The Teakettle Experiment[1]

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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.

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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^{o}C, 30^{o}C, and 3^{o}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

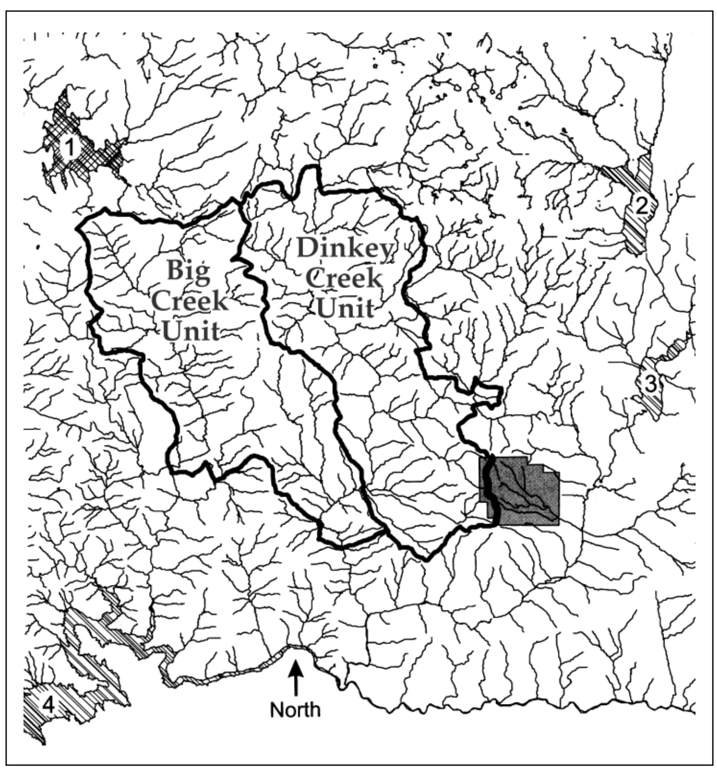

Figure 1—Teakettle Experimental Forest (shaded) abuts the southeastern edge of the Kings River Sustainable Forest Ecosystems Project area. Major water bodies are numbered: 1–Shaver Lake; 2–Courtright Reservoir; 3–Wishon Reservoir; 4–Pine Flat Reservoir.

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.

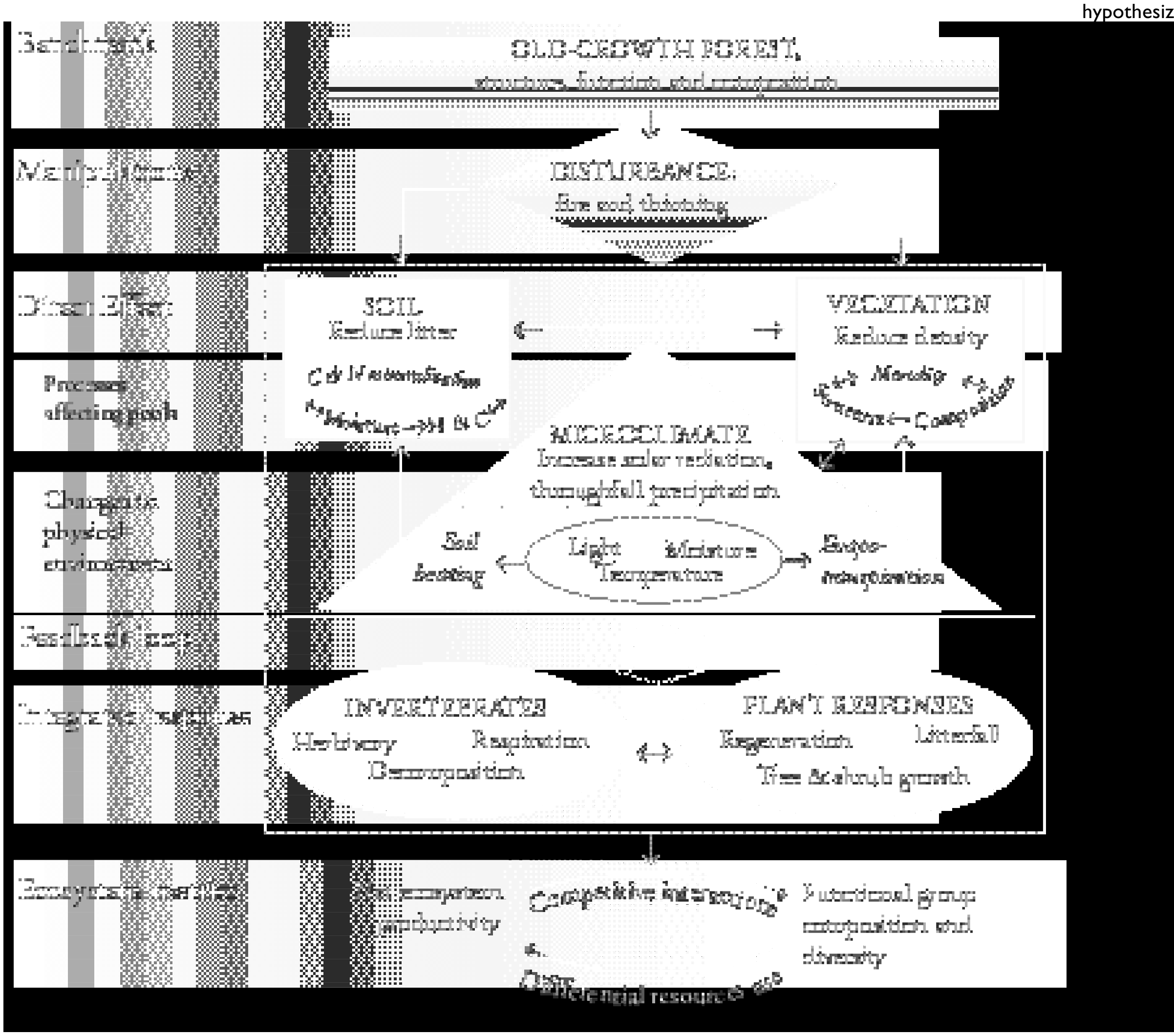

Figure 2—Schematic of the hypothesized interactions of ...mponent studies ...ettle Experiment. ...s in the ... are: the five ... studies; ...interactions that ...hways within the ...erall ecosystem ...hich is shown at ... *C* = carbon, *N* =

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

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