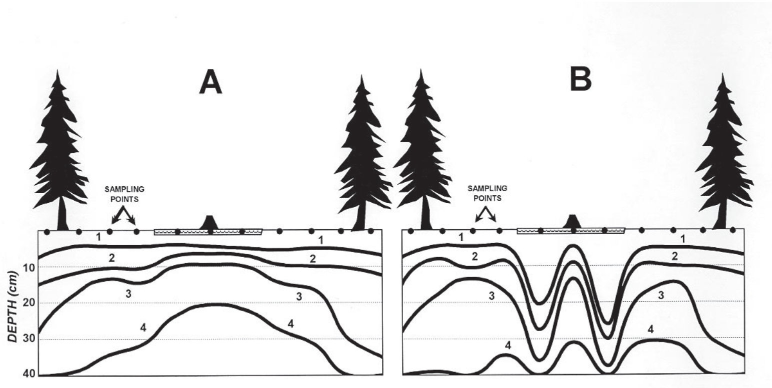

Figure 6—Soil strength MPa isolines at Pondosa in fall 1998 following mechanized thinning of every third row (Powers and others 1999). (A) Thinned only. Friable rooting zone was reduced by half beneath traffic lanes. (B) Thinned and tilled along harvester tracks. Tilth returned to prethinning levels.

I conclude from this that techniques for measuring soil strength, developed from LTSP studies, can be used to distinguish physical changes in the soil that are caused by field operations. Therefore, soil strength should have a prominent place in the operational methods for monitoring soil quality by the USDA Forest Service's Pacific Southwest Region (*table 1*).

The Roseburg Study

To further extend LTSP principles of physical soil mitigation to an operational setting, we began a second experiment in fall 1998 with cooperation from Roseburg Resources Co. in the Pondosa Burn north of Burney, California. The test forest is a 15-year-old plantation of ponderosa pine established after salvage logging in the aftermath of a 1977 wildfire. Although soils were compacted somewhat by salvage logging, tree survival was excellent. Canopies have closed, and the plantation is being thinned by whole-tree harvesting to maintain high rates of tree growth and to reduce fuel buildup. Four primary treatments have been established on 0.4-ha plots in a randomized design of four blocks: (1) unthinned control, (2) thin and remove every third row of trees, (3) thin and remove every third row, subsoil the traffic lanes, and (4) thin and remove every third row, fertilize and subsoil the traffic lanes.

Thinning was done with a three-wheeled Morbark Wolverine shear and grapple skidder. Whole trees were skidded to a landing, where they were chipped. Traffic lanes within thinned strips were tilled to a depth of about 0.5 m along wheel tracks, using two passes of a winged subsoiler drawn by crawler tractor. Fertilization involved granular urea and ammonium triple phosphate applied at 224 kg N ha^{-1} and 336 kg P ha^{-1} in the tilled tracks. Tillage provided an opportunity to work N and P into the rooting zone of residual trees. Penetrometer readings taken shortly after treatment in fall 1998 showed that mechanized thinning led to soil compaction and reduced the friable rooting depth by half (*fig. 6A*). In contrast, subsoiling the compacted traffic lanes lowered soil strength to prethinning levels (*fig. 6B*). This treatment should create a furrow effect that collects and retains soil moisture and extends tree growth into the summer.

Early results from this LTSP-related study reinforce the significance of soil strength for detecting treatment differences on soil's physical properties. They also indicate that: mechanical row thinning compacted the soil beneath the traffic lanes; compaction extended to at least 40 cm; and subsoiling seems to have mitigated the effect. How this translates to soil moisture availability, understory diversity, root growth, and tree growth will be determined in the coming years.

Organic Residues

Principles learned from LTSP indicate that replenishment of organic matter is critical to sustained productivity of forested ecosystems. Organic carbon in forest detritus is the substrate energizing most soil biotic processes that control nutrient and water availability, aeration, and soil structure. Detritus can create a fuel bed that increases the risk of forest destruction by fire, however, particularly in our summer-dry climate. The problem facing management is how to reduce fire risk without depleting organic matter on and within the surface soil.

Conventional methods of managing residues include low-intensity burns or mechanical removal of some of the fuel load through whole-tree harvesting. Both methods remove organic carbon from the site. While solving the immediate fuel problem, they offer nothing for long-term carbon storage or improvement of soil quality. On more mesic to xeric sites with less fertile soils, losses of surface residues likely will lead to deficiencies of N and P when the stand is at leaf-area carrying capacity, and nutrient uptake peaks (Powers 1999). Two experiments are underway and a third is planned to test effective alternatives to burning or removal of organic residues. Each involves retention of residues in chips.

The Sierra Pacific Study

The first experiment in the Sierra Pacific study began in 1993 with commercial harvesting of a 90-year-old mixed-conifer stand on what is now Sierra Pacific Industries land near Blodgett Forest in Eldorado County. Logging slash (about 50 Mg ha^{-1} containing about 640 kg N ha^{-1}) was treated in three ways: residues were scattered and broadcast burned; residues were piled by tractor into windrows and the windrows were burned; and residues were chipped on the site and returned to the ground as linear, 30-m rows of wood and foliage shredded to sizes averaging between 2 and 5 cm in length. The first two treatments are conventional, but the third is an innovative means of retaining organic matter while reducing its flammability and concentrating it to create a critical mass that retains water and perhaps creates an ideal medium for nonsymbiotic nitrogen fixation. Rows of chips resemble large, fallen, decomposing trees spaced about 20 m apart. Treatment plots, 0.2 ha each, were replicated four times and planted with mixed species of conifers in spring 1994.

Concentrating chips into piles offers several benefits. First, it reduces the fuel profile throughout the unit to a compact, localized condition. Second, it avoids high temperature effects in broadcast chip applications that may heat-girdle some conifer seedlings. Third, chip piles dry from the surface inward, creating cool, moist conditions in their interiors and in the soil beneath them. Finally, once chip piles have decomposed, conditions may be ideal for free-living, nitrogen-fixing bacteria. Nitrogen fixation rates have been shown to be much higher in chip piles (because of the organic carbon source and anaerobic conditions) than in any other field medium (Jurgensen and others 1980). The trick is to reduce chips as quickly as possible from large, flat objects with low specific surface area to small, amorphous bodies with great surface area for retaining moisture. This reduction occurs in natural decomposition by the removal by fungi of linear molecular chains of cellulose to leave a residuum of lignin (Blanchette and Shaw 1978). Cooperating with scientists in the USDA Forest Service's Rocky Mountain Research Station, we are attempting to speed this process by inoculating some chip piles with pure strains of *Postia placenta*—an aggressive brown rot fungus particularly adept at consuming cellulosic sugars.

The Roseburg Study

Along with the main-effect treatments with thinning and tillage described previously, four secondary treatments, each occupying 0.1-ha subplots, were added to each block of the Roseburg study at Pondosa as supplements to Treatment 3 described earlier. They involved retention of woody residues as chips to reduce fuel volumes while retaining site organic matter. They were: (3a) all thinnings chipped, returned to traffic lanes, subsoiled, and rototilled; (3b) traffic lanes subsoiled, thinning chips added to the surface; (3c) thinnings chipped and returned, fertilized with N and P, subsoiled, and rototilled; and (3d) traffic lanes subsoiled, thinning chips added to the surface, fertilized with N and P.

Chips were returned to the site to see if residue retention would improve soil water storage capacity, soil fertility, and carbon sequestration. The purpose of chip fertilization was to lower the C:N ratio to favor microbial decomposition (chemical analyses are not available at this time). Chips either were retained on the surface to act as mulch or tilled into the soil to increase decomposition.

The Kings River Study

A third residue modification study is planned for the Kings River Administrative Unit of the Sierra National Forest. The study area is characterized as the drier end of the westside Sierra Nevada mixed-conifer and ponderosa pine forest types. Soil AWCs are moderate to low. Fire suppression has led to heavy fuel accumulations in the understory. The challenge is to manage the Unit for a variety of resources while lowering fire risk. The common strategy when creating fuel breaks or site preparation following timber harvest is to remove whole trees during the harvest and to pile and burn remaining residues. Unfortunately, such treatments deplete the site of organic materials, potentially affecting soil fertility, AWC, and erodibility.

Recent mechanical innovations provide another choice. Preliminary tests of an innovative rotary mulcher in the southern pine region of the eastern United States show a high potential for reducing fuels, retaining site organic matter, and improving physical soil properties important to plant growth. Attached to a crawler tractor, the rotary mulcher grinds stumps, shrubs and logging slash into fine residues. These residues may be left on the soil surface to serve as an evaporative mulch or mixed into the surface soil in a single operation. Grinding residues into a fine particle size not only reduces the fuel profile, but it also increases the specific surface area of the biomass. Higher specific area spells greater rates of microbial decomposition. Incorporating these fine materials into mineral soil offers a huge bonus of increasing AWC, soil aggregate stability, nutrient retention, and carbon sequestration. A small grant was obtained for testing this technique in the fall of 1999. Work will center on shaded fuel breaks and on group selection openings. Rotary mulching will be compared against conventional best-management practices in its effect on seedling survival, growth, and vigor, and on soil AWC, nutrient storage, and aggregate stability.

Emerging Indicators of Sustainability

A major objective of the LTSP effort is to develop effective and practicable methods for monitoring changes in a site's carrying capacity for NPP. Although LTSP is in its infancy, soil strength as measured with a recording cone penetrometer (*figs. 5, and 6*) has emerged as a premier method for assessing soil physical properties. The sensitivity of penetrometer readings to soil moisture and hardness shows its capacity for integrating several soil physical changes that affect root behavior. Management practices that increase soil strength above 2 MPa during the potential growing season indicate that the site's capacity for plant growth has been diminished. Accordingly, and based solely on early findings from LTSP, soil strength has been proposed as the single most useful index of soil physical condition in operational monitoring for sustainable forest management (Powers and others 1998). Other recommendations include anaerobically mineralizable nitrogen as a single, integrative measure of nutrient supply, and the presence or absence of biopores and fecal aggregates as an index of soil invertebrate activity (Powers and others 1998). Declines in either of these properties with time suggest declines in soil biotic function and, most likely, a declining productive potential. The foundation for these biotic indices of sustainable forestry practices was developed in part by regional and national findings from LTSP.

Although the LTSP effort is young, findings are emerging rapidly. Already they are modifying standards for monitoring soil quality for National Forests of the United States, such as standards shown in *table 1*. As the concept of soil quality evolves, so will the effectiveness of soil-based standards. To be practicable, monitoring methods must focus on the simplest possible indices of key physical, nutritional, and biological properties and processes of the soil. Standards will be subject to continual refinement. When strong calibrations emerge between soil variables and NPP, as conditioned by climate and soil type, such indices will be universally accepted. Findings from LTSP research promise to be the primary means for achieving this acceptance.

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Current Investigations of Fungal Ectomycorrhizal Communities in the Sierra National Forest[1]

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Abstract

Progress on two main studies on fungal ectomycorrhizal communities in the Sierra National Forest is discussed. One study examined the short-term effects of ground fire on the ectomycorrhizal community and the other examined the ectomycorrhizal associates of snow plant (*Sarcodes sanguinea*). In the ground-fire study we found that a large initial reduction in ectomycorrhizal biomass is caused primarily by combustion of the upper organic layers; prefire dominants in the Russulaceae and Thelephoraceae are dramatically reduced; and species at greater depths appear to survive the fire. We speculate that fire causes a short-term increase in species evenness. In the field portion of the *Sarcodes* study, we found that *Sarcodes* is specialized on a single mycorrhizal associate, *Rhizopogon ellenae*; the presence of *Sarcodes* is associated with dense islands of *R. ellenae*; *R. ellenae* appears to be a minor below-ground component of the red fir (*Abies magnifica*) community in locations near but not immediately adjacent to *Sarcodes* plants; and the *Abies magnifica* ectomycorrhizal community is dominated by members of the Russulaceae and Thelephoraceae. From studies of *Sarcodes*-*R. ellenae* interactions under laboratory conditions, we report that seed germination is stimulated by isolates of *R. ellenae*, isolates of *R. ellenae* derived from *Sarcodes* and *Abies* roots are capable of forming mycorrhizae on pine (*Pinus*) roots, and we have achieved initial success in establishing a tripartite *Sarcodes*-*Rhizopogon*-*Pinus* association under laboratory conditions.

Ectomycorrhizae (EM) are dual organs composed of the fine roots of plants and fungal mycelia. They are the primary interface through which most temperate forest trees receive their mineral nutrients. All members of the Pinaceae require these mutualistic fungi for normal growth and survival (Smith and Read 1997).

The diversity of EM fungi is extremely high. Over 6,000 species have been described (Molina and others 1992) and, because of the current state of our taxonomic knowledge, this probably represents a gross underestimation of the total number. Even at a local scale, diversity is very high. In single-species pine stands of approximately 0.1 ha, 15 to 35 species of EM fungi are typically reported, single soil cores often contain several species (Eberhart and others 1996), and even adjacent root tips are frequently colonized by different fungi (Bruns 1995).

In spite of the importance of EM fungi, little is known about the structure of the complex communities that they form or the functional differences among the component species. Until recently, almost no quantitative descriptions of the abundance of EM species on roots were reported. This lack of information was largely caused by the difficulty in identifying fungal species in their vegetative states (that is, as mycorrhizae or mycelia). With the advent of the polymerase chain reaction (PCR), molecular-based methods now make identification much

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more feasible. As a result, many EM community studies are beginning to be reported (Erland 1995, Gardes and Bruns 1996a, Horton and Bruns 1998, Horton and others 1998, Horton and others 1999, Kårén and Nylund 1996).

The long-term goals of all our studies are to examine the structure of EM communities in diverse settings, to look for common themes in these structures, and to elucidate the functional differences among EM fungi. Our strategy has been to focus on a series of much smaller but more researchable questions and to assemble results of these studies into a general picture of fungal EM communities. Our prior work in coastal pine and Douglas-fir (*Pseudotsuga menziesii*) forests has shown that the species that dominate fruiting can be minor components of the below-ground community; mature communities are typically dominated by members of the Thelephoraceae and Russulaceae; where roots of Douglas-fir and pine or Douglas-fir and manzanita (*Arctostaphylos* spp.) intermingle, they usually are associated with the same fungal species; and a spore-bank guild, dominated by members of the Suillineae (primarily *Rhizopogon*) and members of the Ascomycota, is present in forest soils, and these species dominate pine seedlings in the first few years after stand-replacing fires (Baar and others 1999, Gardes and Bruns 1996a, Horton and Bruns 1998, Horton and others 1998, Horton and others in press, Taylor and Bruns 1999).

In the Sierra National Forest (SNF) we focused on two studies that complemented our earlier or ongoing studies elsewhere. In the first, we examined the short-term effects of ground fire on the EM community associated with ponderosa pine (Stendell and others 1999). The second study focused on EM associates of snow plant and on the EM community on red fir (*Abies magnifica*) surrounding snow plants. *Sarcodes* (*fig. 1*) is a nonphotosynthetic member of the Ericaceae, subfamily Monotropoideae. It is "epiparasitic" in that it obtains all of its carbon from surrounding trees via an EM fungus. Early studies in our lab on other nonphotosynthetic epiparasitic plants showed that, in contrast to photosynthetic plants, virtually all of the nonphotosynthetic plants that we studied had highly specific fungal associations. The only apparent exception was

Figure 1—*Sarcodes sanguinea.*

Sarcodes, and because it is a common plant in SNF, we decided to sample it more intensively and more locally than in our previous study, which included only 12 *Sarcodes* plants (Cullings and others 1996). In the course of sampling we found a site where *Sarcodes* was unusually abundant. This "high-density" *Sarcodes* site, situated in a red fir monoculture, enabled us to examine the EM community adjacent to *Sarcodes* and compare it with that in the surrounding red fir forest. It also provided an ideal setting for studying the sizes of fungal clones associated with *Sarcodes*.

Methods

Collection locations for fungi and *Sarcodes* were dispersed throughout the mixed-conifer and red fir zones of SNF. Global positioning system (GPS) coordinates were recorded for collection sites and plots. Collections of fungal fruitbodies were dried and retained in our herbarium, later to be deposited in the University of California Herbarium. Larger collections were split, with half of each deposited at Oregon State University. Most hypogeous collections were examined and identified by Dr. Jim Trappe of Oregon State University. In addition, *Rhizopogon* species in section Amylopogon were identified by either restriction fragment length polymorphism (RFLP) or sequence analysis of the internal transcribed spacer region (ITS).

Pine and fir roots were washed from soil cores of 4 X 40 cm. EM were sorted by shape and color, freeze-dried, weighed, and saved for molecular analysis. *Sarcodes* roots were collected by digging alongside flowering spikes until the rootball was encountered. Portions of the rootball were then removed, washed, and freeze-dried or used for isolation of the fungal symbiont into axenic culture. EM fungi were identified by molecular analysis as described previously (Bruns and others 1998, Gardes and Bruns 1993, Gardes and Bruns1996b).

Plots for the fire study were located at 36°58'48"N latitude and 119°8'13"W longitude. Six sampling plots were located in small, mature stands of ponderosa pine on a south-facing slope of approximately 11° on either side of the SNF service road 10S67. North of the road, in an area intended for a prescribed burn, three plots were established prior to the burn, and three control plots were established south of the road outside the designated burn area.

Studies of the EM community surrounding individual *Sarcodes* plants were done in a pure red fir stand near the junction of the SNF service roads 9S62 and 9S10 at 37°09'06" N latitude and 119°07'50" W longitude. Plants in this plot were counted along a 100-m transect, mapped within a 750-m^2 grid, and soil cores were taken along four 10-m transects centered on individual *Sarcodes* plants.

Results and Discussion

Results from the fire study (Stendell and others 1999) showed that the presence of all species was highly patchy in both the prefire samples and postfire control plots. Even two cores taken from a single m^2 plot often contained entirely different species. In spite of this, we observed that members of the Russulaceae and Thelephoraceae dominated the community—a pattern shared by all other undisturbed California pinaceous communities that we have studied (Gardes and Bruns 1996a, Horton and Bruns 1998, Horton and others 1999, Taylor and Bruns 1999). The short-term effect of this ground fire on the mycorrhizal community was an eightfold reduction in ectomycorrhizal biomass. The reduction was directly correlated with incineration of the litter layer and heating of the top few cm directly below it. These two regions accounted for the overwhelming majority of prefire mycorrhizae. There appeared to be a trend toward disproportionate reduction of the most abundant ectomycorrhizal fungi—members of the Russulaceae and Thelephoraceae. We speculate that this resulted because these fungi are primarily dominant in the organic upper soil layers that were destroyed. There appears to be a trend for rare types to be more common at greater depths in all communities we have studied. Thus, one of the immediate effects of fire may be to increase species evenness in the ectomycorrhizal communities by destroying the organic layers where a few species dominate, while preserving the deeper layers where species richness is greatest.

During the summer of 1998, we returned to the fire site and resampled the ectomycorrhizal community to see how it had recovered in the third year after the fire. Although we will not have the answer to this question for several months, we did observe abundant fruiting of *Rhizopogon subcaerulescens* at the site that summer. This is interesting because we knew from our 1-year sample that it is one of the species that survived the fire. We also know from our studies of the Pt. Reyes wildfire that *R. subcaerulescens* is one of the most dominant and responsive members of the sporebank in fire-disturbed settings (Baar and others 1999, Horton and others 1998, Taylor and Bruns 1999). It would not be surprising, therefore, if its abundance increased as a result of the burn.

From our sample of 64 *Sarcodes*, we determined that the only mycorrhizal associate for *Sarcodes* within the SNF and the Tahoe basin is in the *Rhizopogon ellenae* species complex. Previously, we knew that the associate was close to *R. subcaerulescens,* but with a refined ITS sequence database, we discovered that the associate is distinct from *R. subcaerulescens* and closer to *R. ellenae*. This is interesting because it means that snow plant targets a different fungus from its close relative, pine drops (*Pterospora andromedea—fig. 2*); the latter is associated with the *R. subcaerulescens* complex. The fact that these two plants often grow within a few meters of each other demonstrates that the plant-fungal specificity is based on intrinsic factors of the interaction rather than habitat. It also shows that these two fungi, which are difficult to discriminate taxonomically, are not redundant; the absence of either would translate into the absence of either *Sarcodes* or *Pterospora*.

The identification of *R. ellenae* as the associate of *Sarcodes* also revealed the confusion within identified *Rhizopogon* collections. Initially, we thought that *R. ellenae* was rare in the SNF because it did not appear to be included in any of our collections from the area. After we applied ITS-RFLP analysis to our collections, however, and to many of those housed in the Thiers Herbarium at San Francisco State University, we discovered that the names *R. subcaerulescens* and *R. ellenae* have essentially been applied interchangeably, even though two distinct lineages can be identified easily by ITS sequences.

The soil cores taken along four transects and centered on individual snow plants have revealed two interesting results. First, we found that both the presence of *R. ellenae* on fir roots and the number of fir roots are orders of magnitude greater near the rootball of *Sarcodes* than in the surrounding forest. This suggests that *Sarcodes* is either finding dense islands of *R. ellenae*-*Abies* mycorrhizae, or it is creating them. If the latter is the case, then the relationship between snow plant and *Rhizopogon* does not look strictly parasitic, as we had thought, and it opens the question of how this nonphotosynthetic plant is capable of stimulating both its fungal associate and the roots of a photosynthetic host. Second, we found that *R. ellenae* is so rare on the roots of *Abies* 500 cm from *Sarcodes* plants that it is undetected in our sample, and the dominant fungi are members of the Russulaceae and Thelephoraceae. This result provides further evidence that their dominance is a general pattern in California pinaceous ecosystems.

With the knowledge that all *Sarcodes* plants were associated with *R. ellenae,* the flower spikes were used as a convenient way to locate sites where the fungus was present. We selected plants at the high-density site, mapped them, and cultured *R. ellenae* from their roots. We are now analyzing these isolates to determine which, if any, are genetically identical. Because *Rhizopogon* has no

Figure 2—*Pterospora andromedea.*

known asexual spore state, genetic identity can be achieved only by vegetative growth. Therefore, by relating identical genotypes back to their mapped locations in the forest, we will be able to tell the size of a given fungal individual. We did not know what to expect for a *Rhizopogon* species, but we did know that *Suillus* species, which are closely related to *Rhizopogon*, often have individuals that span 100 m^2 or more (Bonello and others 1998, Dahlberg 1997, Dahlberg and Stenlid 1994, Jacobson and others 1993). Our preliminary results from *R. ellenae* at the dense site suggest that the average individual is small and that more than one individual may colonize a single *Sarcodes* plant. If confirmed, this would suggest that the abundance of *R. ellenae* at this site is the result of recent establishment by spore. This may be related to the past history of this site, which was burned after thinning about 6 years prior to this study. We know from our other studies that spores of several *Rhizopogon* species respond positively to fire or soil disturbance (Baar and others 1999, Horton and others 1998, Taylor and Bruns 1999).

Recently we have been using cultures of *R. ellenae* and *R. subcaerulescens* that we isolated from snow plant and pine drops, respectively, to study the physiological ecology of the ectomycorrhizal interaction. Our preliminary results show that both species are capable of forming mycorrhizae with lodgepole pine (*Pinus contorta)* and bishop pine (*Pinus muricata*), which agrees with previous findings by Molina and Trappe (1994). We also have preliminary evidence that *R. ellenae* stimulates the germination of snow plant seeds. This is the first record of *in vitro* germination for this species; ongoing tests will determine whether germination is specific to *R. ellenae.* Very recently we have succeeded in growing

Sarcodes in the laboratory in a tripartite system with lodgepole pine and *R. ellenae*. This is the first time a member of the Monotropoideae has successfully been grown in the laboratory, and it offers us an opportunity to use this system to further study the physiology of these plants.

A general picture of EM communities is starting to come into focus. They are clearly diverse and highly patchy communities, but their structure, at least at the family level, appears to be similar across different types of California pinaceous forests. Understanding the autecology of individual species is a daunting task, but one that is necessary if we wish to understand how these organisms interact with plant and animal communities.

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Seasonality and Abundance of Truffles from Oak Woodlands to Red Fir Forests[1]

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Abstract

Truffles are an important food source for many small mammals in forest ecosystems; however, we know little about the seasonality, abundance, or diversity of the truffle community in the Sierra Nevada. This study examined how truffle abundance and diversity varied between oak woodland, ponderosa pine (*Pinus ponderosa*), mixed-conifer, and red fir (*Abies magnifica*) forests. Species richness (number of species) and abundance of truffles were highest in ponderosa pine stands, but species evenness was greatest in mixed-conifer stands. Truffle biomass peaked in late spring and fall, tracking precipitation patterns with a 1-2 month lag. At least 65 species of truffles were identified in a 1-ha sample of the forest. This number is still only a fraction of the fungal species present, as many mycorrhizae rarely produce fruiting bodies. Truffle production depends on the condition of the truffle's mycorrhizal host trees. Natural or human disturbances, which affect the age and composition of the forest, will affect truffle abundance and the animals that depend on them for a substantial portion of their diet.

Scientists and managers are becoming increasingly aware of the importance of the fungal community in forest ecosystems. Mycorrhizal fungi are essential for plant growth and survival; they provide food for many soil biota (Warnock and others 1982); they reduce soil pathogens and bacteria (Marx 1972); and they improve soil structure (Tisdall and Oades 1979). Fungi also produce fleshy fruiting bodies that are an important part of a forest's food chain. Mycorrhizal fungi form above- and below-ground fruiting bodies known, respectively, as epigeous and hypogeous sporocarps, commonly called "mushrooms" and "truffles." Although many forest animals are opportunistic consumers of sporocarps (mycophagy) (Fogel and Trappe 1978), several species of small mammals rely on truffles for a substantial portion of their diet (Maser and others 1978). Animal mycophagists include many species of Geomyidae (pocket gophers), most Microtidae (voles), and almost all Sciuridae (squirrels and chipmunks) in North America (Fogel and Trappe 1978, Maser and others 1978), as well as many forest-dwelling marsupials in Australia (Johnson 1994, Seebeck and others 1989). Many truffle consumers comprise the base of the forest food chain for higher predators (Grenfell and Fasenfest 1979). A well-know example is the connection between truffles, the dominant food source of the northern flying squirrel (*Glaucomys sabrinus*) (Hall 1991; Maser and others 1985, 1986; McKeever 1960), and the squirrel's importance as the principal prey of the spotted owl (*Strix occidentalis*) in mesic forests (Forsman and others 1984, 1991; Verner and others 1992). It is essential that we understand how truffle abundance changes with forest conditions because of their substantial influence on small mammal populations and, consequently, the higher predators in the forest's food web.

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Changes in forest composition resulting from succession, disturbance, or timber harvesting will affect truffle abundance and diversity because truffles are produced by mycorrhizal fungi, which rely on carbohydrates from their tree hosts (Harley and Smith 1983). Other site characteristics, such as local edaphic conditions (North and others 1997) and the size and the decay state of coarse woody debris, may also influence truffle production (Amaranthus and others 1994). North and Greenburg (1998) found a highly significant association between the most abundant truffle species in western hemlock (*Tsuga heterophylla*) forest and thick organic layers with a high density of fine roots. In stands that lacked these soil conditions because they had been clearcut and burned 60 years earlier, truffle biomass was only 20 percent of that found in adjacent old-growth stands. In the Sierra Nevada, forest managers need information on truffle biomass in different forest types and what forest conditions are associated with truffle production to assess the impact of their management decisions on truffle biomass and to evaluate the potential abundance of this food source for small mammals.

This study was designed to answer two questions regarding truffles in forests of the Sierra Nevada: how do truffle abundance and species diversity vary among forest types and with seasons; and what are the biomass and species diversity of truffles in 1 ha of typical mixed-conifer forest?

Methods

We selected two stands in each of four forest types in the Sierra National Forest: oak woodlands, ponderosa pine, mixed-conifer, and red fir. The two oak woodland stands were at 320 m in elevation and dominated by blue oak (*Quercus douglasii*), interior live oak (*Q. wislizenii*), and a mixture of exotic grasses. The two ponderosa pine (*Pinus ponderosa*) stands were at 1,400 m in elevation, dominated by ponderosa pine but with a substantial density of smaller white fir (*Abies concolor*) and incense cedar (*Calocedrus decurrens*) stems. The two mixed-conifer stands, within the Teakettle Experimental Forest at 2,200 m in elevation, had white fir, red fir (*Abies magnifica*), incense cedar, Jeffrey pine (*Pinus jeffreyi*), and sugar pine (*Pinus lambertiana*). The red fir stands were at 2,800 m in elevation and dominated by red fir and occasional lodgepole pine (*Pinus contorta*).

Beginning in February of 1996, all eight stands were sampled each snow-free month. In each stand, two parallel transects 10 m apart were randomly located, and 4-m^2 circular plots were raked for truffles every 10 m along each transect. New transects and plots were sampled with each stand visit because raking disturbed soil structure and mycorrhizae. A total of 100 m^2 was sampled in each stand during each sample period. All truffles were labeled, bagged, cut in half, and dried for 48 hr at 60^o C. Truffles were identified to species using a combination of visual cues and microscopic spore patterns against published keys. Difficult identifications were sent to Dr. Jim Trappe at Oregon State University.

To investigate biomass, diversity, and stand conditions associated with truffles, we selected a 1-ha plot in mixed-conifer forest near Ross Crossing, at 1,500 m in elevation. All locations of truffles, trees, snags, logs, and shrubs were recorded using a surveyor's total station. For weather data, we relied on records from two long-established weather stations. One, at the USDA Forest Service's Trimmer Guard Station near Pine Flat Reservoir, was at the same elevation (300 m) as the oak woodland stands. The other was at Wishon Reservoir, about equidistant between the mixed-conifer and red fir sites, at an elevation of 2,400 m.

Results

The highest truffle abundance was in the ponderosa pine stands, where the biomass in June 1996 was 4.4 kg/ha (*fig. 1*). Truffle biomass, at 2.2 kg/ha, also peaked in the mixed-conifer at this time. All stands in oak woodlands and red fir

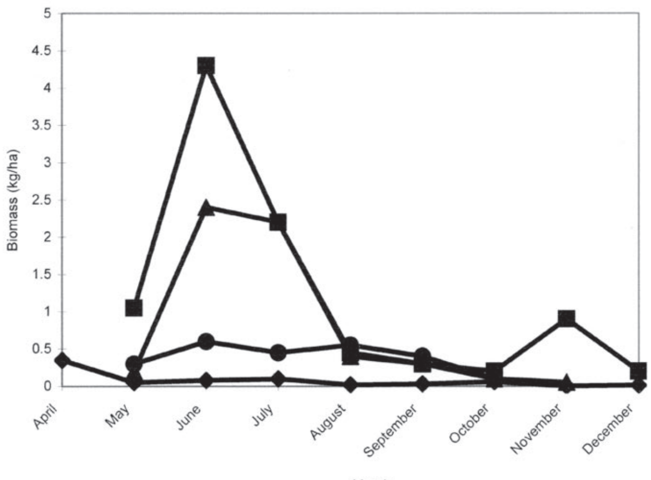

Figure 1—Truffle biomass by forest type and month (diamonds = oak woodlands, squares = ponderosa pine, triangles = mixed conifer, and circles = red fir).

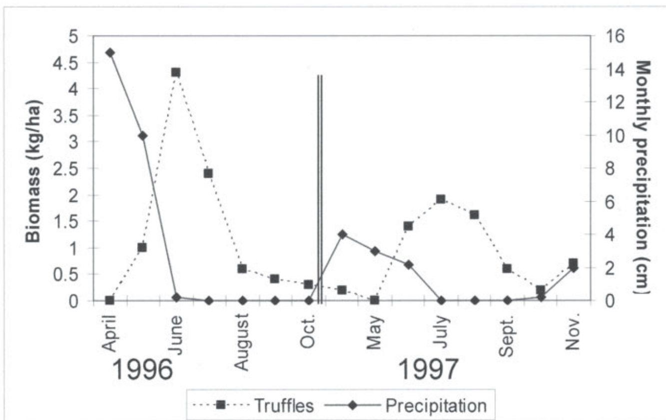

Figure 2—Truffle biomass and precipitation by month from April through October in 1996 and April through November in 1997.

Table 1—*Truffle species richness (number of species) and evenness in four forest types. Evenness values, using the Berger-Parker diversity index (Magurran 1988), indicate whether the truffle community is dominated by a single species (lower values) or if species are equitably distributed (higher values)*

Forest type	Richness	Evenness
Oak woodlands	14	1.63
Ponderosa pine	22	3.12
Mixed-conifer	9	4.35
Red fir	6	1.80

forest had consistently low truffle biomass. The highest values for all sites occurred in the spring and late fall. Fluctuations in truffle biomass correlated with the abundance of precipitation. With a lag of 1-2 months, the peaks in truffle biomass during the spring and fall were closely and positively correlated with total rainfall at the Trimmer weather station (*fig. 2*). Species richness was highest in ponderosa stands (*table 1*), but species evenness was greatest in mixed-conifer stands, indicating a community in which no single species dominated truffle abundance.

In the 1-ha plot, we located 869 truffles of 65-71 species, with a total dry biomass of 573 gm (*table 2*). Several individuals were immature, precluding a determination of whether they were new species or one already tallied. Nine new, undescribed species collected from the 1-ha plot now await final taxonomic classification at Oregon State University.

Table 2—*Number of individuals and biomass (gm) of truffles by species found in a 1-ha plot in mixed-conifer forest. The 65-71 species (some truffles were too immature to identify) include nine new, undescribed species*

Sum of biomass	Number of individuals	Species
0.01	1	*Mycolevis siccigleb*
0.04	1	*Hymenogaster* sp (immature)
0.06	1	*Endogone flammicorona*
0.07	1	*Martellia brunnescens*
0.16	9	*Hymenogaster alnicola*
0.16	3	*Hymenogaster* sp. nov. #19914
0.21	8	*Hymenogaster gilkeyae*
0.25	3	*Martellia* sp. (immature)
0.25	1	*Rhizopogon roseolus*
0.26	8	*Genea intermedia*
0.27	2	*Gymnomyces cinnamomeus*
0.32	3	*Gymnomyces* sp. (immature)
0.36	1	*Rhizopogon ellipsosporus*
0.45	5	*Endogone lactiflua*
0.53	1	*Hysterangium setchellii*
0.57	1	*Alpova trappei*
0.57	4	*Endogone* sp. nov. #19927
0.60	11	*Rhizopogon evadens* A.H. Smith var. *evadens*
0.66	1	*Tuber gibbosum*
0.76	3	*Hysterangium* sp. nov. #19912
0.81	3	*Martellia californica*
0.83	1	*Tuber shearii* Harkness
0.91	2	*Gymnomyces* sp. nov. #22596
0.91	1	*Leucogaster microsporus*
0.93	2	*Trappea darkeri*
1.00	1	*Arcangiella crassa*
1.03	5	*Hysterangium coriaceum*
1.05	6	*Macowanites luteolus* Smith and Trappe
1.19	7	*Martellia fallax*
1.27	7	*Hysterangium separabile*

(continues on page 95)

Sum of biomass	Number of individuals	Species
1.29	2	*Martellia gilkeyae*
1.41	1	*Gautieria parksiana*
1.47	30	*Genabea cerebriformis*
1.54	4	Unknown (too immature)
1.90	14	*Tuber* sp. immature
1.99	2	*Gautieria crispa*
2.39	4	*Hymenogaster sublilacinus*
2.39	7	*Martellia foetens*
2.63	3	*Radiigera* sp. (immature)
2.85	7	*Tuber rufum var. nitidum*
3.66	11	*Gymnomyces* sp. nov. #19913
3.79	7	*Rhizopogon vulgaris*
3.98	2	*Tuber californicum*
4.19	2	*Rhizopogon subcaerulescens*
4.76	11	*Melanogaster tuberiformis*
5.02	13	*Tuber murinum*
5.20	20	*Rhizopogon* sp. immature
5.41	10	*Balsamia magnata* Harkness
5.60	7	*Rhizopogon pedicellus*
5.70	11	*Martellia subochracea*
6.64	28	*Tuber monticola*
6.85	59	*Zelleromyces* sp. nov. #19929
9.56	6	*Rhizopogon* sp. nov. w/pink stain
9.57	4	*Rhizopogon subgelatinosus*
12.40	8	*Rhizopogon variabilisporus*
12.46	13	*Hydnotryopsis setchellii*
12.75	5	*Balsamia nigrens*
13.00	1	*Rhizopogon* sp. nov. #19920
14.42	9	*Gautieria gautierioides*
17.64	27	*Hydnotryopsis* sp. nov. #19890
18.16	51	*Tuber rufum* var. *rufum*
18.77	7	*Gautieria graveolens*
19.98	7	*Geopora cooperi f. gilkeyae*
20.13	19	*Hydnotrya cerebriformis*

(continues on page 96)

Sum of biomass	Number of individuals	Species
20.13	19	*Hydnotrya cerebriformis*
21.60	23	*Rhizopogon brunnescens*
22.63	10	*Gautieria caudate*
22.68	50	*Leucophleps spinispora*
24.57	100	*Hydnoplicata* sp. nov. #19923
35.28	12	*Gautieria monticola*
35.28	57	*Leucogaster rubescens*
96.45	74	*Radiigera taylori*
573.58	869	Total

Discussion

Forest types with the highest densities of truffle consumers also contain the greatest truffle abundance. Ponderosa pine and mixed-conifer forests are home to most Sierra forest mycophagists, including the northern flying squirrel. Low truffle abundance in oak woodlands may correspond to long dry seasons or a low density of tree hosts. In red fir forests, long, cold winters probably reduce the duration of available soil moisture and may depress truffle production.

The observed relation between truffle productivity, with peaks in late spring and fall, and precipitation patterns in the Sierra Nevada, is consistent with other studies of both epigeous (Richardson 1970) and hypogeous fruiting bodies (Hunt and Trappe 1987). It is reasonable to infer from these results that fungal fruiting is strongly conditioned on soil moisture, which is certainly influenced by a variety of stand factors, including canopy cover, litter depth, and root density. Truffle production should follow peak periods of nutrient and moisture uptake because mycorrhizal fungi require carbohydrates from their host plant to produce fruiting bodies.

The observed patterns of species diversity are consistent with theories of fungal community competition. In ponderosa pine stands, which may have the longest period of available soil moisture, a high number of species may occur in the soil, but truffle production is dominated by a few superior competitors. In mixed-conifer forests, fewer species occur but dominance is less pronounced.

The 1-ha plot was searched in June of 1997, after an exceptionally dry spring. Even under these conditions, 65-71 species were collected from the plot. Much of the Sierra Nevada has not yet been sampled for truffles, so probably many new species of truffles are as yet undescribed. Furthermore, because truffles are produced by only a fraction of the fungal species in the soil, even the 65 identified species in this sample comprise only a portion of the species present. As such, the data suggest that the soil fungal community may have even more species than the invertebrate community. We have yet to identify many of these species and to understand their role in "healthy" ecosystem functions.

The observation that truffles are most abundant in the ponderosa pine and mixed-conifer forests is reason for extra care in planning for forest management, as most stand altering projects occur in these forest types. Further research is needed to understand the effects of thinning, burning, soil scarification, and compaction on this important below-ground food source.

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Diets of California Spotted Owls in the Sierra National Forest[1]

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Abstract

From May 1987 through October 1992 and from July through August 1998, we studied diets of California spotted owls (*Strix occidentalis occidentalis*). Regurgitated pellets were collected at roost and nest sites between 1,000 and 7,600 ft elevation in the Sierra National Forest and were examined for remnant bones, feathers, and insect exoskeletons. Remains of 2,038 individual prey were identified in 1,140 pellets. Woodrats (*Neotoma spp*.) were the predominant prey in low-elevation oak woodlands and riparian-deciduous forests, accounting for 74.3 percent of the biomass in diets during the breeding period and 81.9 percent during the nonbreeding period. In coniferous forests, northern flying squirrels (*Glaucomys sabrinus*) were the major prey, comprising 45.6 percent and 77.3 percent of prey biomass during the breeding and nonbreeding periods, respectively. Pocket gophers (*Thomomys spp*.) were the second largest component of owl diets, by biomass, in both vegetation types. In the breeding period, birds were a larger part of the owl's diet in coniferous forests (12.9 percent) than in the riparian-deciduous and oak habitats (1.8 percent). Other small mammals, insects, and lizards were also found in pellets. Diets differed among years.

Concern over the status of the California spotted owl (*Strix occidentalis occidentalis*) increased when the U. S. Fish and Wildlife Service listed the northern spotted owl (*S. o. caurina*) and then the Mexican spotted owl (*S. o. lucida*) as "threatened." Although not currently federally listed, the California spotted owl is classified as a "sensitive species" by the Pacific Southwest Region (Region 5) of the USDA Forest Service.

Several studies have examined diets of California spotted owls in the Sierra Nevada (Kadoch 1997, Laymon 1988, Marshall 1942, Thrailkill and Bias 1989, Verner and others 1992), but additional information on diets is needed to better understand the relations between owl occurrence and breeding and the availability of prey. An adequate understanding of diets can then guide studies of the ecological requirements of key prey species and help to guide forest management in ways that will favor conditions for the prey species and, in turn, for the owls.

We studied California spotted owl diets in the southern Sierra Nevada to describe prey composition and to examine annual and seasonal variations in the diets. We also compared diets between owls in coniferous forests and owls in oak woodlands and riparian-deciduous forests.

Study Area

We studied spotted owl diets in a 265-mi^2 study area in the Sierra National Forest, Fresno County, California, about 30 mi east of Fresno (Steger and others, in this volume). Twenty-three percent of the study area was below 4,000 ft in

1 An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Projects: Progress and Current Status, January 26, 1998, Clovis, California.

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elevation, in oak-pine woodlands, blue oak (*Quercus douglasii)* savannas, and dense riparian-deciduous forests (Verner and Boss 1980). Coniferous forests covered the remainder of the study area, from about 4,000 to 9,600 ft in elevation. Ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), and black oak (*Quercus kelloggii*) were the dominant tree species below 8,000 ft. Inclusions of Jeffrey pine (*Pinus jeffreyi*) and red fir (*Abies magnifica*) occurred near 8,000 ft. Above that, forests were dominated primarily by red fir, lodgepole pine (*Pinus contorta*), and western white pine (*Pinus monticola*).

Methods

Owls regurgitate the less-digestible parts of consumed prey (bones, feathers, exoskeletons, fur, and so on) in formed pellets. Prey remains in these pellets have long been used to study the diets of owls (Glading and others 1943, Marti 1987). From May 1987 through October 1992, and from July through August 1998, we studied diets of the owls by examining prey remains in regurgitated pellets collected below roost and nest sites. Pellets were classified as egested during either the breeding (March 1 through August 31) or nonbreeding (remainder of the year) period, and we analyzed only pellets that could be assigned unambiguously to either period. Identification to species was impossible for some specimens because remains were incomplete.

Sampling intensity varied considerably among sites, seasons, and years. From May 1987 through March 1990, we collected pellets opportunistically throughout each year while studying home ranges and habitat use of radio-tagged spotted owls. Thereafter, we collected pellets in conjunction with demographic studies, when most of the collected pellets were egested during the breeding period. Pellets collected at the same site on the same day, or within a brief period of a few days, were aggregated into one sample because remains of the same individual prey can be egested in more than one pellet (Forsman and others 1984).

As described by Munton and others (1997), pellets were dissected and skeletal remains, feathers, and pieces of exoskeleton were identified to species when possible, using a reference collection of specimens from the Carnegie Museum of Natural History, together with selected references and keys (Borror and DeLong 1964, Burt and Grossenheider 1976, Dunning 1984, Forsman and others 1984, Ingles 1990, Jameson and Peeters 1988, Robbins and others 1983, Swan and Papp 1972). These same sources were used to assign weights to prey items. Prey species with mean weight of at least 3.5 oz were considered to be "large prey." The number of individual prey items in a sample was tallied as the largest number of skulls or identical bone parts for each prey type per sample (the aggregate of pellets from a single site in one to a few days). The number of insects was estimated either from the largest number of heads, paired mandibles, or one-sixth the number of legs. The estimated mean weight of each prey type was multiplied by its observed frequency in each sample to convert counts to biomass.

Results

Coniferous Forests

In 620 pellets collected in coniferous forests, more than 94 percent from the breeding period, we identified remains of 1,344 individual prey, an average of 2.12 prey items per pellet. Excluding insects—highly variable in number in pellets and of little consequence to total biomass—pellets averaged 1.48 prey items each. At least 35 species (13 mammals, 11 birds, 10 insects, and 1 lizard) were present. Mammals comprised 57.8 percent of all prey and 87.2 percent of the biomass; the remainder consisted of birds, lizards, and insects (*table 1*). Large

Table 1—*Percent frequency and percent biomass of prey in California spotted owl pellets from coniferous forests, Sierra National Forest*

Wildlife	Breeding period[1]		Nonbreeding period[2]		Mean annual percent of biomass
	Percent of individuals	Percent biomass	Percent of individuals	Percent biomass	
Bats	0.7	0.1	0	0	0.1
Birds	10.5	12.9	4.0	4.6	8.7
Diurnal squirrels	1.0	0.9	0	0	0.4
Flying squirrels	21.1	45.6	46.7	77.3	61.5
Gophers	11.0	18.4	9.3	11.5	15.0
Insects	32.3	0.6	24.0	0.3	0.5
Lizards	0.2	<0.1	0	0	<0.1
Mice	12.9	5.5	5.3	1.7	3.6
Moles	1.8	1.5	2.7	1.7	1.7
Shrews	1.7	0.2	6.7	0.6	0.4
Unidentified mammals	1.9	1.3	1.3	2.3	1.8
Voles	1.8	1.2	0	0	0.6
Woodrats	3.0	11.8	0	0	5.9

[1] n = 1,269 individual prey.

[2] n = 75 individual prey.

prey—flying squirrels (*Glaucomys sabrinus*), woodrats (*Neotoma* spp.), pocket gophers (*Thomomys* spp.), Steller's jays (*Cyanocitta stelleri*), northern flickers (*Colaptes auratus*), a western screech-owl (*Otus kennicottii*), an unidentified quail, and some unidentified mammals—accounted for 36.5 percent of the individual prey items and 78.3 percent of the biomass. Over the course of a year, flying squirrels contributed the most biomass to owl diets, followed by pocket gophers, birds, and woodrats (*table 1*). Owls were seldom found above 8,000 ft in elevation, and we found no pellets above 7,600 ft, probably because of low sampling intensity there.

We identified enough prey in five breeding periods to evaluate annual variations in biomass. The proportion of birds in diets was least variable (CV = 16.0 percent, *table 2*), followed by flying squirrels (CV = 22.8 percent). Interestingly, flying squirrels were most prevalent (54.1 percent of the biomass) in diets in 1992, when 87 percent of owl pairs produced young. No clear pattern emerged, however, when comparing percent biomass of flying squirrels in the diet and overall reproductive success of owls in the study. For example, flying squirrels were only slightly less prevalent (52.6 percent of the biomass) in 1988 diets, a year when pellets were collected from nonreproductive owls; and flying squirrels represented only 38.3 percent of the diet biomass in 1990, when 72 percent of pairs fledged young.

Table 2—*Annual variation in percent biomass of prey in pellets of California spotted owls during the breeding period in conifer habitats of the southern Sierra Nevada; sample sizes (numbers of individual prey in parentheses beneath each year)*

Wildlife	1988 (83)	1989 (295)	1990 (227)	1992 (362)	1998 (278)	Mean ± SD	Percent CV
Bats	0.1	0.1	0.2	0.1	0.1	0.1 ± 0.05	41.1
Birds	10.1	14.5	13.1	11.4	15.0	12.8 ± 2.05	16.0
Diurnal squirrels	1.7	0.3	1.0	0.2	2.1	1.1 ± 0.83	77.3
Flying squirrels	52.6	47.7	38.3	54.1	30.1	44.5 ± 10.16	22.8
Gophers	21.1	19.3	23.8	12.3	23.5	20.0 ± 4.70	23.5
Insects	0.6	0.8	0.5	0.4	0.8	0.6 ± 0.20	33.1
Lizards	0.0	0.0	0.1	0.0	0.0	<0.1 ± 0.03	223.6
Mice	1.7	3.1	3.5	6.0	11.7	5.2 ± 3.95	75.9
Moles	3.3	2.8	1.3	0.7	0.8	1.8 ± 1.18	66.4
Shrews	0.1	0.4	0.1	0.1	0.3	0.2 ± 0.13	66.6
Unidentified mammals	0.0	1.3	0.4	0.5	4.9	1.4 ± 2.02	141.8
Voles	0.7	0.8	0.3	0.6	3.2	1.1 ± 1.20	106.3
Woodrats	8.0	9.0	17.4	13.6	7.5	11.1 ± 4.28	38.6

Oak Woodlands and Riparian-Hardwood Forests

Data from low elevations in oak woodlands and riparian-deciduous forests are summarized from Munton and others (1997). In 520 pellets collected primarily during the nonbreeding period in 1988-1992, we identified remains of 664 individual prey, an average of 1.28 per pellet. Excluding insects, pellets averaged only 0.96 prey items each, 35 percent fewer than identified in pellets from the conifer forests. At least 20 species—nine mammals (70.0 percent of prey by frequency, 96.5 percent by biomass), six birds, and five insects—were identified (*table 3*). Large prey accounted for 48.5 percent of the total by frequency and 91.8 percent by biomass. Species included were woodrats, pocket gophers, western screech-owls, and unidentified mammals and owls. Woodrats were consistently the dietary staple—74.3 percent of prey biomass during the breeding period and 81.9 percent during the nonbreeding period. Pocket gophers comprised only 12.9 percent of the prey biomass over the full year; other mammal species, each contributing less than 5 percent of the total biomass, included mice (mainly *Peromyscus* spp.), voles (*Microtus* spp.), broad-footed moles (*Scapanus latimanus*), and shrews (*Sorex* spp.). Western scrub-jays (*Aphelocoma californica*) were the most numerous birds identified, followed by other species of owls.

Discussion

Diets of spotted owls at higher elevations (coniferous forests) and at lower elevations (oak woodlands and riparian-deciduous forests) were similar in dominance by a single prey species (flying squirrels at high elevations, woodrats

Table 3—*Percent frequency and percent biomass of prey in California spotted owl pellets from low-elevation oak savannas, oak/foothill pine forests, and riparian-deciduous forests, Sierra National Forest (after Munton and others 1997)*

Wildlife	Breeding period[1]		Nonbreeding period[2]		Mean annual percent of biomass
	Percent of individuals	Percent biomass	Percent of individuals	Percent biomass	
Birds	2.2	1.8	6.7	4.2	3.0
Gophers	11.9	18.5	7.3	7.3	12.9
Insects	44.6	0.1	11.1	0.1	0.1
Mice	7.6	2.2	24.1	4.7	3.5
Moles	0.0	0.0	0.5	0.2	0.1
Shrews	0.4	<0.1	0.3	<0.1	<0.1
Unidentified mammals	1.1	0.2	1.6	0.7	0.5
Voles	5.0	2.7	2.6	0.9	1.8
Woodrats	27.3	74.3	45.9	81.9	78.1

[1] n = 278 prey items.

[2] n = 386 prey items.

at low elevations), increased reliance on the dominant prey species during the nonbreeding period, pocket gophers as the second greatest contributor to diet biomass and a higher proportion in diets during the breeding than the nonbreeding period, and higher frequency of insects during the breeding period. Main differences were the absence of flying squirrels from low-elevation diets (generally absent from those vegetation types); a greater reliance on the main prey species (woodrats) at low elevations; greater consumption of birds in coniferous forests, especially during the breeding period; greater consumption of birds and mice in coniferous forests in the breeding period than in the nonbreeding period, while the opposite trend occurred in oak woodlands and riparian-deciduous forests; and 1.55 times as many vertebrate prey per pellet in samples from the conifer forest than in samples from low-elevation sites.

The different numbers of prey items per pellet between high- and low-elevation sites most likely reflected the prevalence of woodrats in diets of owls in the low-elevation sites. Because woodrats outweigh flying squirrels by a factor of 1.82, one flying squirrel would provide only about 55 percent of the biomass available in one woodrat. Interestingly, note the close correspondence between the factor of 1.82 for the difference between weights of woodrats and flying squirrels and that of 1.70 for the difference between the numbers of prey items per pellet in the two areas.

Other studies (Kadoch 1997, Marshall 1942, Verner and others 1992) also found that flying squirrels dominate the diets of California spotted owls in coniferous forests of the southern Sierra Nevada during the breeding period. In addition, pocket gophers were found to be important prey in the Sequoia and Kings Canyon National Parks (Verner and others 1992) and in the Sierra National Forest by Kadoch (1997). Birds averaged 13.3 percent of the diet biomass during the breeding period on the Sierra National Forest in 1995 and 1996 (Kadoch 1997).

Diets of spotted owls in the Eldorado and Stanislaus National Forests from 1982 to 1984 were dominated by dusky-footed woodrats (*Neotoma fuscipes*) (31 percent) and flying squirrels (25 percent), followed by diurnal squirrels (14 percent) (Laymon 1988). Thrailkill and Bias (1989) also found that woodrats (37.4 percent) and flying squirrels (31.2 percent) dominated spotted owl diets in the Eldorado National Forest, with birds making up another 12.4 percent of the biomass during studies in 1986 and 1987. The higher proportion of woodrats and lower proportion of flying squirrels found in their studies, in comparison with results of the present study in the southern Sierra Nevada, probably reflect the fact that the study areas in the central Sierra Nevada included considerable landbase at lower elevations, probably in the transition zone where flying squirrels are less abundant and woodrats more abundant than at the higher elevations corresponding to those in the coniferous forests of our study area.

The studies by Laymon (1988) and Thrailkill and Bias (1989) both found a markedly higher percentage of diurnal squirrels (14.0 and 6.7 percent, respectively) than we found (0.9 percent) in the conifer zone of the Sierra National Forest. Pellets examined by Thrailkill and Bias (1989) included golden-mantled ground squirrels (*Spermophilus lateralis*) and a western gray squirrel (*Sciurus griseus*). Laymon's (1988) pellets included chipmunks (*Eutamias* spp.), California ground squirrels (*Spermophilus beecheyi*), western gray squirrels, and Douglas' squirrels (*Tamiasciurus douglasii*). Kadoch (1997) found no diurnal squirrels in spotted owl diets in the Sierra National Forest in 1995 and 1996.

Other authors have observed annual (Kadoch 1997, Laymon 1988) and seasonal (Kadoch 1997, Munton and others 1997) variations in diets of the California spotted owl, although this study was the first to examine diets in the nonbreeding period in coniferous forests of the Sierra Nevada. Verner and others (1992) suggested that we need to manage for thriving populations of northern flying squirrel populations in Sierra coniferous forests and woodrats in other areas occupied by California spotted owls. The greater dominance of flying squirrels in coniferous forests and woodrats in riparian-deciduous and oak vegetation types in diets during the nonbreeding period emphasizes this need in the southern Sierra Nevada.

Differences in diets of this owl have been observed during the same season and year between pairs in sites in similar habitats (Kadoch 1997, Laymon 1988) and between breeding and nonbreeding pairs (Barrows 1987, Smith and others 1999, Thrailkill and Bias 1989, White 1996). Although we found annual and seasonal shifts in spotted owl diets, sampling effort was not consistent from site to site, period to period, or year to year, so our results must be viewed with caution. We did not factor the breeding status of pairs into our analysis, primarily because pellets were collected only incidental to home-range and demographic studies. Nonetheless, we believe that results reported here are indicative of the overall trends of the owls' diets in our study area. Additional studies are needed that focus on diets in relation to prey populations to determine whether the relative importance of different prey species in their diets reflects changing owl preference, prey availability, or a mix of these factors.

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Demography of the California Spotted Owl in the Sierra National Forest and Sequoia/Kings Canyon National Parks[1]

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Abstract

Nine years (1990–1998) of demographic data on California spotted owls (Strix occidentalis occidentalis) in two study areas on the western slopes of the Sierra Nevada—one in the Sierra National Forest (SNF), the other in Sequoia/Kings Canyon National Parks (SNP)—are summarized. Numbers of territorial owls fluctuated from 85 to 50 in SNF and 80 to 58 in SNP over the period from 1990 to 1998, and demographic parameters indicate significantly declining populations in both study areas during the same period. Owl densities in conifer forests, reproductive performance, and survival rates did not differ significantly between the two study areas. These results suggest that factors influencing population trends may be more than local in scope, such as weather and/or prey populations. Local forest management may compound the regional variation, however, as may be reflected in the lower adult/subadult survival rates in the SNF study area compared to the SNP study area. Continual timber harvest has occurred in SNF since the late 1800's, but SNP has had little harvesting activity. Prescription burning and recreation continue to occur on both sites. Declining trends in owl numbers also reflect poor breeding success from 1995 through 1998, apparently attributable to unseasonal storms during the breeding period, especially during the incubation and nestling phases. Results suggest the hypothesis that spotted owls are "pulse" breeders that exhibit unusually successful reproduction only at intervals of several years, when all conditions are favorable. Continuation of these studies as part of the Kings River Sustainable Forest Ecosystems Project within boundaries of SNF will provide opportunities to explore relations among spotted owl demographics and timber harvest, weather, and prey availability.

California spotted owls (*Strix occidentalis occidentalis*) in the western Sierra Nevada show a close association with dense forest and woodland ecosystems and their nesting/roosting stands typically have much "decadence" in the form of standing dead trees (snags), diseased and/or deformed live trees, and decaying wood on the forest floor. Pairs in Sierra conifer forests use home ranges that average about 3,400 acres during the breeding period and about 9,700 acres during the nonbreeding period (Verner and others 1992). Consequently, maintenance of sufficient habitat to assure viability of the Sierra population represents a substantial cost in allowable timber volume. The California spotted owl is not currently listed as a threatened or endangered species, although major environmental organizations are poised to petition the U.S. Fish and Wildlife to list the subspecies.

Nests are typically in large trees—mean of about 45 inches in diameter at breast height (dbh)—with broken tops and cavities large enough to accommodate a female owl and two or three young (Steger and others 1997b). Nesting in the southern Sierra Nevada is intermittent, involving from none to as many as 95 percent of pairs in any given year (50 percent of pairs nesting is regarded as a

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"good" year). Details of the structure and composition of owl habitat in relation to successful breeding are still uncertain.

The California spotted owl uses a diverse array of vegetation types, from riparian hardwood forests in the western Sierra Nevada foothills to red fir forests at high elevations. A recent technical assessment of the current status of the California spotted owl (Verner and others 1992) concluded that research is needed to distinguish levels of habitat quality for the birds by relating forest structure and composition to owl population parameters.

This paper provides information on the California spotted owl's adult survival rates, population turnover rates, reproductive rates, site fidelity, mate fidelity, and other population characteristics on two study sites under different management regimes, and it assesses the effects of management at landscape scales.

The specific objectives of this study were to:

- Estimate spotted owl density and territorial occupancy status by area.
- Estimate vital rates (reproduction, mortality) by age class.
- Assess site fidelity among individual spotted owls.
- Estimate turnover rates (annual replacement of vacancies in occupied territories).
- Estimate lambda (λ), the finite rate of population change under the null hypotheses, the population of resident owls is stable ($\lambda = 1$) in all study areas; and vital rates (age at first reproduction, reproductive rate, and survival rate) do not differ among years, between sexes, or between study sites.
- Quantify the distribution of vegetation types within each study area.

Study Areas

The two study areas were selected for their proximity and vegetative similarities. The Sierra National Forest (SNF) study area, located in the southern Sierra Nevada about 30 mi east of Fresno, California, covered 160 mi^2 from 1990 to 1993, when the area was enlarged to 265 mi^2 as the Kings River Sustainable Forest Ecosystems Project began. The additional 105 mi^2 was labeled the New Sierra (NS) study area. The 132-mi^2 Sequoia and Kings Canyon National Parks study area (SNP) was also in the southern Sierra Nevada, about 50 mi east of Visalia, California. All three study areas included three habitat zones:

- The oak-woodland type, at the lowest elevation—1,000 to 4,000 ft—had a canopy dominated by blue oak (*Quercus douglasii*), live oak (*Quercus wislizenii*), and foothill pine (*Pinus sabiniana*). Various foothill chaparral species were abundant.
- The mid-elevation coniferous forest—4,000 to 8,000 ft—made up the majority of each study area. Vegetation was dominated by ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), and black oak (*Quercus kelloggii*). Sites nearer to 8,000 ft had inclusions of Jeffrey pine (*Pinus jeffreyi*) and red fir (*Abies magnifica*). Nearly all of the SNF and NS sites had been logged since 1880, and only small, scattered patches of old-growth forest remain. Forest regeneration programs are in place on both public and private lands. Nearly all logging was some form of selective cutting; the little clear cutting that occurred was in scattered patches, typically smaller than 20 acres. The SNP included large stands of giant sequoia (*Sequoiadendron giganteum*) and large tracts of old-growth,

mixed-conifer forest. Some logging occurred in the late 1800's and early 1900's, but most stands were in mature or old stages of growth.

- The high-elevation coniferous forest—8,000 to 9,600 ft—was dominated primarily by red fir, lodgepole pine (*Pinus contorta*), and western white pine (*Pinus monticola*).

Methods

These demographic studies involved surveying, banding, determining age and reproductive success, and rechecking owls on an annual basis from 1990 to 1998. Data from a few birds in the SNF study area included the period from 1987 through 1989, when we were studying movements, home ranges, and vegetation types used by radio-tagged spotted owls. In addition, we have added information to the SNP database from birds studied in 1988 and 1989 by Roberts (1990) within boundaries of our SNP study area. Spotted owls were located by night and day surveys, by observers imitating calls of owls to elicit responses. Surveying included point, leapfrog road, walking cruise, and walk-in methods (Forsman 1983). Survey period and the duration of surveys have been described by Steger and others (1993).

Owl surveys in all study areas began in the first week of March each year and ended on 30 September. Changes in survey effort that occurred over time usually resulted from poor weather conditions or inability to access sites. Several changes in survey effort occurred in 1997 and 1998 because of budget constraints. We chose a system that provides survey priority to pair sites, then sites with past owl detections, and finally sites with no previous owl detections. Surveys continued from March through September or until funding was exhausted.

Birds were captured with either a noose pole or mist net (Forsman 1983). All individuals were banded with a U.S. Fish and Wildlife Service leg band and a colored, plastic band on the opposite leg. A colored vinyl tab 0.8 inches long was attached to each color band (Franklin and others 1987), allowing hundreds of unique combinations. Sex and age classes of owls were determined following Forsman (1981, 1983). Fledgling, subadult, and adult age classes were recognized.

Owls were assessed for social status, reproductive status, and turnover (replacement) on sites using standard techniques (Miller 1990). Protocols for determining these attributes were described by Steger and others (1993).

Vegetative sampling was used to determine if nest sites differed in canopy cover, species composition, and size class between study areas. Nest trees were located from 1990 to 1998 using methods described by Forsman (1983), and sampled using methods described by Steger and others (1997a, 1997b).

Data were analyzed by using a variety of statistical tests (Sokal and Rolf 1981, Zar 1984). Annual survival rates (the probability of surviving from age x to $x + 1$) were calculated for subadults and adults combined as one age class using the Jolly-Seber (J-S) capture-recapture model for open populations (Jolly 1965; Seber 1965, 1982), which allows for losses and gains to the population between sampling periods. A sampling period was defined as one field season, for example from March 1 to September 30. The J-S model assumes that all individuals in the population have equal probabilities of survival, capture, and recapture (resighting in this case); that emigration is permanent, although the model partially adjusts for emigration vs. mortality using the rate at which emigrants return to the study area in later years; and that the sampling period is instantaneous (Nichols and others 1981, Seber 1982). A small percentage of our color-banded owls are more difficult to resight (read their band colors) than most banded owls because they tend to remain more concealed, and few have lost their colored bands. We consider these to be a minor violation of the first assumption. The second assumption is probably violated a few times because not all emigrants from the study area are likely to return in later years. Finally, the third assumption is probably violated to a small degree because of the relatively long, 7-month sampling interval, although the very low mortality rate during this period mitigates this effect (Nichols and others 1981).

We could not estimate juvenile survival rates for our study areas because of insufficient data. Instead, we have used 0.3278 as our estimate of juvenile survival rate, based on data from a similar demographic study of spotted owls in the San Bernardino Mountains, where probably few if any juveniles leave the study area (LaHaye and others 1997).

Fecundity was calculated as the number of female offspring produced per territorial female checked for reproduction (Noon and others 1992). Turnover rates were calculated as the proportion of marked adults and subadults that were replaced annually on their territory by another owl.

Lambda (λ) was calculated using the Lefkovitch stage-projection matrix model (Lefkovich 1965). Population trends were considered to be increasing if $\lambda > 1.0$, stable if $\lambda = 1.0$, and in decline if $\lambda < 1.0$. An estimate of λ and its standard error allowed the tests of hypotheses: H_o: $\lambda \geq 1$, versus the alternative H_a: $\lambda < 1$. The appropriate test statistics followed a Z-distribution, given by: $Z = |(\lambda - 1)/\lambda_{\lambda}|$. We followed the method adopted by Noon and others (1992) in testing the significance of λ values, in which the appropriate test statistics followed a Z-distribution, and the specified probability of a Type I error = 0.05.

Results

Estimates of abundance, productivity, and population change, in most instances, were similar in the three study areas (*table 1*), although we consider the data for the NS study area to be marginal because it has been under study only since 1994. The numbers of territorial owls increased from 1991 through 1994 in SNF and 1991 through 1995 in SNP, but they have since declined in all areas. Densities in the conifer forest zones (3,400-7,600 ft in SNF; 3,600-8,000 ft in SNP) did not differ significantly between SNF and SNP (t = 0.02; P = 0.98) but was considerably lower in NS. Productivity (young/pair) was marginally higher in SNF than in SNP, but turnover rates were lower in SNP (suggesting higher survival there). Although the average percentage of territorial birds disappearing each year was slightly higher in SNF than in SNP, the net loss of territorial birds (loss minus replacement rates) was essentially the same in those study areas.

We have color banded 256 of 289 young owls known to fledge from the three study areas over the 9 years of study (129 of 140 fledglings in SNF, 108 of 128 in SNP, and 19 of 21 in NS). Of 242 fledglings banded prior to 1988, 42 (17 percent) have been recaptured within study area boundaries, another seven have been resighted but not recaptured, for an observed return rate of 20 percent. The fledgling sex ratio of 72:50 (male:female), determined from blood samples of 122 birds from 1993 to 1998, was significantly different from a ratio of 1:1 (P = 0.0284, binomial test). (Note: the fledgling sex ratio in 1999 was 13:30, bringing the overall total to 85:80—not significantly different from 1:1.)

Reproduction differed markedly among years. The percent of pairs fledging young averaged at least 45 percent in 1990-1994 in all study areas but less than 16 percent in 1995-1998 (*table 2*). Generally, however, reproductive performance differed little among the study areas—when it was a "good" year in one area, it was good in all and, when it was a "bad" year in one area, it was bad in all. In most instances, poor reproduction was associated with unseasonably stormy weather in March, April, and/or May (North, "Environmental Factors Associated with Spotted Owl Reproduction," this volume).

Cumulative rates of population change (λ) from 1988 to 1998 were significantly less than 1 in all populations (*table 1*), indicating that all were

Table 1—*Measures of owl abundance, productivity, and population change on the three study areas*

Measure	Sierra National Forest	New Sierra	Sequoia/Kings Canyon National Parks
Most territorial owls (year)	85.00 (1990)	37.00 (1994)	80.00 (1995)
Fewest territorial owls (year)	50.00 (1998)	24.00 (1998)	58.00 (1998)
Mean number of pairs	28.30	12.80	27.50
Mean number of owls/mi^2	0.44	0.29	0.50
Mean number of young/year	15.00	3.80	13.20
Mean number of young/pair	0.62	0.33	0.58
Mean survival rate of banded males	0.80	0.81	0.88
Mean survival rate of banded females	0.80	0.87	0.86
Mean annual percent of territorial owls moving to new territory in the study area	6.00	3.00	3.00
Mean loss rate (percent) of territorial owls	20.00	18.00	14.00
Mean turnover rate (percent) of territorial owls[1]	17.00	8.00	11.00
Highest lambda value[2] (year)	1.00 (1993)		1.04 (1993)
Lowest lambda value[2] (year)	0.90 (1998)		0.95 (1998)

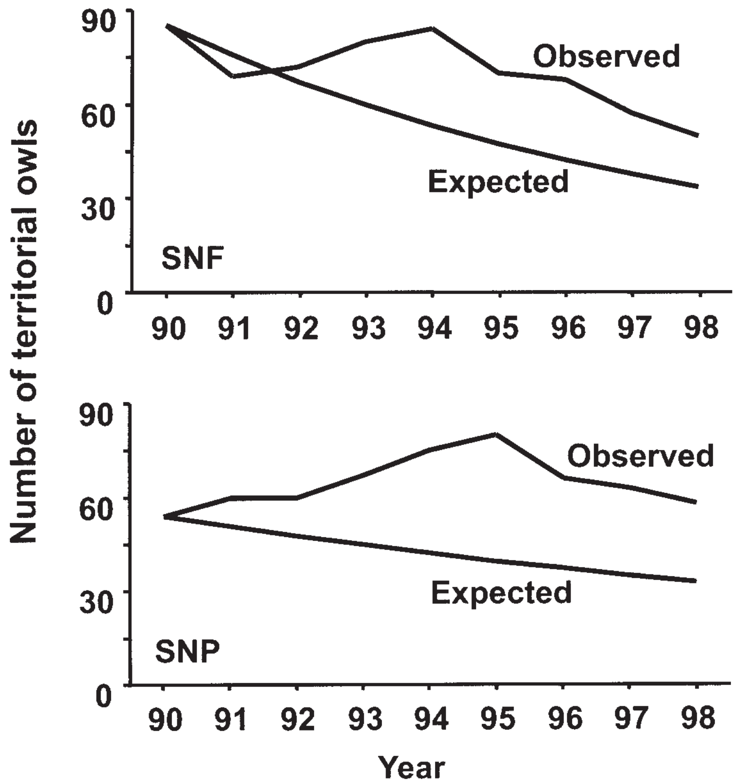
[1] Turnover rate is the annual replacement rate of vacancies in territories.

[2] Too few years in the New Sierra study area to compute these values.

Table 2—*Percent of pairs sampled to established protocols that fledged young in the three study areas*

Year	Sierra National Forest	New Sierra	Sequoia/Kings Canyon National Parks
1990	72	—	88
1991	38	—	8
1992	87	—	85
1993	42	—	44
1994	42	45	48
1995	4	7	6
1996	12	8	7
1997	24	20	22
1998	10	20	27

Figure 1—Observed numbers of territorial California spotted owls compared to projected numbers, based on the numbers expected each year from 1990 through 1998 if the estimate of *lambda* (λ) is correct for the Sierra National Forest study area (λ = 0.90) and the Sequoia/Kings Canyon National Parks study area (λ = 0.95).



declining. Projected rates of decline of the SNF and SNP populations, using the λ-values through 1998, exceeded those based on the known numbers of territorial birds in each population (*fig. 1*).

Observed survival rates of banded males and females did not differ significantly (t = 1.96, P = 0.079; and t = 0.98, P = 0.35) between SNF and SNP. Among adult owls in the three study areas, males in SNF had the lowest mean annual survival rate (0.80 percent), and males in SNP had the highest (0.88 percent) (*table 1*). These survival rates suggest that an original cohort population of 100 males in SNF might have a single individual survive to age 20; similarly a cohort of 100 males in SNP might have one surviving representative after 34 years. In fact, some of the owls in our study areas are at least as old as the studies. A male banded as an adult in SNF in 1987 was still occupying a territory in 1998, giving it a minimum age of 14 years (an unbanded bird classified as an adult would be at least 3 years old), and a pair banded by Roberts (1990) as adults in SNP in 1989 were still in their territory in 1998, at a minimum age of 12 years.

Discussion

Population Trend

The general picture emerging to date from the demographic studies of these spotted owl populations in the southern Sierra Nevada is puzzling and certainly warrants further study. The poor reproductive performance in 1995-1998 appeared to result primarily from late seasonal storms that probably reduced the ability of males to deliver prey to their mates as they incubated eggs or brooded young. This interpretation is supported by the fact that reproductive failures occurred not only in SNF and NS but also in SNP, where owl habitats have not been altered by logging, and North (personal communication) found no difference between mean annual reproduction in SNF and SNP study areas.

Further support comes from the fact that 9 of 11 owl pairs nesting in 1998 failed after an unusually powerful storm in May.

In other years with unseasonal storms late in the winter or early spring, even when our sampling to full protocols indicated no nesting by a pair, we sometimes observed that the female had a brood patch, indicating that she had been incubating but deserted her nest. Because males provide food for the incubating female, and for her and the nestlings during the early part of the nestling period, a marked decline in his ability to capture and deliver prey to the nest site could force the female to leave the nest and forage for herself, thus jeopardizing the eggs or nestlings.

It is a troubling fact that both the demographic data (λ) and the actual numbers of territorial birds indicate that all three study populations are declining. We believe, however, that our estimates of λ are negatively biased because permanent emigration of banded adults from a study area would lead to an underestimate of adult survival rate, and because our estimate of yearling survivorship also may be less than the true value. Consequently, we would expect population trajectories based on λ-values to be too steep, as we see in the comparison between those and empirical trajectories based on numbers of territorial birds (*fig. 1*). The difference in λ-values between study areas is attributable to higher adults/subadult survival rates in SNP than in SNF.

Following the highly productive breeding season in 1992, the number of territorial owls increased in both SNF and SNP, reaching peak counts in 1994 and 1995, respectively. This rise is consistent with the fact that most newly fledged spotted owls take 2-3 years to enter the territorial population. Declining numbers since then reflect the poor breeding years from 1995 to 1998. We should expect the number of territorial birds to increase markedly after the next productive nesting season. In this sense, we hypothesize that California spotted owls, at least in the southern Sierra Nevada, are "pulse" breeders, characterized by intermittent periods of unusually successful reproduction when all determining factors are favorable, but we would expect only moderate to poor success between pulses, depending on the mix of determining factors. This hypothesis not only fits our observations to date but also is consistent with the owl's life history strategy, in particular its relatively low reproductive rate, its relatively long life span, and usually a delay in its age at first attempted reproduction.

Relationship to Management

Twenty-eight territories of California spotted owls are located within boundaries of the study area for the Kings River Sustainable Forest Ecosystems Project, and each has a protected activity center of about 300 acres set aside to protect the core area used by the owls. Over the course of the project, we expect to learn how these owls respond to the various silvicultural treatments within the two 32,000-acre watersheds that comprise the study area. Controls for these "experimental" treatments will be available in the remaining 105,000 acres within boundaries of the demographic study areas in SNF and NS. An additional level of control is available in the 83,200-acre study area in SNP, where timber management is absent but prescribed fire and recreation occur. This study thus may provide some answers to some fundamental questions about the responses of spotted owls to timber harvesting and prescribed fire within their home ranges.

Our current operating hypothesis is that successful breeding by the owls depends to a major extent on favorable weather conditions during the early stages of nesting—egg laying, incubation, and early nestling periods. Because we have experienced only 1 year (1992) when most pairs of owls in our study area nested, and the last 4 years (1995-1998) were poor for breeding by the owls, it may require a decade or two to fully understand the nature of the interacting factors needed to assure a self-sustaining population of spotted owls in ponderosa pine and mixed-conifer forest of the southern Sierra Nevada.

Acknowledgments

Temporary field crews too numerous to name here have dedicated themselves to hard work in steep terrain at night, often during severe weather conditions, to help collect the data reported here. The study would have been impossible without their able and dedicated assistance over the past 9 years. Gordon I. Gould, Jr., and Jared Verner provided constructive reviews of the draft manuscript. We deeply appreciated the contributions made by all of these persons.

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Environmental Factors Associated with Spotted Owl Reproduction[1]

Malcolm P. North[2]

Abstract

Although research on spotted owls (*Strix occidentalis*) has increased dramatically in the last decade, factors influencing owl reproduction still are poorly known. This ongoing study uses 9 years of demographic data to analyze associations between owl reproduction and weather, cone crop abundance, and nest-site structure. Initial results indicate no correlation between cone crop abundance and owl reproduction, but significant associations between owl reproductive success and spring weather conditions and nest-site structure.

The management of many western forests has been directly influenced by legal and biological requirements for maintaining viable populations of the spotted owl (*Strix occidentalis*). Although most of the controversy has focused on protecting the old-growth habitat associated with the owl, the long-term viability of the species will also depend on its reproductive success. It has been difficult to assess owl population trends because owls disperse over large areas, and demographic studies rarely have a closed population in which a thorough, long-term census has been done. In the absence of better demographic data, identifying factors that may influence reproduction can be an important tool for inferring population response to changing environmental conditions.

Several studies of the spotted owl have inferred that habitat quality, prey abundance, and weather are likely influences on reproduction (Franklin and others 2000, Thomas and others 1990, Zabel and others 1996). Reproduction by the northern spotted owl (*S. occidentalis caurina*) may be negatively correlated with current winter precipitation (Wagner and others 1996, Zabel et al 1996). In the San Bernardino Mountains of southern California, however, reproduction by the California spotted owl (*S. occidentalis occidentalis*) was shown to be positively correlated with rainfall during the preceding winter (LaHaye and others 1997). Spotted owls in the San Bernardino Mountains are part of a southern California subpopulation, geographically isolated from a larger subpopulation in the Sierra Nevada of California, and with a diet largely dependent on woodrats (*Neotema* sp.). This contrasts with most other populations of spotted owls, for which northern flying squirrels (*Glaucomys sabrinus*) dominate diets, especially in conifer forests.

Our objectives in this study are to assess the possible relations between weather conditions and California spotted owl reproduction, to look for nest-site attributes correlated with reproductive success, and to characterize nest-site structure for owls in the southern Sierra Nevada (North and others 2000).

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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Preliminary Results and Discussion

On the basis of a 9-year demographic study in the Sierra National Forest and in Sequoia/Kings Canyon National Parks, two observed trends are being explored in this study. First, reproductive success of all surveyed owls tended to be synchronous throughout both study areas within any given year. The common reproductive response produces distinct annual fluctuations, with good years in which each owl pair averaged from 0.6 to 1.7 fledged young, and bad years with pairs averaging fewer than 0.4 fledged young. This pattern suggested the operation of a factor with an extensive regional influence on owl reproductive success.

Weather and the abundance of prey are two possible explanations for this regional effect. The possible role of weather in the reproductive performance of the owls is under investigation (North and others 2000), but region-wide data on the abundance of prey are not available. An alternative is to infer prey availability indirectly from studies of the two food sources most widely consumed by small mammals—truffles and conifer seeds. Truffle abundance did not vary significantly over a 2-year study, and the available standing crop always exceeded a hypothesized consumption rate of 0.6 kg/ha (North and others 1997). By using data from the USDA Forest Service's tree nursery at Placerville, California, the annual quantity of dried seed per bushel of cones of conifer species was compared to the annual reproductive rates of owls in the study area (*table 1*). Although some of the correlation coefficients were above 0.50, owl reproduction was not significantly correlated with any of the previous year's conifer seed abundance.

The second trend noted over the 9-year study was that some nests had consistently higher reproductive success than others. Even during several "bad" years, some nests with repeated use continued to produce young. To rank nests in terms of their reproductive performance, I weighted reproductive success of each nest in the study area by dividing the number of fledglings produced in each nest in a given year by the mean, annual reproductive rate for all surveyed owl pairs in the study (*table 2*). This increased the ranking scores of nests that produced young in bad years and gave less weight to nests that were productive in years when most pairs nested. On this weighted scale, the 117 nests found during the study ranked from 0 to 34 in weighted reproductive success. Most of the nests with higher reproduction have been used year after year, but commonly the nests with low ranking scores were used only once. This pattern suggested that, in addition to regional influences that affect all owl pairs, local nest-site factors must also influence reproduction

Table 1—*Correlation coefficients (P-values) for seed crop abundance and spotted owl reproduction, 1989-1998*

Species	Correlation coefficient
White fir (*Abies concolor*)	0.61 (0.15)
Red fir (*Abies magnifica*)	0.57 (0.32)
Jeffrey pine (*Pinus jeffreyi*)	0.01 (0.97)
Sugar pine (*Pinus lambertiana*)	-0.25 (0.51)
Ponderosa pine (*Pinus ponderosa*)	0.42 (0.27)
Mean seed abundance	0.57 (0.11)

Table 2—*Mean weighted number of young per owl pair and number of nests, classed by years of nest use*

Number of years a nest was used	Number of nests	Mean weighted number of young per owl pair[1]
1	76	1.61[a]
2	30	2.54a[b]
≥ 3	11	3.29[b]

[1] Values with different superscripts are significantly different ($P < 0.05$, posthoc ANOVA).

Acknowledgments

This work has been a collaboration with George Steger, Gary Eberlein, Renee Denton, Tom Munton, and Ken Johnson, all from the Forestry Sciences Laboratory, Fresno, California, and the many field assistants who have collected spotted owl information for 9 years. Bill Laudenslayer and George Steger provided helpful comments on the manuscript.

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Abundance and Productivity of Birds Over an Elevational Gradient[1]

Kathryn L. Purcell[2]

Abstract
This study is investigating the abundance and productivity of birds breeding in four forest types over an elevational gradient in conifer forests of the southern Sierra Nevada of California to identify the most productive habitats for each species, and to examine elevational shifts in abundance, especially as they relate to temperature and precipitation. Species richness and abundance decreased with increasing elevation, although higher elevations were important for cavity-nesting species. Abundance and nest success varied across years and forest types. Dark-eyed juncos (*Junco hyemalis*) were most abundant at the lowest and highest elevations and had their highest nest success in the lodgepole pine (*Pinus contorta*) forest type. Excluding the ponderosa pine (*Pinus ponderosa*) forest type, where they were rare, dusky flycatchers (*Empidonax oberholseri*) were least abundant in true fir sites but had their highest nest success and productivity there. Abundance vs. nest success and number of young fledged were both negatively correlated, suggesting that dusky flycatchers were unable to assess the probability of successfully nesting in a given habitat prior to settling. In accordance with expectations, 15 species exhibited downslope elevational shifts following severe winters in 1995 and 1998, and six species exhibited upslope shifts.

USDA Forest Service lands include many forest types, broadly distributed along elevational and latitudinal gradients. Specific management activities are often concentrated in certain elevational bands and forest types, and wildlife species are affected according to their distribution and response. Identification of species' requirements for survival and reproduction and knowledge of their responses to forest management practices are crucial to maintaining biodiversity.

To manage for a species, we need to know what limits its abundance and distribution, whether it is primarily interactions between species, abiotic factors such as temperature and precipitation, or factors relating to historical and evolutionary constraints. Individuals of a species do not survive independently of individuals of other species. Predation, competition, and parasitism are often cited as potential factors regulating the organization of bird communities (Hairston and others 1960, Hudson and Dobson 1991, MacArthur 1958, Price 1986). Interspecific competition for resources has received much attention in this regard, especially in birds, although the importance of competition has been challenged (for review see Wiens 1989). Disproportionate predation on prey species may favor differences in relative abundance of coexisting species. Nest predation is recognized as a major cause of reproductive failure in birds (Ricklefs 1969), and it may be an important selective force affecting the distribution of species across habitats (Martin 1988a).

[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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Weather can also be an important factor influencing bird abundance in temperate montane forests (Hejl and Beedy 1986, Hejl and others 1988, Raphael and White 1984). The response of a particular species may be mediated by migration status or nest type, with neotropical migrants and cavity nesters generally less negatively impacted by harsh winters (Bock and Lynch 1970). Weather conditions can exert an influence on both the upper and lower elevational limits of species, with some species moving upslope in years with light precipitation and downslope in years with heavy precipitation (DeSante 1990). Extreme weather conditions can also exert a strong influence on bird abundance, and the resulting changes in abundance do not necessarily reflect habitat choice (Hejl and Beedy 1986, Hejl and others 1988). To include the range of variability encountered, long-term studies are required to examine the effects of yearly variations in weather on bird abundance and productivity (Verner and Purcell 1999).

Monitoring programs based solely on census data may detect population problems only long after they have occurred. Healthy populations are those in which reproduction is sufficient to maintain population size. Unhealthy populations can be maintained only by immigration from healthy populations, causing some population problems to go undetected for years. Presence of a species may not reflect a population's health because data on species abundance may not be a reliable indicator of the value of a habitat (Purcell and Verner 1998, Van Horne 1983). Identification of productive or source habitats is crucial when managing for species persistence. When bird abundance and productivity shift in response to weather conditions, source habitats may shift as well and an understanding of these relations and the ability to predict this response is also needed. Relations between bird abundance and productivity can help elucidate the mechanisms by which birds select breeding habitat, whether those choices are adaptive, and, if not, what the mechanism for settling on breeding territories might be.

Long-term studies, involving multiple species at large spatial scales are needed to assess the response of a bird community to silvicultural methods, with results being used to improve future planning (so-called adaptive management). Nongame birds are particularly appropriate for monitoring environmental health. Breeding productivity is more easily monitored for birds than for any other group of vertebrate taxa.

The objectives of this study were to assess the abundance and productivity of bird species in four forest types over an elevational gradient in the southern Sierra Nevada of California; to identify species' breeding habitat requirements, including identification of the most productive habitats for each species; to assess current population health of a wide range of species, including the identification of source and sink habitats; to examine relations between abundance and productivity across the four forest types; to develop models of habitat needs for healthy populations of coexisting species and to predict species' vulnerabilities to habitat change; and to examine elevational shifts in bird abundance, especially as they relate to the severity of the previous winter's weather, and to examine whether, in years of unusual weather conditions, variations in productivity are associated with these shifts. This paper reports preliminary results from the first 4 years of a planned 10-year study.

Methods

Eighteen study sites in four forest types were selected on the King's River Ranger District of the Sierra National Forest in 1994 (*fig. 1*). Sites at the lowest elevations are in ponderosa pine (*Pinus ponderosa*) stands (elevation 1,024-1,372 m), followed by mixed-conifer stands (elevation 1,707-2,012 m), and true fir stands (elevation 2,170-2,347 m), with lodgepole pine (*Pinus contorta*) stands at the highest

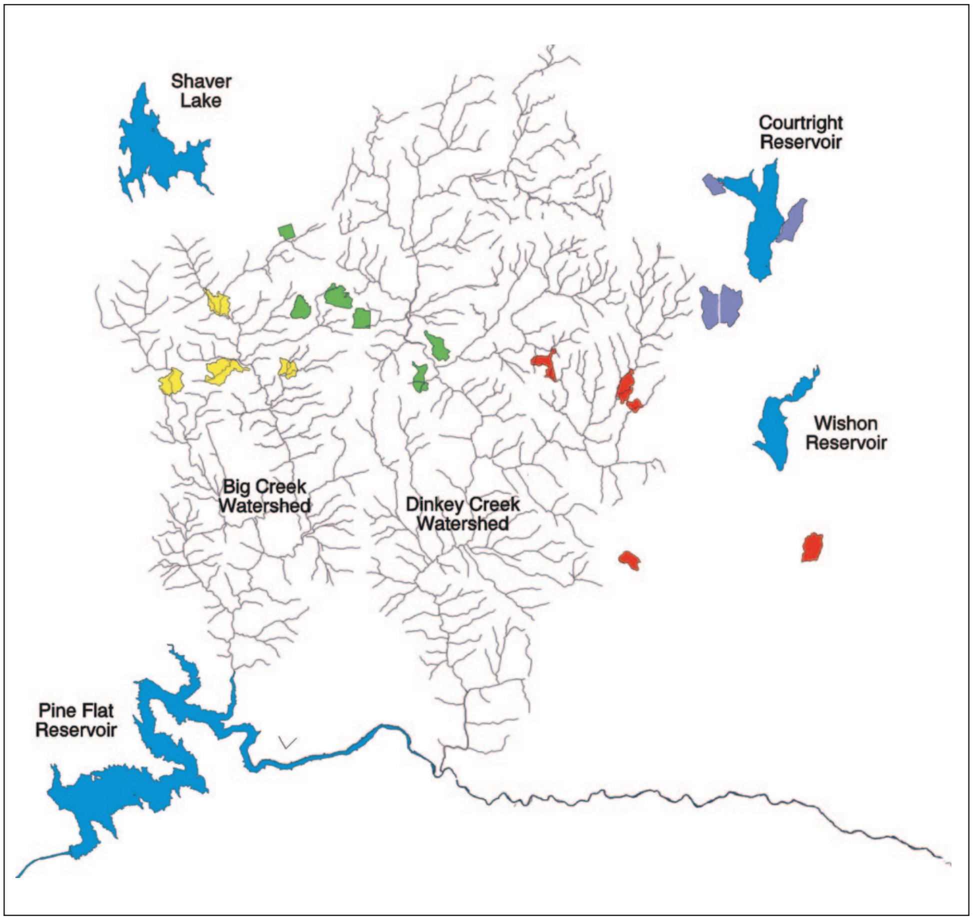

Figure 1—Locations of study sites in the Sierra National Forest, California: yellow = ponderosa pine (elevations 1,04 1,372 m); green = mixed conifer (elevations 1,701–2,012 m); red = true fir (elevations 2,170–2,347 m); and purple = lodgepole pine (elevations 2,469–2,774 m).

elevations (2,469-2,774 m). Each forest type has four replicates, except mixed conifer, which has six replicates. Of the six mixed-conifer sites, three lie in each watershed of the Kings River Sustainable Forest Ecosystems Project area. All sites are protected from major disturbance for 10 years, including timber harvest, road construction, and major fuel breaks, after which they will be incorporated into the adaptive landscape treatment appropriate to their watershed. All sites consist of at least 60 ha of mature forest with relatively high canopy cover. A 40-ha gridded plot has been established in each of the 60-ha sites to allow censusing and to facilitate mapping and relocation of nests.

From 1995 to 1998, field crews censused birds on 8 (1995) or 16 (1996-1998) plots each year, using a timed transect method. Transects were 1000 m long and observers walked at a rate of 50 m per 3 min. Observers recorded all birds seen or heard <50 and >50 m from the transect line. Censusers were trained during a 2-week period at the beginning of the field season, with additional training as they moved into higher forest types and encountered new species; each observer's hearing was tested yearly. Each transect was counted six times during the breeding season, with two visits by each of three observers. The order of census visits and starting points of observers were randomly selected, with the constraint that visits were evenly divided between the two starting points. Censuses began at 07:00 PDT in all forest types except ponderosa pine, where they began at 07:30 PDT to accommodate the shorter day lengths earlier in the season. All censuses were completed within 1.5 hr. In 1996 through 1998, field crews recorded the percent cover and depth of snow in a 1-m-radius circle around the census markers on each plot following each census.

We searched for nests of all bird species and monitored nests every 3 to 4 days, following the methods of Martin and Geupel (1993). Open nests were checked directly, where possible, or with a mirror on a pole or a small video

Figure 2—Operational use of a fiberscope to check the contents of a white-headed woodpecker's cavity nest.

Figure 3—Climbing a large pine tree by using a stacked set of Swedish climbing ladders that are secured to the bole of the tree.

camera mounted on an extendable fiberglass pole. Cavity nests were checked with a fiberscope (Purcell 1997) (*fig. 2*). When nests were too high to reach from the ground and nest substrates were sturdy, field crews climbed to nests by using a variety of climbing techniques (*fig. 3*). Prior to field operations, field assistants received training in tree climbing techniques and were certified to national Forest Service standards.

Habitat measurements were taken at the nest site and at random sites on each plot each year. The variables recorded described the nest site and the habitat surrounding the nest. They included, but were not limited to: basal area of trees and snags; number and species of trees and snags by size class; canopy cover; litter depth; slope; aspect; length, diameter, and decay class of logs; and percent cover of grasses, forbs, rock, soil, litter, logs, shrubs, and trees in the understory. Variables specific to the nest included nest height; species, height, and diameter of the nesting substrate; variables describing placement of open nests; and dimensions and orientation of cavity nests.

I estimated nest success and daily mortality rates based on Mayfield's methods (1961, 1975), with variances calculated following Hensler and Nichols (1981). Differences among daily mortality rates were tested using program Contrast (Hines and Sauer 1989), as described by Sauer and Williams (1989). I used two-way analysis of variance to test differences in abundance across years and forest types.

Results

From 1995 through 1998, crews detected a total of 92 bird species and monitored 1954 nests of 66 species. Thirty-five percent of the species recorded during censuses occurred in all four forest types. Eighteen percent, or 17 species, occurred in only one forest type; of these, 14 species only in the ponderosa pine forest type. Many of these 14 species are typical of drier, low-elevation habitats, such as ash-throated flycatcher (*Myiarchus cinerascens*), western scrub-jay (*Aphelocoma californica*), bushtit (*Psaltriparus minimus*), blue-gray gnatcatcher (*Polioptila caerulea*), Hutton's vireo (*Vireo huttoni*), Bullock's oriole (*Icturus bullockii*), and Lawrence's goldfinch (*Carduelis lawrencei*).

Species richness declined with increasing elevation (*fig. 4a*), and abundance followed the same pattern (*fig. 4b*). Abundance of the cavity-nesting guild, however,

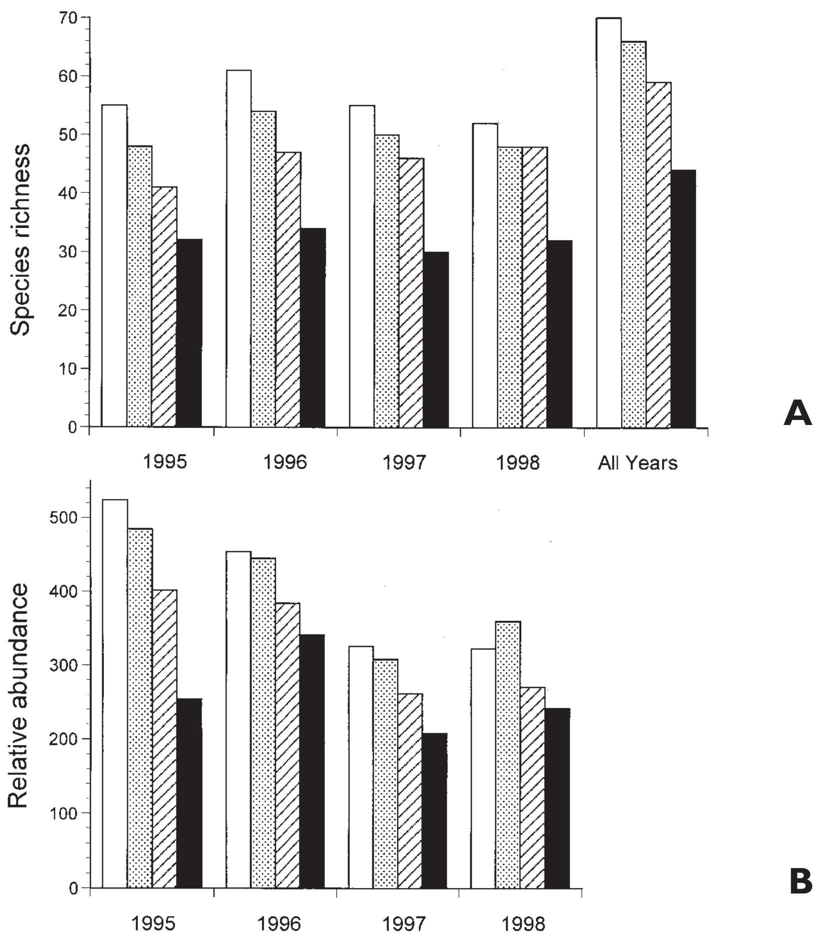

Figure 4—Yearly species richness (number of species detected at unlimited distance) and relative abundance (total count per plots, detected within 50 m.) in four forest types over an elevational gradient (open bars = ponderosa pine, stipled = mixed conifer, cross-hatched = true fir, solid = lodgepole pine).

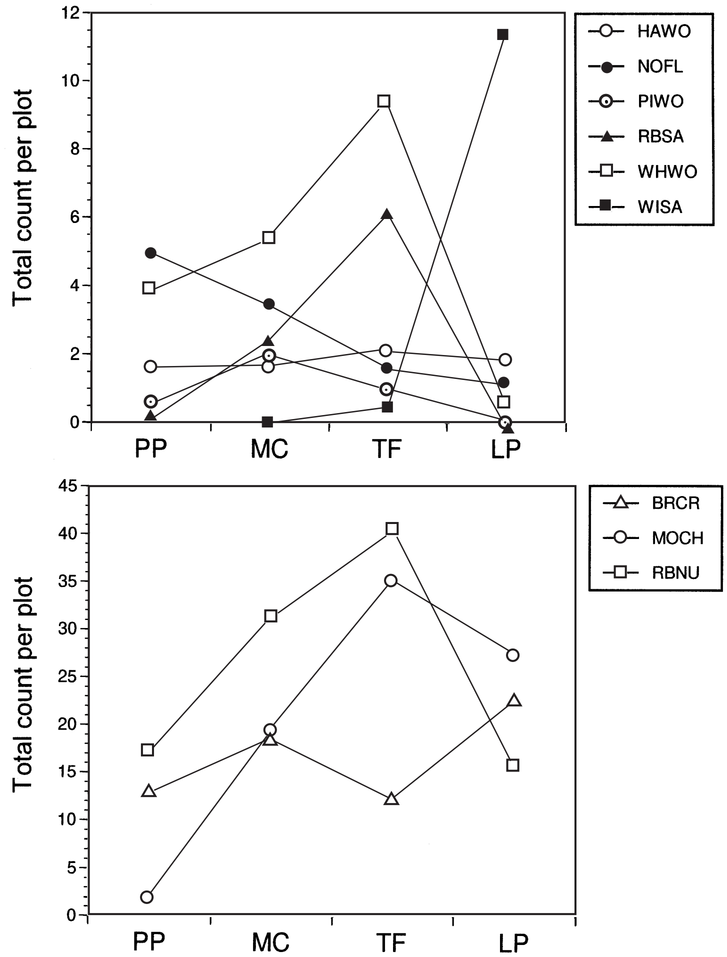

Figure 5—Relative abundance (total count per plot) of cavity-nesting birds in four forest types over an elevational gradient (PP = ponderosa pine, MC = mixed conifer, TF = true fir, LP = lodgepole pine). HAWO = hairy woodpecker, NOFL = northern flicker, PIWO = pileated woodpecker, RBSA = red-breasted sapsucker, WHWO = white-headed woodpecker, WISA = Williamson's sapsucker, BRCR = brown creeper, MOCH = mountain chickadee, RBNU = red-breasted nuthatch.

showed the reverse pattern, with all but two species attaining their highest abundance in true fir or lodgepole pine sites (*fig. 5*). The two exceptions were northern flickers (*Colaptes auratus*), which decreased in abundance with increasing elevation, and pileated woodpeckers (*Dryocopus pileatus*), which reached their maximum abundance in mixed-conifer sites (*fig. 5*). Abundance of open nesters showed no clear trend, as might be expected in such a diverse group.

Abundance of dark-eyed juncos (*Junco hyemalis*) was variable across years (Type III sums of squares, $F_{3,40} = 9.04$, $P = 0.0001$) and across habitats (Type III sums of squares, $F_{3,40} = 6.40$, $P = 0.0012$). Abundance was low in 1997 and 1998, and in mixed-conifer and true fir sites (*fig. 6a*). Nest success did not differ significantly across years ($P = 0.17$), although variability was high. Nest success increased with increasing elevation ($P = 0.02$), with the highest nest success in lodgepole pine forests ($P = 0.0045$; *fig. 6b*).

The abundance of dusky flycatchers (*Empidonax oberholseri*) was lower in 1997 and 1998 than in other years (Type III sums of squares, $F_{3,30} = 9.28$, $P = 0.0002$; *fig. 7*) and lowest in true fir habitat (Type III sums of squares, $F_{3,30} = 9.53$, $P = 0.0006$; *fig. 7*). Nest success, on the other hand, was highest in true fir habitat ($P = 0.0359$; *fig. 7*), yielding a negative, although nonsignificant, relationship between abundance and nest success ($r = -0.41$, $P = 0.19$; *fig. 8*).

Clutch size of dusky flycatchers did not differ across forest types (*fig. 9*), but the number of young fledged per attempt was highest in true fir (*fig. 9*). After removing small sample sizes for year/forest type combinations ($n < 8$), the correlation between abundance and clutch size was nonsignificant ($r = -0.57$, $n = 6$, $P = 0.24$; *fig. 10*), but abundance and number fledged per attempt was significantly negatively correlated ($r = -0.78$, $n = 8$, $P = 0.02$; *fig. 10*).

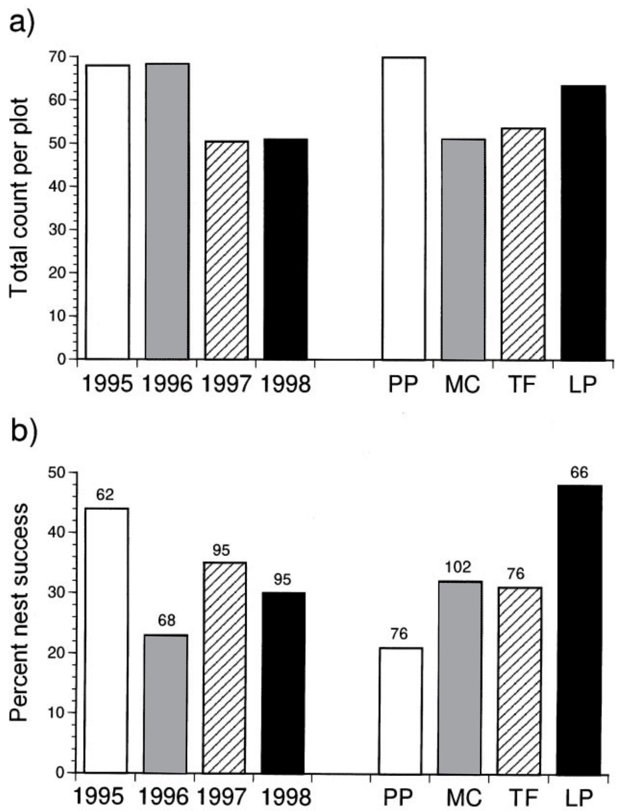

Figure 6—Relative abundance (total count per plot) and nest success of dark-eyed juncos by year and forest type (PP = ponderosa pine, MC = mixed conifer, TF = true fir, LP = lodgepole pine), from low to high elevation. Sample sizes for nest success are shown above columns.

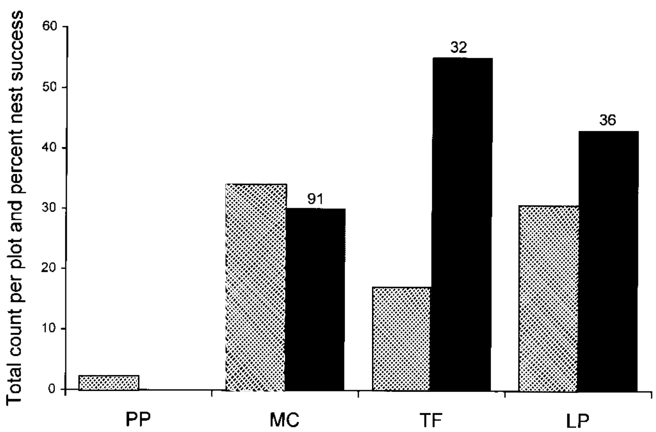

Figure 7—Dusky flycatcher abundance (cross hatched columns) and nest success (solid columns) by forest type (PP = ponderosa pine, MC = mixed conifer, TF = true fir, LP = lodgepole pine) from low to high elevation. Sample sizes for nest success are shown above columns.

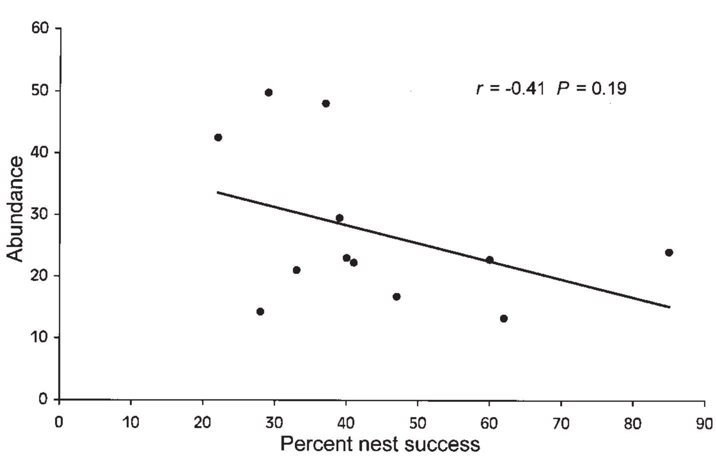

Figure 8—Relative abundance (total count per plot) vs. nest success of dusky flycatchers.

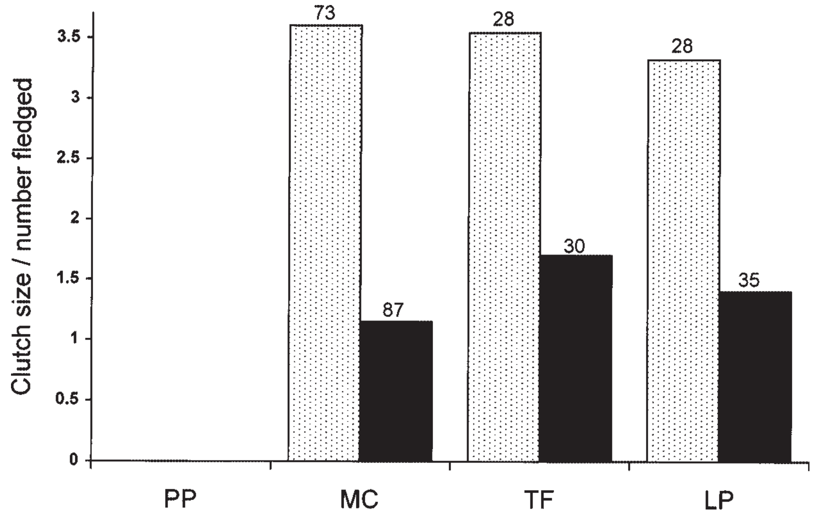

Figure 9—Clutch size (stippled columns) and number of young fledged per nesting attempt (solid columns) by dusky flycatchers by forest type (PP = ponderosa pine, MC = mixed conifer, TF = true fir, LP = lodgepole pine) from low to high elevation. Sample sizes are shown above columns.

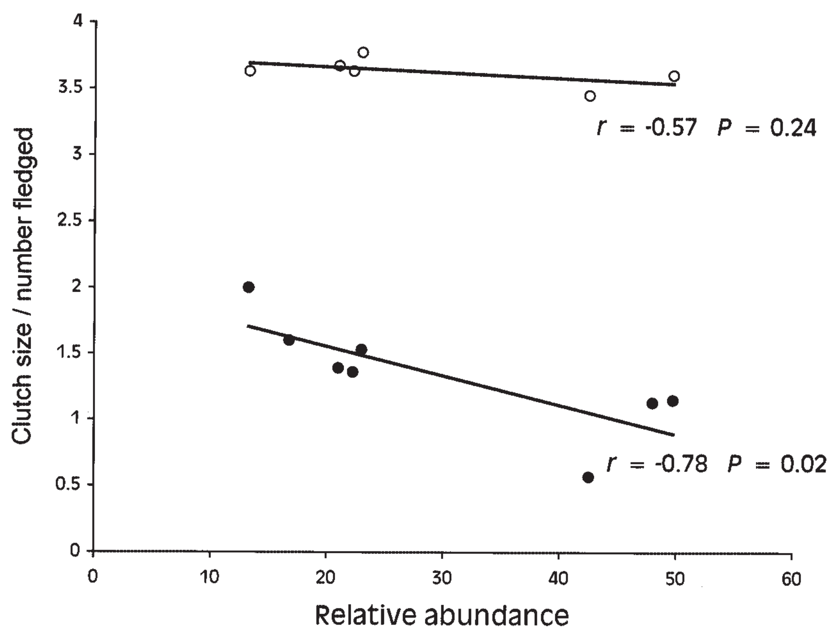

Figure 10—Relative abundance (total count per plot) vs. clutch size (open circles) and number of young fledged per attempt (closed circles) for dusky flycatchers. Small sample sizes (n < 8) for year/forest type combinations were deleted.

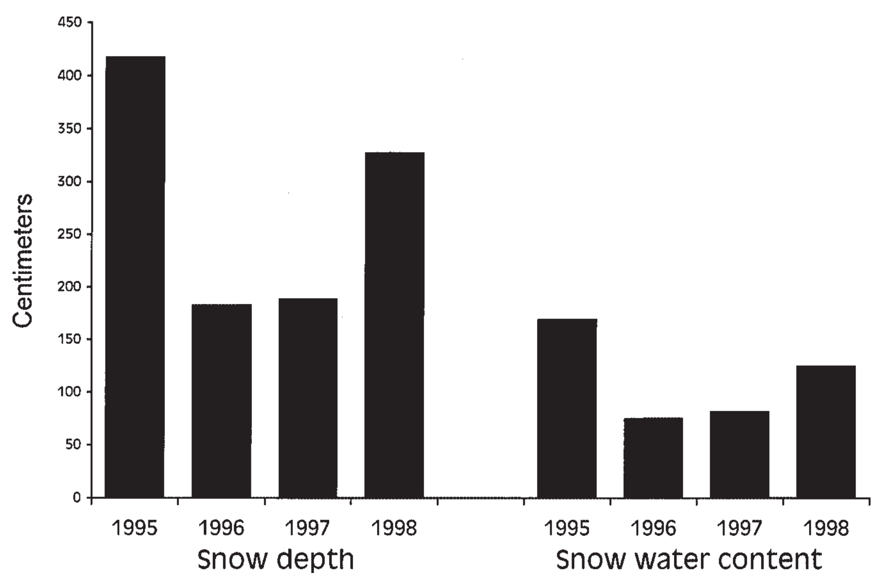

Figure 11—Snow depth and snow water content recorded 1 April each year at Courtright Reservoir (elevation 2,570 m).

The 1995 and 1998 breeding seasons followed severe winters, with snow remaining on the ground until well into the breeding season. Snow-depth data from Courtright Reservoir (elevation 2570 m) showed high snow depths on 1 April of 1995 and 1998, compared to 1996 and 1997 (*fig. 11*). Field personnel did not record snow data in 1995, but 38-46 percent of the census markers had snow during the census period in mixed-conifer, true fir, and lodgepole pine forest types in 1998. No snow was recorded at the census markers in 1996 or 1997.

We expected to observe downslope shifts in populations of some species in years with heavy precipitation. Looking only at presence/absence data and examining species that either disappeared from habitats where they had occurred or appeared in habitats where they were absent in 1996 and 1997, I found 15 downslope shifts of species in 1995 and 1998 compared with six

Table 1—*Downslope and upslope shifts of species of species in the breeding season after the severe winters of 1994-95 and 1997-98, based on presence/absence data and disappearance of species from forest types where they had occured in the previous year, or their appearance in forest types where they were absent in the previous year*

Forest type	Bird species	Year	Direction of shift
Ponderosa pine	Ash-throated flycatcher *(Myiarchus cinerascens)*	1998	down
	Western scrub-jay *(Aphelocoma californica)*	1995	down
	Winter wren (*Troglodytes aedon)*	1995	up
	Bewick's wren (*Thryomanes bewickii)*	1998	up
	Song sparrow (*Melospiza melodia)*	1998	up
	Fox sparrow *(Passerella iliaca)*	1998	down
	Cassin's finch *(Carpodacus cassinii)*	1995, 1998	up
Mixed-conifer	Mourning dove (*Zenaida macroura)*	1995, 1998	down
	Wrentit (*Chamaea fasciata)*	1995, 1998	down
	Brown-headed cowbird (*Molothrus ater)*	1998	down
True fir	Brown-headed cowbird (*Molothrus ater)*	1995, 1998	down
	Williamson's sapsucker (*Sphyrapicus thyroideus)*	1995, 1998	down
	Pacific-slope flycatcher (*Empidonax difficilis)*	1995, 1998	up
	Ruby-crowned kinglet (*Regulus calendula)*	1998	down
	Lincoln's sparrow (*Melospiza lincolnii)*	1995	down
Lodgepole pine	White-headed woodpecker (*Picoides albolarvatus)*	1998	down
	Western wood-pewee (*Contopus sordidulus)*	1998	down
	Golden-crowned kinglet (*Regulus satrapa)*	1995	down
	Hermit warbler (*Dendroica occidentalis)*	1995	up
	White-crowned sparrow (*Zonotrichia leucophrys)*	1998	down
	Purple finch (*Carpodacus purpureus)*	1995, 1998	down

upslope shifts (*table 1*). Abundance of dusky flycatchers in ponderosa pine habitat in 1995 and 1998 was more than twice that in 1996 and 1997. The spotted towhee (*Pipilo maculatus*), a species found only in ponderosa pine and mixed-conifer types, was only half as abundant in the mixed-conifer type in 1995 and 1998 as it was in 1996 and 1997. Dusky flycatchers nested in ponderosa pine habitat for the first time in 1998, and one nest of the mountain chickadee (*Poecile gambeli*) was found in a ponderosa pine site in both 1995 and 1998.

Discussion

A consensus has emerged in recent years that the appropriate focus for wildlife issues by the Forest Service is on maintaining native biodiversity. Conservation of biological diversity depends on identification and preservation of habitat conditions that sustain healthy populations of coexisting species. Results obtained from this research are important to resource specialists and agency biologists in managing for and maintaining biodiversity. Identification of source and sink habitats and understanding their dynamics are crucial for maintaining healthy populations of these species.

Among the four forest types under study, ponderosa pine provides habitat for the most species and the most individuals. Many of the species found there are more typically found at lower elevations in vegetation types that are not well represented on public lands.

Abundance and nest success have varied significantly across years and forest types, underlining the need for long-term studies. Some of the variability in abundance and nest success appeared to be related to winter weather conditions preceding the breeding season. The lower nest success at lower elevations found in some species might be compensated by the longer breeding seasons at lower elevations and the possibility of multiple breeding attempts.

A lack of correlation between abundance and nest success suggests that individuals are not able to judge the probability of nesting successfully in a particular habitat. A negative relation suggests inappropriate choices. This pattern is consistent with density-dependent predation, where, at high densities, predators can specialize on the nests of a particular species, resulting in low nest success. At low densities, nest predators cannot specialize on the more rare nests, leading to low rates of nest predation (Major and others 1994; Martin 1988a, 1988b, 1996). If density-dependent predation is acting, dusky flycatchers cannot make appropriate choices regarding nesting habitat, as they will experience low nest success wherever they settle in high densities. Social interference might also cause low nest success at high densities (Jones and Leopold 1967, Tompa 1964), if adults are forced to spend more time away from their nests defending territories and mates, leaving the nest undefended and exposed to predation. Poor post-fledging survival in true fir sites could also account for a lack of recruitment in high-quality habitat, although no a priori reason exists to expect lower survival in fir than in other habitats.

Although I did not report analyses of habitat data here, the accumulating vegetation and nest-site data will be important for describing habitat characteristics of nest sites used by birds, it will allow identification of variables important to successful nesting, and it will allow prediction of the effects of forest management practices on forest birds.

After 10 years, when these sites are to be managed according to the silvicultural prescription appropriate to each of the two watersheds, the efficacy of these approaches for maintaining biodiversity will be assessed. The hope is that, by maintaining a mosaic of forest stand structures using uneven-aged management practices and reintroducing fire into the ecosystem, all species will be retained. "To keep every cog and wheel is the first precaution of intelligent tinkering" (Leopold 1966).

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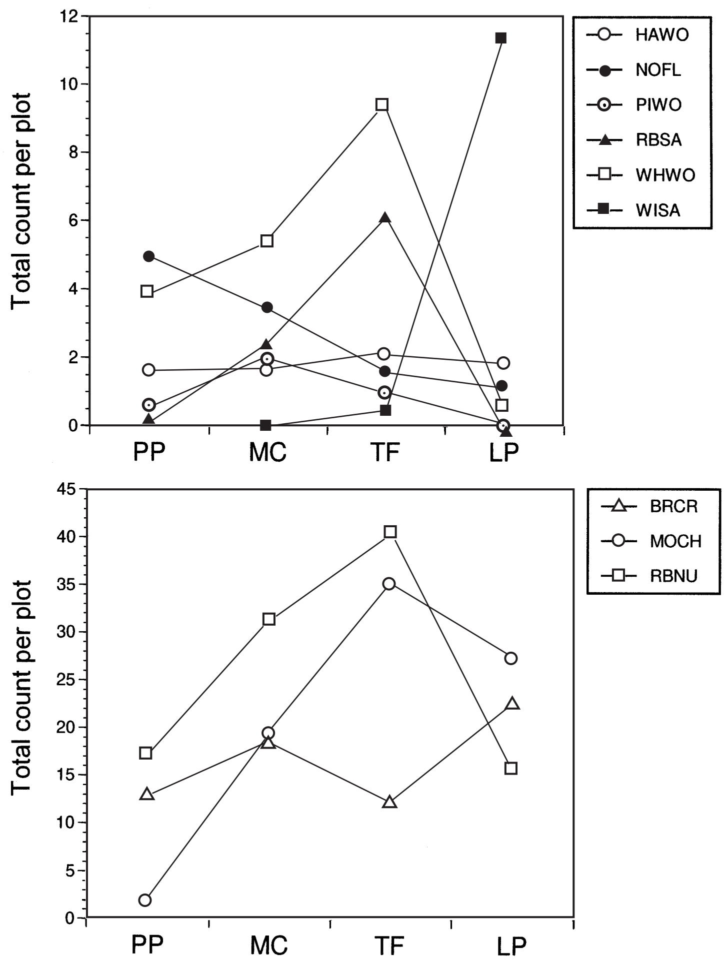
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MOCH
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Small Mammal Populations and Ecology in the Kings River Sustainable Forest Ecosystems Project Area[1]

William F. Laudenslayer, Jr.[2] and Roberta J. Fargo[3]

Abstract

Small mammals are important components of woodlands and forests. Since 1992, we have been studying several aspects of small mammal ecology in oak woodlands in western foothills of the southern Sierra Nevada. Assemblages of small, nocturnal mammal species are dominated by the brush mouse (*Peromyscus boylii*), California mouse (*P. californicus*), and dusky-footed woodrat (*Neotoma fuscipes*). Brush mice and California mice were found in highest numbers on sites with the densest vegetative cover. Populations of both species generally appeared to decline over the 4 years of study. Dusky-footed woodrats in our study sites were arboreal and often used specific travel paths to move about their home ranges. These behaviors made them difficult to capture with standard trapping grids, and we found that capture success was increased markedly by placing traps near their houses, either on the ground or in trees. Woodrats on our sites constructed several kinds of houses—some of which were difficult to detect—and house use was difficult to detect. We did not find a close correspondence between the numbers of woodrats and the numbers of their houses.

Small mammals, principally rodents, are important residents of a variety of habitats in the Kings River Sustainable Forest Ecosystems Project Area. They affect the composition and structure of their environment through consumption and distribution of foliage, plant seeds, and fungal spores. They also serve as food for larger predators, including species of concern, such as the northern goshawk (*Accipiter gentilis*), California spotted owl (*Strix occidentalis occidentalis*), marten (*Martes americana*), and fisher (*Martes pennanti*). Although existing literature includes some reports of small mammal assemblages in California's oak woodlands, information on species composition is lacking, even in relation to gross vegetation structure and particularly in relation to predator activity.

The initial objective of this study was to learn more about small mammal-spotted owl relations where the owls breed in riparian hardwood forests of the oak woodland zone of the western Sierra Nevada foothills. Critical methodical questions surfaced during the course of the work, however, some of which required answers before we could move forward effectively with studies of the mammal-owl relations.

Repeat live trapping on grids is commonly used to detect the presence and estimate the abundance of small mammals. If traps or trapping locations are biased, however, comparisons between sampling locations and species are probably unreliable. Different types of traps may bias trap success toward some species and against others (Laudenslayer and Fargo 1997, O'Farrell and others 1994, Willy 1985). The placement of traps within or outside of particular

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microhabitats, and their proximity to travel paths, may also bias trap success for some species. Reliable data on arboreal and fossorial species can be especially difficult to obtain because of uncertainties associated with identifying appropriate microhabitats and travel paths for setting traps.

Typically, dusky-footed woodrats (*Neotoma fuscipes*) (hereafter, woodrats) build stick houses in which to nest. These houses are conspicuous and often are used as an index of woodrat presence and abundance (Hamm 1995, Sakai and Noon 1993, Vogl 1967). Some studies have suggested, however, that woodrat numbers are poorly correlated with numbers of houses (Fargo and Laudenslayer 1999, Hamm 1995, Humphrey 1988).

Woodrats are often arboreal, but little is known about their activity patterns on the ground and in the trees. Studies of the ecology of nocturnal small mammals, such as the woodrat, have used various methods, such as mark-recapture, radio telemetry, and laboratory simulations. Although these approaches provide important ecological information, data on behavior and home-range use are often incomplete. For example, mark-recapture and telemetry data usually provide two-dimensional spatial information on animals. This is often incomplete, however, because many small mammals, including woodrats, are at least partially arboreal and thus use a third dimension.

Since 1993, we have been studying small mammal assemblages in three 2.25-ha oak woodland sites in eastern Fresno County, California. Efforts to date have examined rodent responses to five general questions: Are standard trapping grids for small mammals effective for estimating presence and abundance of nocturnal small mammals in these oak woodland habitats? Do the abundances of small mammal species vary in relation to habitat structure and through time? Do woodrats construct their visually obvious stick houses under all habitat structures examined? Can surveys of stick houses suffice to estimate relative abundance of woodrats? How do woodrats use their three-dimensional environment?

Study Sites

Our study sites are adjacent to Pine Flat Reservoir on the Kings River, Fresno County, California. All sites are within 2 km of the Kings River, and elevations range from 300-450 m. We chose three 2.25-ha study sites—Pine Flat, Camp 4-1/2, and Secata. Although all sites were classified as oak woodland, they differed markedly in the structure and composition of their vegetation (*table 1*).

Table 1—*Percent of plant species 1-4 m and >4 m high at Pine Flat, Secata, and Camp 4-1/2 study sites (frequency is based on the species of tree or shrub providing the highest percentage of canopy cover over each survey point)*

Species	Pine Flat		Secata		Camp 4-1/2	
	1–4 m	>4 m	1–4 m	>4 m	1–4 m	>4 m
Blue oak	4.0	16.7	50.0	68.4	4.3	21.7
California ash	4.0	4.2	—	—	13.0	4.3
California buckeye	—	—	5.6	5.3	17.4	13.0
California redbud	—	—	—	—	4.3	—
Foothill pine	—	20.8	—	—	—	—
Interior live oak	40.0	54.2	11.1	21.1	39.1	60.9
Manzanita	16.0	4.2	22.2	5.3	—	—
Poison oak	8.0	—	—	—	—	—
Redberry	8.0	—	—	—	4.3	—
Wedgeleaf ceanothus	20.0	—	11.1	—	17.4	—

The Pine Flat site, with 80 percent canopy cover, is characterized by a dense, shrubby cover dominated by interior live oak (*Quercus wislizenii*), wedgeleaf ceanothus (*Ceanothus cuneatus*), and poison oak (*Toxicodendron diversiloba*), with some manzanita (*Arctostaphylos* sp.), blue oak (*Q. douglasii*), and foothill pine (*Pinus sabiniana*). The Camp 4-1/2 study site, with 65 percent canopy cover, is dominated by interior live oak, blue oak, and California buckeye (*Aesculus californica*) and has a moderately open understory of poison oak and ceanothus. The Secata study site is relatively open—45 percent canopy cover—with patches of large trees dominated by blue oak and lesser amounts of interior live oak, California buckeye, and manzanita.

The largest oaks in bole and canopy diameter are at Secata, followed by Camp 4-1/2, and then Pine Flat. The tallest blue oaks are at Secata and the tallest interior live oaks are at Camp 4-1/2. Shrubs also vary in size across the sites with the largest poison oaks at Camp 4-1/2 and largest manzanitas at Secata (*tables 2, 3, and 4*).

Table 2—*Mean bole diameters (cm) of trees and shrubs at Pine Flat, Secata, and Camp 4-1/2 study sites*

Species	Pine Flat	Secata	Camp 4-1/2
Blue oak	13.4	34.0	18.8
California ash	2.7	1.2	10.2
Foothill pine	28.0	—	—
Interior live oak	8.3	20.6	15.0
Manzanita	5.5	11.7	—
Poison oak	1.1	1.0	3.5
Wedgeleaf ceanothus	3.6	5.5	5.4

Table 3—*Mean crown diameters (m) of trees and shrubs at Pine Flat, Secata, and Camp 4-1/2 study sites*

Species	Pine Flat	Secata	Camp 4-1/2
Blue oak	2.9	5.0	3.5
California ash	1.2	1.0	3.2
Foothill pine	4.5	—	—
Interior live oak	3.4	4.3	3.3
Manzanita	2.4	2.9	—
Poison oak	1.1	1.0	1.6
Wedgeleaf ceanothus	2.0	1.7	1.7

Table 4—*Mean heights (m) of trees and shrubs at Pine Flat, Secata, and Camp 4-1/2 study sites*

Species	Pine Flat	Secata	Camp 4-1/2
Blue oak	5.1	9.9	7.8
California ash	1.8	1.0	4.3
Foothill pine	10.0	—	—
Interior live oak	4.8	5.6	6.3
Manzanita	2.7	3.0	—
Poison oak	1.4	1.0	2.6
Wedgeleaf ceanothus	2.0	2.0	2.0

Methods

Effectiveness of Standard Trapping Grids

Initially, we randomly placed a 7 x 7 trap-station grid with 15-m spacing in each study site. We positioned one Sherman XLK (7.7 x 9.5 x 30.5 cm) and one Tomahawk 201 (12.7 x 12.7 x 40.6 cm)[4] at each station in 1993. Because attempts to capture woodrats on the grid were essentially unsuccessful, we also set Tomahawk traps at woodrat houses, both on the ground and in trees. Traps set at houses on the ground were positioned along woodrat travel paths, if evident. Because this approach was successful, in 1994 and 1995 we set only one Sherman XLK at each grid station, in addition to Tomahawks at the houses. In 1995, we also used Shermans at houses on the ground and in trees for a short period to confirm that the woodrats were not avoiding this type of trap. In 1996, we concentrated the trapping adjacent to woodrat houses, based on questions that had arisen during the previous years of trapping. Nocturnal trapping was done in the spring (April-June) and in the late summer/early fall (September-November), and traps were checked in the early morning to reduce incidental mortality from long exposures to the weather.

Woodrat Stick Houses

Each study site was thoroughly surveyed for woodrat houses. In addition to houses found during initial establishment of study sites, newly built houses found over the course of the study were added to the inventory. Occupancy of individual houses was determined by observations at the houses and by the presence or absence of woodrat "sign." Direct observations of woodrats often indicated which houses were being used. For other houses, the presence of fresh vegetative cuttings, recently deposited fecal matter, and travel paths and house entrances clear of debris and spider webs demonstrated their current use. All houses found were classified as typical, intermediate, or atypical, based on stick content and nest location.

We did vegetation surveys in the spring of 1998 to compare house types with vegetation structure and composition on the sites. House information collected included house type, size, substrate, and cover. Site information included tree and shrub characteristics such as species, bole diameter, height, and percent cover; and ground cover attributes such as rock outcrops, logs, vegetation, and woody material.

Woodrat Behavior and Movements

To study the behavior and track the movements of woodrats, we set 10 Tomahawk traps at randomly selected, active woodrat houses each night of tracking. The first two adult or subadult woodrats captured were generally selected as the subject animals for the night. Each was equipped with a light-emitting diode (LED) package and dusted with fluorescent powder before release. Different colors of LEDs and fluorescent powder permitted discrimination of activity patterns between the two woodrats being observed (Fargo and Laudenslayer 1997).

Using audio cassettes, two observers (one per woodrat) verbally recorded the movements of the tagged woodrats throughout each night of observation, noting the time and duration of each detection of an animal, microhabitat at the animal's location (for example, tree canopy), characterization of the animal's location as a "travel route" or "destination," position of the animal (height above the ground and the azimuth and distance from its house), and the animal's activity (for example, walking, tail and foot tapping).

The evening following observations, woodrats were recaptured to remove the LED units, and their fluorescent powder trails were tracked. Information

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[4] Mention of trade names or products is for information only and does not imply endorsement by the U.S. Department of Agriculture.

collected included length of the powder trail within each microhabitat, characterization of sections of the powder trail as "travel route" or "destination," position of the powder trail (height above the ground and the azimuth and distance from the woodrat's house), and canopy cover over each powder trail.

Vegetation surveys will be done to compare each woodrat's use of the microhabitat in its range with what is available. For each woodrat observed, vegetation information within a specified area around each house will be collected as described above for woodrat houses.

Results

Small Mammal Fauna

Nine species of small mammals were captured at the study sites, with most being active mainly at night (*table 5*). The brush mouse, California mouse, and dusky-footed woodrat were the most abundant mammal species captured. Six other species were captured but in low numbers. Despite their occurrence in similar habitats elsewhere in California, we have yet to capture any piñon mice (*Peromyscus truei*).

Effectiveness of Standard Trapping Grids

Both Sherman and Tomahawk traps successfully captured woodrats, but few were captured on trapping grids. Instead, most were captured at woodrat houses, either on the ground or in nearby trees (*table 6*). Both species of mice were captured more successfully in Sherman than in Tomahawk traps. This was especially true for brush mice, regardless of trap placement (*table 6*), because nearly all of them could escape through the Tomahawk trap's mesh and the space around the door. Although results are inconclusive because of changes in trapping methods, capture rates for both mice may be better at traps associated with trees and woodrat houses (*table 6*).

Abundance of Small Mammals

Woodrat numbers varied markedly over the 4 years of the study, but the annual variability was not consistent among the study sites (*table 7*). Woodrats were most abundant at Pine Flat, which generally had the most immatures and the highest female to male ratio. This site also had the greatest canopy cover and

Table 5—*Small mammal species captured in oak woodland study sites between 1993 and 1996*

Common name	Scientific name	Activity period
Brush mouse	*Peromyscus boylii*	Nocturnal
California ground squirrel	*Spermophilus beecheyi*	Diurnal
California mouse	*Peromyscus californicus*	Diurnal
California pocket mouse	*Chaetodipus californicus*	Nocturnal
California vole	*Microtus californicus*	Nocturnal
Deer mouse	*Peromyscus maniculatus*	Nocturnal
Dusky-footed woodrat	*Neotoma fuscipes*	Nocturnal
Merriam's chipmunk	*Tamias merriami*	Diurnal
Shrew	*Sorex* sp.	Nocturnal
Western harvest mouse	*Reithrodontomys megalotis*	Nocturnal

Table 6—*Small mammal capture success [pct success = 100 x (number captured/number of trap nights)] compared by trap type and trapping location (numbers of trap nights: on grid—Shermans = 4,525, Tomahawks = 2,183; at houses on ground—Shermans = 52, Tomahawks = 2,106; at houses in trees—Shermans = 10, Tomahawks = 1,877)*

Animal	On grid[1]		At houses on ground[2]		At houses in trees[3]	
	Sherman[4]	Tomahawk[5]	Sherman	Tomahawk	Sherman	Tomahawk
Brush mouse	17.46	1.05	26.92	0.09	70.00	0.11
California mouse	2.34	0.78	9.62	0.57	10.00	0.59
Dusky-footed woodrat	0.49	1.65	23.08	8.74	10.00	12.63

1 Traps set in grid on the ground and in trees.

2 Traps set at woodrat houses on the ground.

3 Traps set at woodrat houses in adjacent trees.

4 Sherman XLK trap.

5 Tomahawk 201 trap.

Table 7—*Numbers of individuals captured on trapping grids from 1993 to1996*

Animal	Pine Flat				Secata				Camp 4-1/2			
	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996
Brush mouse	55	59	54	15	47	8	15	6	104	37	50	24
California mouse	21	14	13	5	2	0	0	0	19	6	4	2
Dusky-footed woodrat	24	34	19	25	10	13	12	18	9	25	16	20

densest understory vegetation. Captures at Secata, which had the least canopy cover and sparsest understory vegetation, were approximately half the number at Pine Flat in 1993 and 1994, but increases at Secata and decreases at Pine Flat narrowed the difference in 1995 and 1996 (*table 7*).

Both brush mice and California mice appeared to be generally more abundant at Camp 4-1/2 and Pine Flat than at Secata, and our capture rate tended to show a general decline from 1993 to 1996, although a decline in brush mice at Pine Flat was evident only in 1996 (*table 7*).

Woodrat Stick Houses

Typical and intermediate woodrat houses were found in high numbers at Pine Flat, where they were primarily found on rock outcrops or at the bases of shrubs or trees (*fig. 1*). Atypical houses were prevalent at Secata, where most were associated with tree cavities or rock outcrops. Camp 4-1/2 had nearly equal numbers of the three house types, with many in tree cavities.

Individual woodrats used one to four houses at any given time, and this number often changed over time.

Woodrat Behavior and Movements

Results to date indicate that woodrats spent slightly more time in trees (45.27 percent) than on the ground (40.01 percent) (*table 8*). While on the ground,

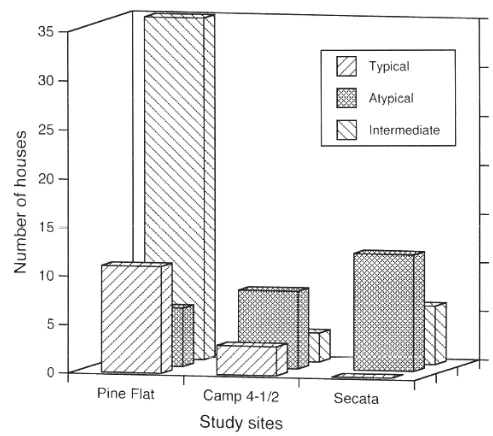

Figure 1—Numbers of typical, atypical, and intermediate woodrat houses at Pine Flat, Camp 4-1/2, and Secata study sites.

Table 8—*Amount of time woodrats spent in various microhabitats in the three study sites combined*

Microhabitat	Time (seconds)	Percent of time
Downed log	11	0.08
Downed woody material	336	2.44
Ground (unknown substrate)	3,222	23.43
Grass/forb	184	1.34
Rock outcrop	2,360	17.16
Shrub canopy	314	2.28
Shrub limb	999	7.27
Tree Bole	1,142	8.31
Tree canopy	1,227	8.92
Tree limb	3,955	28.76

however, they spent much of their time on rock outcrops. Whether remaining stationary or moving about, they usually stayed under dense canopy cover. They tended to use established travel paths along limbs, on rocks, or on the ground. Travel paths on the ground were characteristically clear of debris and vegetation.

Discussion

Effectiveness of Standard Trapping Grids

Our results indicate that capture success for different species of small mammals varies by trap type and trapping location. Effects of trap type on capture success were based, at least in part, on the ability of small mammals to escape from the traps and probably to some extent on selection of particular trap types by certain species and/or individuals. Similarly, Willy (1985) found that Tomahawk traps captured only woodrats, and at a higher rate than Shermans, whereas Shermans captured woodrats as well as other species. O'Farrell and others (1994) also found variation in capture success based on trap type, with wire mesh traps generally capturing more species and individuals of small mammals than Shermans in a variety of western habitats and geographic locations.

Variation in our trapping success in relation to trap location appeared to be associated with microhabitat affinities and travel corridors. Similarly, Murray (1957) reported varying trap success between parallel trap lines depending on the structure and composition of vegetation, such that small differences in trap placement could seriously alter results. Differences in capture success could bias estimates of small mammal populations, thereby affecting decisions based on the assessments. It is important, therefore, to carefully evaluate methods to ensure that they are unbiased, or at least biased equally among the habitats and species being compared.

Kirkland and Griffin (1974), Price (1978), Sakai and Noon (1993), and Tietje (1995) all found that patchiness of the animals' habitat and their use of it influenced capture success. We captured woodrats more successfully in traps placed at their houses than on the trap grid, indicating that these animals, too, are not randomly distributed in their habitat.

Several species of *Peromyscus*, including the piñon mouse and the California mouse, often construct their nests within woodrat houses (Cranford 1982; Merritt 1974, 1978). Our findings, based on only a few trap nights, show that both brush and California mice are more successfully captured near woodrat houses. We did not, however, confirm cohabitation by searching woodrat houses for *Peromyscus* nests.

Abundance of Small Mammals

Although preliminary and without replication, our data suggest that these three study sites support different numbers of the three commonly captured rodent species. Secata, the most open site, supported the lowest numbers of all three species. Both Pine Flat and Camp 4-1/2, with denser vegetation, support higher numbers of all three species.

Only a few California mice were captured at Secata, and in only 1 year, suggesting that California mice are not typically resident there, that they are present only in low numbers, or that our trapping methods are ineffective for capturing California mice at this site.

Additional work is needed over a longer period to more clearly understand the relations between populations of these small mammals and the vegetation.

Woodrat Stick Houses

Woodrat houses have been described as conspicuous, conical piles of sticks with many passageways and compartments (Ashley and Bohnsack 1974, Cameron 1971, English 1923, Gander 1929, Linsdale and Tevis 1951). Some observers have described "atypical" houses built in hollow limbs and rock crevices (Davis 1934, Gander 1929), but these are usually mentioned only briefly and apparently are considered to be uncommon.

The presence of numerous atypical and cryptic woodrat houses in our study sites, however, suggests potentially large biases in estimates of woodrat populations if based on house counts. The Key Largo woodrat (*Neotoma floridana smalli*), for example, is generally known for its large stick houses, but it is also known to reside within rock crevices in some habitats, thereby escaping detection during house-count surveys (Barbour and Humphrey 1982). In spite of this problem, some observers have based population estimates on counts of houses (Hammer and Maser 1973, Sakai and Noon 1993, Vogl 1967), either assuming that each active house contained one woodrat (Vestal 1938, Vogl 1967) or applying some standard number of houses per woodrat across the entire study area. Not all locations may include cryptic houses, however, so investigators need to become familiar with all house types characteristic of their study site and to search accordingly for all houses before using house counts to estimate population size.

Woodrats in our study sites also differed in the number of houses they used, and that number changed over time. English (1923) reported that dusky-footed woodrats near Corvallis, Oregon, were familiar with several houses in their home range, and Cranford (1977), in a study of radio-tagged woodrats, found that they resided within a house for an average of 34 days. When a home range contained only one house, it tended to be larger than average, and the woodrat resided in it for a longer period. Such variation in house use may also bias population estimates when based on one woodrat per house. In some seasons, more than one woodrat may reside in a house, especially during spring and summer when males reside with females for breeding (Donat 1933, English 1923) and when females are nursing young (Linsdale and Tevis 1956). Without further study, we consider it risky to use counts of woodrat houses for much more than determining woodrat presence (but not absence!).

Woodrat Behavior and Movements

Woodrats in our study sites appear to restrict their travel routes to limbs, rocks, and cleared paths that likely expedite their movements and reduce the noise produced. These travel paths are also generally beneath dense canopies. This behavior probably aids in reducing predation. As our research progresses and questions are answered about woodrat ecology (for example, habitat requirements), management decisions can be better informed regarding this species and others that depend upon it for their sustenance.

Acknowledgments

Annette Tenneboe, Tamra Sandoval, Jeff Schneiderman, and Ruth Elbert assisted with field work, including vegetation surveys and trapping of small mammals. Sandi Andreas advised us on database design, helped to convert data for analysis from the Data General minicomputer to the Macintosh for analysis, and converted data to IBM computer formats. David Grubbs and Michelle Selmon provided constructive suggestions on a draft of this paper. We gratefully acknowledge all of these contributions.

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Fisher Research and the Kings River Sustainable Forest Ecosystems Project: Current Results and Future Efforts [1]

Brian B. Boroski,[2] Richard T. Golightly,[3] Amie K. Mazzoni,[4] and Kimberly A. Sager[5]

Figure 1—Fisher in a pine tree on the study area in the Sierra National Forest.

Abstract

The Kings River Sustainable Forest Ecosystems Project was initiated on the Kings River Ranger District of the Sierra National Forest, California, in 1993, with fieldwork beginning in 1994. Knowledge of the ecology of the fisher (*Martes pennanti*) in the Project area, and in the Sierra Nevada of California in general, is insufficient to develop empirically based management strategies or to respond to the challenge of sustaining viable local populations concurrent with projected human population growth in the Sierra. Using a combination of track-plate surveys, snowtrack searches, and live-trapping, we documented a reproducing population of fishers between 1,067 and 2,438 m in elevation within much of the Project area. Whether survivorship and reproductive rate are sufficient to maintain the population within the Project area is unknown. Given current viability concerns for fishers in the Sierra Nevada, it would be prudent that, concurrent with future research, management activities in the areas occupied by fishers that are outside the forest carnivore network also conserve or promote habitat elements used by fishers.

The Forest and Rangelands Renewable Resources Planning Act of 1974 and the National Forest Management Act of 1976 (NFMA) mandated additions to the process by which the USDA Forest Service manages its public lands (Dana and Fairfax 1980). A key section of the NFMA directed the Secretary of Agriculture to write regulations specifying guidelines that "provided for diversity of plant and animal communities based on the suitability and capability of the specific land area in order to meet overall multiple-use objectives." The challenge to meet this provision is significant for National Forests in the Sierra Nevada. Land area developed for human settlement within the mountains could quadruple from 1990 to 2040 as a result of a tripling in the human population within the region (Duane 1996). Ecological ramifications of the mosaic of forest ownership and differing owners' objectives are many.

Despite substantial efforts (Grenfell and Fasenfest 1979; Zielinski and others 1995b, 1997, 1999), knowledge of the ecology of fishers (*Martes pennanti*) in the Sierra Nevada (*fig. 1*) is insufficient for development of empirically based management strategies that will ensure viable local populations in the face of increased demands on forest resources that will inevitably accompany the projected growth of the human population in the Sierra Nevada (Graber 1996, Ruggiero and others 1994). Ruggiero and others (1994) recommended a comprehensive, programmatic approach of research to acquire the information needed for developing conservation strategies.

The Kings River Sustainable Forest Ecosystems Project (hereafter, the Project) was initiated in 1993 on the Kings River Ranger District of the Sierra National Forest, Fresno County, California, with fieldwork beginning in 1994 (Verner and

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[1] An abbreviated version of this paper was presented at the Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and Current Status, January 26, 1998, Clovis, California.

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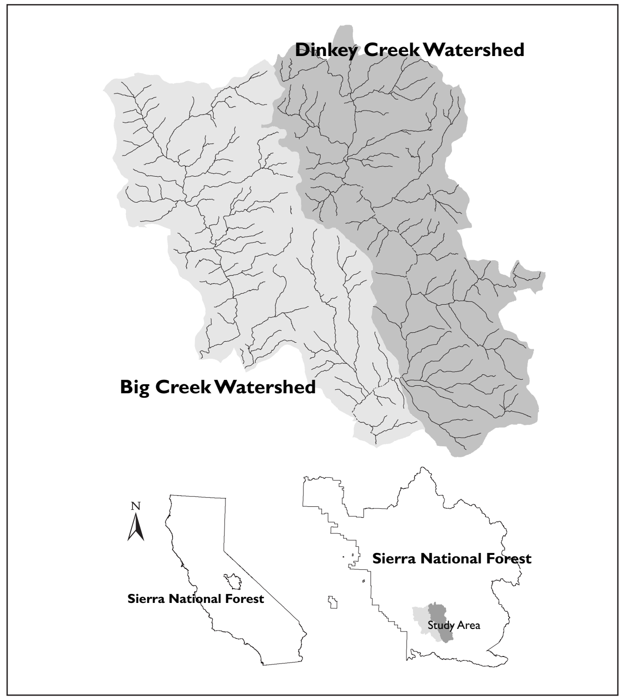

Figure 2—The Kings River administrative study area in the Sierra National Forest in central California includes the 64,000-acre Big Creek and Dinkey Creek watersheds (indicated by shading).

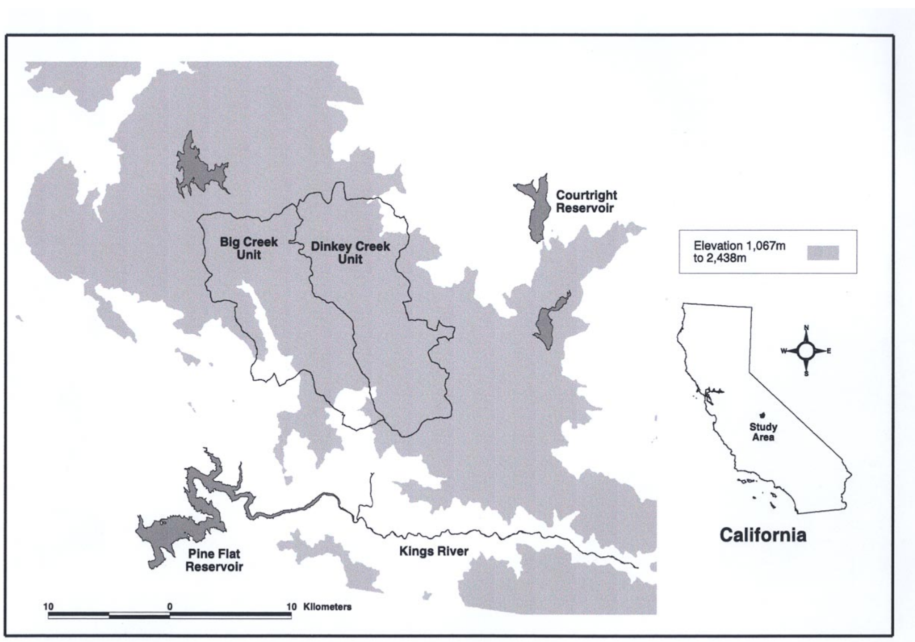

Figure 3—Big Creek and Dinkey Creek units treated by the Kings River Sustainable Forest Ecosystems Project, Sierra National Forest, Fresno County, California.

Smith, this volume). The Project area of 26,000 ha encompasses about 13,000 ha in both the Big Creek and Dinkey Creek watersheds (*figs. 2, 3*). This was a collaborative Administrative Study among Forest Service managers and researchers to investigate whether forest ecosystems in the southern Sierra Nevada can be managed to maintain essential ecosystems components, processes, and interactions and still support a variety of other uses (Gill and others 1997). The Project is a unique opportunity to meet existing information needs for conservation planning for fishers because it is within a geographic area of concern, it is highly integrated with other disciplines, and it is committed to developing a comprehensive body of knowledge through a long-term, adaptive-management approach.

This paper describes our general programmatic approach to understand use by fishers within the Project area, presents our current, preliminary results, and discusses the logical expansion of this research as the Project proceeds, with an ultimate goal of determining the fisher's responses to landscape-level silvicultural treatments in the two watersheds.

Study Area

Forest management in the Big Creek watershed is applying uneven-aged, small-group selection with a 200-year rotation, which will result in 0.5 percent of the land area being harvested each year and half of the landbase supporting forests at least 100 years old. The primary goal is to maintain a continuous forest canopy, retain mature vegetation in riparian areas, retain large trees (crown diameter >12.2 m) on half of the landscape capable of growing them, and maintain and enhance riparian systems in streamside-management zones.

In the adjoining Dinkey Creek watershed, a three-tiered forest landscape has been implemented—a riparian emphasis zone (20 percent of the landscape) at the bottom, a mid-slope zone of continuous forest cover (50 percent of the landscape) on side slopes, and a ridge-top zone managed as a shaded fuelbreak to provide a first line of defense against wildfires (30 percent of the landscape) (Smith and Exline, this volume).

General Programmatic Approach

Balancing multiple-use on lands managed by the Forest Service is a significant challenge for the National Forest System. Uses change, technologies evolve, and ecosystems respond concurrently, but at different rates. The approach chosen by managers must ensure timely responses to these issues. The approach must also involve direct participation among practicing resource planners, managers, and a variety of specialists studying diverse topics. The general programmatic approach of the research presented here emphasizes our commitment to respond to information needs. For the duration of the Project, we propose to conduct annual, systematic surveys of the fisher population within the Project area using base funding. These surveys will be augmented by studies to examine specific questions that emerge from management activities that cannot be addressed through survey results.

Track-Plate Surveys

Our initial survey of the Project area was designed to determine the occurrence and distribution of forest carnivores, especially fishers and martens (*Martes americana*). Over two consecutive field seasons in 1995 and 1996, we placed sooted aluminum track-plates (Fowler and Golightly 1994) at 160 stations along 8 cross-elevation routes to cover all elevations in the Project area, based on 7-1/2 minute series maps (1:24,000 scale, U.S. Geological Survey, Menlo Park, California). The routes followed roads or trails accessible during fall when snow was present. Stations included one track plate in a wooden box, systematically placed at 1-km intervals along the eight routes (*fig. 4*). Stations were placed as far as 70 m from the road, although most were within 50 m. The boxes housing the sooted plates were positioned in the field with one open end against a tree, rock, or log and then camouflaged with forest litter. Stations were often located in drainages with the boxes facing down slope to prevent rain and snow from falling on the plate and destroying the soot or track impressions.

We conducted four (two each season) 22-day surveys because Fowler and Golightly (1994) reported that surveys at least this long maximized the probability of detecting martens. The first survey occurred from 17 October to 7 November 1995 and included 81 high-elevation stations (1,275-2,592 m) divided among four routes. The second occurred from 17 November to 8 December 1995 and consisted

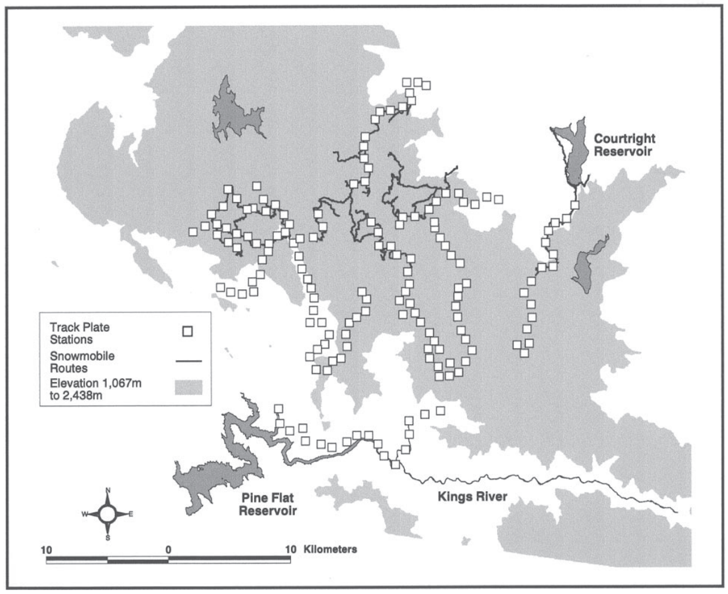

Figure 4—Track plate stations and snowmobile routes used to determine the occurrence and distribution of fishers and martens within the south zone of the Sierra National Forest.

of 79 stations divided among four routes at lower elevations (294-1,662 m). The same stations were surveyed again the following summer to measure potential seasonal variations in carnivore detection and increase our power to detect animals. The low-elevation stations were surveyed from 1 to 22 June 1996 and the high-elevation stations were surveyed from 7 to 28 July 1996. Each station was examined every other day. We replaced any track plate that contained tracks on either the soot or contact paper or if the soot had been disturbed so that it was no longer effective. Chicken wings were used as bait and replaced when desiccated or when rodents or insects removed meat.

Detection ratios were calculated for fishers and martens by dividing the number of stations that had detected animals by the total number of available stations between the highest and lowest detection for each species, plus or minus 200 m. This allowed assessment within a range of realistically available habitat. No survey station was higher than the highest marten detection; therefore, we included stations from the highest to those as low as 200 m below the lowest detection.

Results of Track-Plate Surveys

Fishers occurred at elevations between 1,114 and 2,040 m, whereas martens were found at elevations between 1,992 and 2,520 m (*fig. 5*). The detection ratio for martens (0.38) was twice that for fishers (0.19). Martens were detected at 20 of 53 stations, 15 in 1995 and 7 in 1996; 2 stations had detections both years. Fishers were detected at 14 of 72 stations, 8 in 1995, and 7 in 1996; only 1 station detected fishers in both years.

Snow Track Searches and Camera Stations

With confirmation of the occurrence of fishers and martens in the Project area, and preliminary assessments of their distribution, study priorities were focused on fishers, especially on the size and composition of the areas used and how the habitats within these areas have changed over time. Answers to these questions for martens would be equally interesting, but limited resources and the fact that the Project area encompassed habitats mainly within the range of fishers led us to focus on this species.

These new objectives required live-trapping and radio-collaring fishers, which began in February 1999. Because it had been 2½ years since our last survey, we needed more current information on areas being used by fishers. By

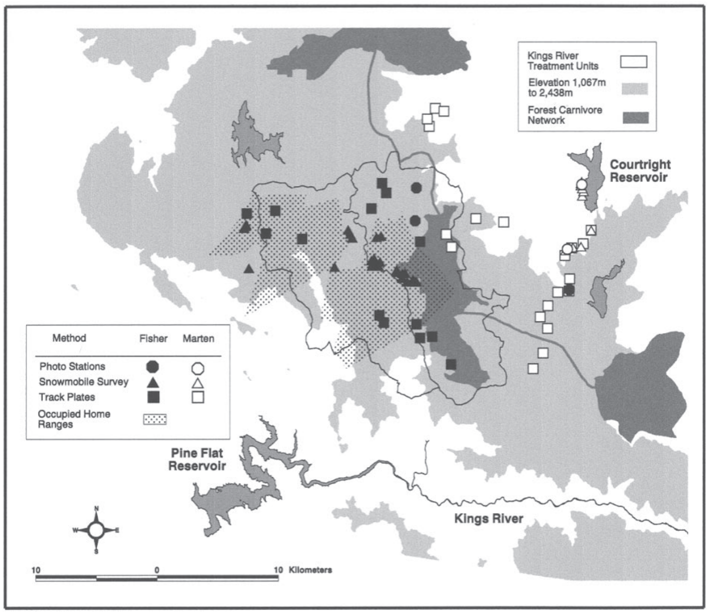

Figure 5—Locations where fishers and martens were detected in the Kings River Sustainable Forest Ecosystems Project Area, south zone of the Sierra National Forest, Fresno County, California. Occupied home ranges represent the aggregated minimum convex polygon home range estimates of nine animals.

using snowmobiles to travel along roads within the Project area, we searched for fisher tracks (*fig. 4*). To help resolve uncertainties about the distinctions between tracks of fishers and martens, we placed Trail Master passive infrared monitoring setups (Model TM500 with TM 35-1 camera kit)[6] at six locations above 1,830 m where we expected both species to occur. We used a combination of a scent call (Gusto by Caven Lures, Minnesota Trapline Products, Pennock, Minnesota) and approximately 5 kg of raw pork as attractants at each camera station. The pork was secured at least 2 m above the ground in trees with diameters exceeding 61 cm at breast height. The dimensions of snow tracks left by animals photographed at the camera stations were compared to previously identified tracks to confirm that they had been classified correctly.

Results of Snow Track Searches and Camera Stations

We traveled 157 km of roads in 10 days between 3 February and 14 April 1999. Identifiable tracks of fishers and martens were found crossing these routes in 38 locations, 28 by fishers and 10 by martens (*fig. 5*). Fishers or martens were detected at five of the six camera stations but never both species at a single station (*fig. 5*). Multiple pictures at each station confirmed fishers at 2,160 m and 2,360 m and martens at 2,490 m and 2,550 m. The presence of two separate martens at the station located at 2,490 m was confirmed by an image with both animals in the same frame. Snow depths where tracks or images of fishers were recorded ranged from 5 to 124 cm. Marten tracks and images occurred at locations with snow depths ranging from 87 to 185 cm.

Live-Trapping

Capture and radio collaring began in August 1999. Live traps (Model 207 Tomahawk Live Trap Company, Tomahawk, Wisconsin) modified to include wooden nest boxes (Seglund 1995) were placed in areas where track-plate surveys and track searches had detected fishers (*fig. 5*). Traps were typically placed next to downed logs within 10 m of a stream and preferably where two or more streams met. To attract fishers, the Gusto scent call was poured onto Prowick™ scent dispensers (by Wildlife Research Center, Inc. available through Minnesota

[6] Mention of trade names or products is for information only and does not imply endorsement by the U.S. Department of Agriculture.

Table 1—*Physical parameters measured on anesthetized fishers live-trapped within the Sierra National Forest, Fresno County, California*

Weight
Length (nose to end of vertebrae of tail, axis of body to vertebrae of tail)
Hind foot length (heel to end of longest claw)
Ear length (lateral notch to tip)
Neck circumference
Canine lengths (each tooth)
Canine diameters (base and tip of each tooth)
Dimensions of the testes (anterior to posterior and medial to lateral)
Diameter and height of each nipple

Trapline Products, Pennock, Minnesota) suspended above each trap. A chicken leg was securely tied within the trap on the side along the log and in the rear next to the wooden nest box. Traps were checked daily and re-baited or re-scented at least every fourth day depending on the condition of the bait and potency of the scent call.

Captured animals were coaxed into a handling cone attached to the rear of the nest box following methods of Seglund (1995) and anesthetized with a mixture of ketamine and diazepam (1 mg of diazepam per 200 mg of ketamine) injected intramuscularly at a dosage of 11-24.2 mg/kg of body weight (California Department of Fish and Game 1996, Seglund 1995). Anesthetized fishers were removed from the handling cone, weighed, and examined. In addition to determining the sex of the animal and assessing overall condition, we assessed the development of the sagital crest, mammae, or testes and baculum. A series of measurements used by Zielinski and others (1999) were made to describe the morphological characteristics of each animal (*table 1*).

We implanted subcutaneous, passive, integrated transponders (125 kHz, TX1405L, Biomark™, Boise, Idaho) in the nape of each fisher for permanent and unique identification. In addition, color-coded ear tags were fastened into each ear to outwardly identify animals recaptured or recorded at future camera stations. The small amounts of ear tissue displaced by the tags were preserved for genetic analysis.

Each animal was also fitted with a radio transmitter with a 16-hour on- and 8-hour off-duty cycling option to extend battery life (Models 080 for females, 205 for males, Telonics, Mesa, Arizona) and a mortality sensor to alert biologists when an animal had died. Animals were placed back in the wooden nest box of the trap after being processed and then released after about an hour, when fully recovered from the anesthesia.

Live-Trapping Results

Three females and six males were caught on 11 occasions during 326 trap nights between 4 August and 15 November 1999—a capture rate of 0.0337 animals/night. That is, 10 traps open for 10 nights were likely to capture fishers on about 3 occasions. This capture rate was 2.8 times that reported by Zielinski and others (1999) for their work in the Sequoia National Forest from 26 May to 6 July 1999. The trap design, microhabitat placement, bait, and scent call were similar in the two studies. Trap latency (the mean number of nights that traps for fishers remained open before a fisher was captured) for the two studies provides evidence of this similarity. Our trap latency was 6.1 trap nights ($n = 9$, range 1 to 15); that of Zielinski and others (1999) was 7.7.

The sex ratio of captured fishers (6 males: 3 females) is probably not representative of the population in the Project area, as the sample is small and it

Table 2—*Physical measurements (weight in kg, lengths in cm) from anesthetized fishers captured on the Sierra National Forest, Fresno County, California*

Parameter	Sex	n	Median	SD	Min.	Max.
Weight	Male	6	3.6	0.5	3.3	4.5
	Female	3	2.1	0.1	2.0	2.2
Total length	Male	6	100.1	2.2	98.7	105.0
	Female	3	89.0	2.5	87.5	92.3
Tail length	Male	6	37.6	1.0	36.8	39.7
	Female	3	35.0	0.5	34.5	35.5
Right hind foot length	Male	6	12.7	0.4	12.0	13.0
	Female	3	10.9	0.6	10.0	11.2
Left hind foot length	Male	6	12.1	0.4	11.9	12.9
	Female	3	10.5	0.5	10.0	11.0
Right ear length	Male	5	10.5	0.7	3.5	5.1
	Female	3	4.3	0.8	3.0	4.4
Left ear length	Male	5	4.9	0.7	3.0	5.0
	Female	3	3.9	0.7	3.2	4.5
Neck circumference	Male	6	20.9	2.2	17.0	23.8
	Female	3	16.0	1.2	14.9	17.3

is well known that both live-trapping and fur-trapping methods for mustelids are biased toward males (Buskirk and Lindstedt 1989, King 1975).

The number of animals handled thus far is too small for multivariate analyses of body weight, length, or tooth measurements. Sexual dimorphism has been reported in the species elsewhere in California (Seglund 1995, Zielinski and others 1995a). Our male fishers were significantly larger than the females (Mann-Whitney U test, $P < 0.05$), based on every physical parameter measured except ear length ($P = 0.09$) (*table 2*). Preliminary tests also suggest that additional data will reject the hypothesis that canine lengths and diameters are the same for the two sexes (*table 3*). Given only tooth size, we found canine diameter at the base of the tooth most useful to distinguish between the sexes. The diameter at the tips of the canines appears to be similar between the sexes, and canine length is subject to more variability than diameter at the base due to breakage.

Nipple dimension (length x width) in female fishers can provide information on their breeding status (Frost and others 1999, Zielinski and others 1999). Frost and others (1999) reported mean anterior nipple sizes of 45 mm^2 for current breeders, 12 mm^2 for former breeders; and 6 mm^2 for nonbreeders, and Zielinski and others (1999) reported a mean anterior nipple size of 21 mm^2 for a lactating female and values of 2 mm^2 and 8 mm^2 for nonlactating females. The nipple dimensions on two of the three females we captured suggest that they had previously produced offspring (*fig. 6*) and that the third female was a nonbreeder.

Six of the animals had signs of past physical damage that included broken canines, torn ears, and scars, but all nine animals appeared healthy based on body weight, the relative amount of fat covering the ribs, coat condition, and external parasite loads. External parasites were rare on the nine animals trapped, agreeing with Powell (1993) that fishers exhibit a low incidence of parasites. Our assessment of their health at the time of capture was supported by the survivorship of the all individual animals through winter, at least to April 1, 2000.

Table 3—*Median canine length (mm) and diameter (mm) for fishers captured on the Sierra National Forest, Fresno County, California. Three broken canines were removed from the length measures*

Characteristic	Sex	Right tooth length (n)	Left tooth length (n)
Upper canine			
Length	Male	14.73 (5)	15.68 (5)*1
	Female	11.44 (3)	11.62 (3)*
Diameter of base	Male	6.74 (5)*	6.75 (5)*
	Female	5.02 (3)*	4.81 (3)*
Diameter of tip	Male	2.50 (5)	1.90 (5)
	Female	2.50 (5)	1.90 (5)
Lower canine			
Length	Male	14.50 (5)*	15.32 (6)*
	Female	9.47 (3)*	9.57 (3)*
Diameter of base	Male	7.00 (5)	7.07 (5)*
	Female	5.47 (3)	5.59 (3)*
Diameter of tip	Male	1.83 (5)	2.00 (5)
	Female	1.73 (3)	1.58 (3)

[1] Asterisks represent significant differences between the sexes, based on a Mann-Whitney U statistic an and alpha level of 0.05.

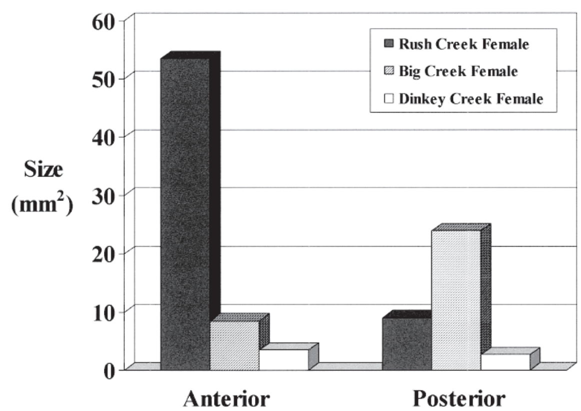

Figure 6—Nipple dimensions (length x width) of three female fishers captured in autumn within three drainages on the Sierra National Forest, Fresno, County, California.

Home-Range Size

Locations used to estimate home-range size came from trap sites and radio telemetry locations between August 1999 and May 2000. Trap sites where animals were captured were treated as known locations. Relocations using radio telemetry relied on a scanner/programmer with a receiver (Models TS-1, TS-2, Telonics Inc., Mesa, Arizona) to detect radios. Receivers were attached to a 2- or 3-element, hand-held antenna or a truck-mounted, manually rotated, Yagi direction-finding antenna array. Walking to the animal and identifying the physical structure it occupied was the preferred method of relocation, but locations in some instances were determined by a minimum of three azimuths from known locations. Azimuths were measured using a hand-held compass (Model Type 15T, Silva, Binghamton, New York). Locations of trap sites and physical structures occupied were determined using a global position system with real-time correction capability (Centurion, Trimble Navigation, Inc., Sunnyvale, California or PLGR, Rockwell International Corporation, Cedar Rapids, Iowa).

We used the minimum convex polygon method (Mohr 1947) to estimate home-range size because of the small number of locations currently available for each animal, and all locations were used for each animal because outliers were difficult to identify with the small samples.

Home-Range Results

The cumulative area used by the three female and six male fishers with radio collars included much of the Project area within the elevations that fishers inhabit (*fig. 5*). Preliminary estimates of home-range size were derived from as few as 10 locations for males (n = 6, median = 13, range = 10-23) and 19 locations for females (n = 3, median = 26, range = 19-42). Median home range area for males (2,150 ha; sd = 1,873) was more than twice that for females (964 ha; sd = 748). The lack of power to detect a significant difference (alpha level 0.05) between the areas used by males and females emphasizes the preliminary nature of these results (Mann-Whitney U = 3, P = 0.12, X^2 = 2.4, 1 df).

Changes in Habitat Within Home Ranges

The distribution and numbers of fishers have decreased in California over the past few decades, despite their receiving protection from trapping. Because of this, Zielinski and others (1995b) suggest that the decline is attributable to a reduction in suitable habitat. In the summer of 2000, we began to examine changes in habitat composition and patterning within fisher home ranges in the Project area by comparing current conditions to those existing in 1958. Aerial photographs taken in 1996 were interpreted to produce a classification scheme similar to that produced by a timber stand-vegetation cover map completed in 1958. Descriptions of habitat within each home range will be determined by using a geographic information system to intersect the boundaries of the home ranges with the 1996 aerial photo data and the 1958 vegetation cover map. Timber growth models, data on fire frequency and intensity, and timber harvest activities since 1966 will be used to explain changes in composition and patterning over the 38-year period.

Monitoring Long-Term Trends

Monitoring of fisher populations is difficult. Individuals are solitary outside the breeding season, densities are low, and sample sizes needed to detect change can be large (Zielinski and Stauffer 1996). In light of the fisher's status (Lamberson and others 2000), the population of these animals within the 26,000-ha Project area must be monitored for both population numbers and demographic parameters. Baited track plates have been successful for monitoring local project areas (Fowler and Golightly 1994) and have been proposed for use to detect regional changes in an index of the occurrence and distribution of fishers throughout California (Zielinski and Stauffer 1996). Indeed, we have successfully used them to determine the occurrence and distribution of fishers within the Project area. Live trapping and telemetry will provide data on population parameters, including the number of individuals, age structure, survivorship, and possibly gene flow. Our preliminary results on nipple dimensions suggest that information on the past reproductive activity of females might also be obtained. Continuing research with radio-collared animals will also provide a marked population with a known distribution on which to assess biases associated with the live-trapping method.

Systematic live-trapping is proposed to occur from July through October within a 168-cell grid that spans elevations from 1,067 m to 2,438 m across the Project area (*fig. 7*). This trap period was chosen because access is good, it is still

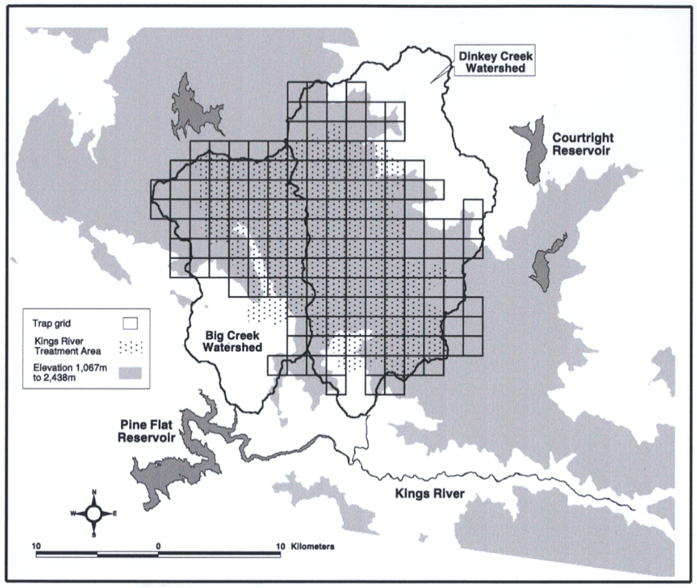

Figure 7—Systematic trap grid proposed for use to monitor fishers within the Kings River Sustainable Forest Ecosystems Project Area, Sierra National Forest, Fresno County, California.

possible to examine nipple enlargement to assess breeding status in females (Frost and others 1999), capture rates are good during this period, and it occurs after the nursing period. A single trap would be placed within suitable habitat for fishers within each 2.56-km^2 cell and used to trap animals at that locale for 12 days. Only once has it taken us longer than 12 days to capture a fisher at a trap site where one was eventually caught. On the basis of our preliminary estimates of home-range sizes, a grid cell size of 2.56 km^2 will result in an average of three traps per female home range and eight traps per male home range. This design would enable three biologists to complete 2,016 trap nights in 4 months and handle fishers on 68 occasions, based on our previous trap success. Fewer captures than this are expected, however, because our previous efforts targeted the highly suitable habitat between 1,372 m and 1,829 m in elevation.

Conclusions

We found a reproducing population of fishers inhabiting much of the land base between 1,067 and 2,438 m in elevation within the Project area. Whether survivorship and reproductive rate within the Project area are sufficient to maintain the population is unknown. The fate of the population depends primarily upon the management direction taken by the Forest Service, which administers 85 percent of the land base within the Project area. A regional management directive has deferred activities that would significantly decrease the persistence of large-diameter live trees, snags, and downed logs in forest carnivore habitat networks not covered by standards set for the California spotted owl (*Strix occidentalis occidentalis*) (Verner and others 1992). The current forest carnivore network within the Sierra National Forest, however, encompasses only 18 percent of the Project area (*fig. 5*). Given current viability concerns for fishers in the Sierra Nevada, and because we still know too little about the survivorship and reproductive rate of fishers within the Project area, it would be prudent that, concurrent with future research, management activities in areas occupied by fishers that are outside the forest carnivore network also conserve or promote habitat elements used by fishers.

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