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Modeling Sierran Forests: Capabilities and Prospectus for Gap Models

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Introduction

This paper responds to the desire of the Sierra Nevada Ecosystem Project (SNEP) to address current capabilities for projecting Sierran forest ecosystems into an uncertain future, relying on available modeling techniques. Here we present an overview of the forest gap model ZELIG as implemented for Sierran forests, emphasizing specific concerns of SNEP but putting these into the context of our overall goals for the Sierra Nevada and elsewhere. This overview is divided into several parts: a short history and lineage of gap models; our efforts to date in the Sierra Nevada as part of the National Park Service's (now NBS) Global Change Research Program. We should emphasize that, as the NBS program is not scheduled for completion until after 1996, this report describes "work in progress." We close with a final prospectus as to our capabilities in the near-term future and how our efforts can be reconciled with other modeling approaches.

Background

Gap models (Shugart and West 1980) simulate forest dynamics as the manifestation of tree-by-tree demographic processes: establishment, growth in a competitive milieu, and mortality. Relative to other tree-based models, gap models make the simplifying assumption that at a small spatial scale the environment can be considered relatively homogeneous in the horizontal dimension and that trees within this area mutually influence each other. Thus, a gap model simulates a small model plot corresponding to the zone of influence of a canopy-dominant tree (or conversely, the gap one creates when it dies). The history and philosophy of gap models is detailed by Shugart (1984) and Botkin (1993); Urban and Shugart (1992) have traced the lineage of several variant models and illustrate recent trends in these models.

Gap models share a logic that distinguishes them from many other forest simulators, in that trees do not interact directly with each other; neither do trees react to an extrinsically specified environmental context. Rather, individual trees influence their environment (*e.g.*, through leaf area), and the collective influences of many trees define the environmental context of the model plot. This collective environment then influences individual trees (*e.g.*, through shading). Thus, gap models are unique in that the trees generate their own environmental context during the course of the simulation.

Gap models also share a common logic in the implementation of the demographic processes of establishment, growth, and mortality. Each of these is specified as a maximum potential that could be achieved under optimal conditions; that is, optimal establishment rate, optimal annual diameter increment, or optimal longevity. These potentials are then reduced to reflect suboptimal environmental conditions on the plot (shading, drought, cold temperature, lack of fertility). Thus, as the environmental conditions of the plot change through time, the trees respond dynamically to these changing conditions. Because the influence of each tree on its environment depends on its species and size (the models use species-specific allometric relationships to simulate leaf area, height, and biomass of various tree components), and because the response of each tree to its environment may also vary with size (shading by taller trees, allometric N demand) or by species (shade tolerance, drought tolerance, temperature response, tissue chemistry and N demand), gap models are especially powerful in simulating mixed-age, mixed-species stands.

Because of the logic of the implementation of tree demographics, gap models have also been especially appealing as tools for exploring the consequences of novel environmental conditions, including climatic variability (Solomon 1986, Pastor and Post 1988, Urban *et al*. 1993, among others) and management activities (Aber *et al*. 1979; Smith *et al*. 1981; Hansen *et al.* 1995). This capability to explore novel environmental conditions, including unprecedented management tactics, affords gap models an important advantage over models tightly calibrated to measured field conditions, such as stand yield models based on regressions. Such regression-based models are by their structure restricted to an empirical domain dictated by the data used to construct the model. Because the NBS research program is a global change program concerned primarily with anticipating forest response to novel environmental conditions, the use of a gap model was clearly recommended.

The original gap models (Botkin *et al*. 1972, Shugart and West 1977) made a variety of assumptions to simplify model parameterization. These included simple schemes for estimating allometric relationships (*e.g*., the height-diameter curve) and initial growth rates. These early models also simulated the physical environment in rather simple ways (*e.g*., the soil water balance, soil fertility). More recently, the models have shown a tendency to become much more data-intensive and to incorporate increasingly sophisticated submodels of the physical environment (reviewed in Urban *et al*. 1991, Urban and Shugart 1992).

Some of these trends are easily illustrated with the current Sierra Nevada implementation of the gap model ZELIG (Urban *et al., in prep*.)

ZELIG version FACET 3.1: the Sierran Model

ZELIG is a second-generation gap model in the sense that it retains much of the philosophy and logic of its parent models (JABOWA and FORET), but it has been completely rewritten with new algorithms and parameterizations. ZELIG is especially configured for spatial applications (Smith and Urban 1988, Urban and Smith 1989, Urban *et al*. 1991, Weishampel *et al.* 1992, Urban and Shugart 1992). This model, unlike other gap models, is implemented as a grid of model plots; trees on adjacent grid cells may influence each other through shading. ZELIG also serves as the framework for model-based comparisons among a variety of forest ecosystems under contrasting environmental regimes (Lauenroth *et al*. 1993), and also for comparisons between grasslands and forests (Coffin and Urban 1993). The model is currently implemented or under testing in the Oregon Cascades (Urban *et al*. 1993; Hansen *et al., in press*), the Olympics (N. Zolbrod, U. Washington, thesis *in prep*.), the White Mountains of New Hampshire (Schwarz 1993, Schwarz *et al*. 1994), the southern Appalachians in North Carolina (K. Allen, Duke University, master's thesis *in prep*.), and in the Sierra Nevada (Urban *et al., in prep*; Miller and Urban, *in prep*.).

The Sierran implementation of ZELIG has been developed under the NBS's Sierra Nevada Global Change Program. The major projects contributing to this research program are represented in Figure 1, and our modeling effort has served to help integrate these various studies. The overall concern of this program is anthropogenic environmental change; specific concerns are the role of the water balance as this might be altered under climatic change, and fire regimes as these might respond to changing climate and also to changing fire management practices. These foci reflect our consensus that soil moisture and fire are primary constraints on Sierran forest ecosystems.

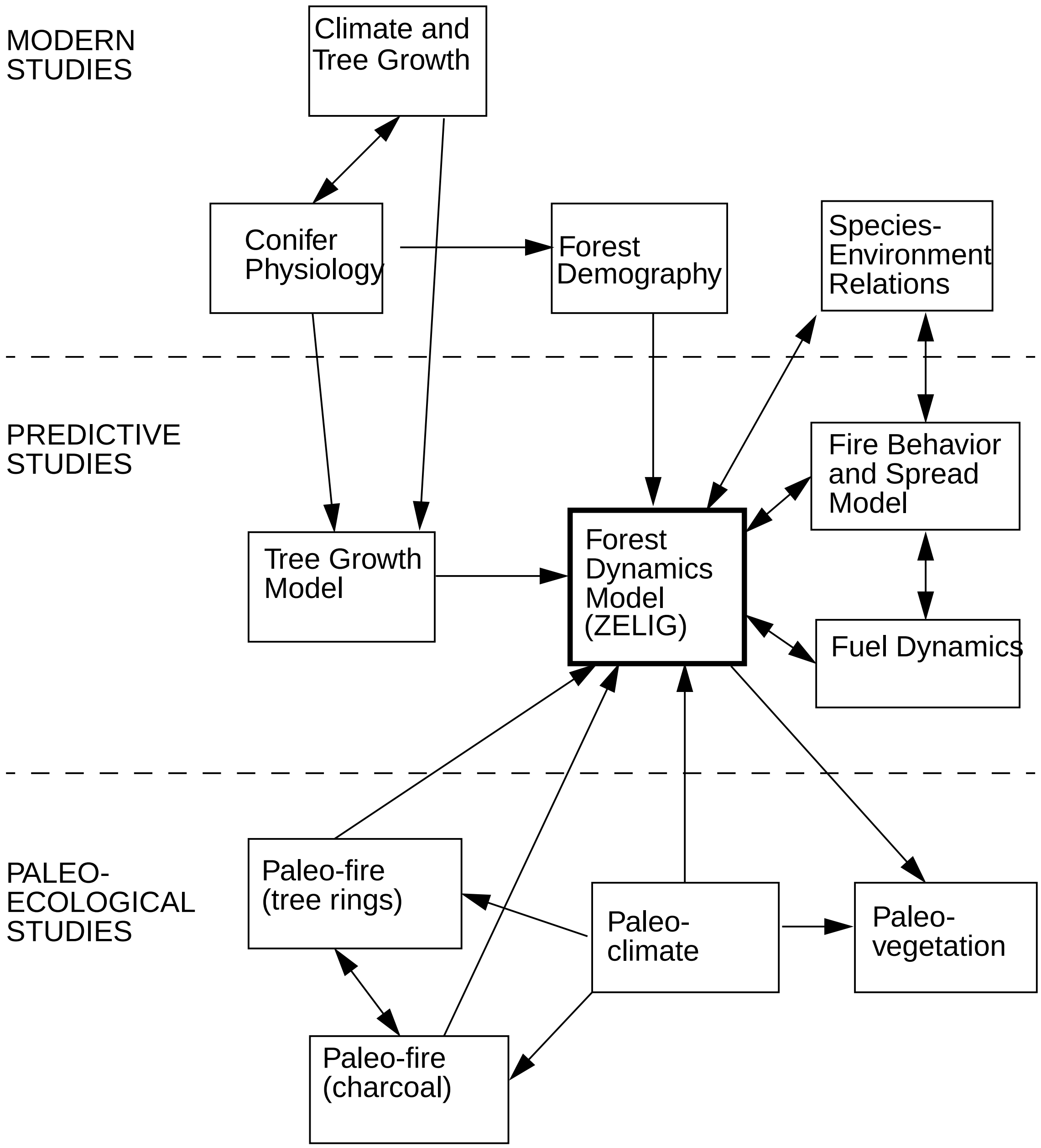

Figure 1. The relationships among studies within the Sierra Nevada Global Change Research Program (redrawn from Stephenson and Parsons 1993). Boxes represent individual studies and arrows represent some of the major linkages.

Our approach to modeling Sierran forests has been to develop model components (especially a soil moisture model and a fire model) that are sufficiently general and robust that, once developed and verified for our primary study site (Sequoia National Park), could be implemented readily at other Sierran sites (especially Yosemite), or indeed, in another region. This is in keeping with the general ZELIG philosophy: the same code is being used at all study sites in various regions of the United States.

Our strategy in model development has been to incorporate as much local data and expertise as possible, and to encode these as algorithms that are as general and site-independent as possible. The initial version of the model is then benchmarked and further tested to ensure it is robust. Current efforts are geared toward further refinements in response to our initial model tests.

Current Status

The ZELIG model itself is largely free of internal site-specific parameters. Rather, the model is driven by two parameter files: a *site* file and a *species* file. The site file includes climate and soils data. The Sierran model is a FACET variant of ZELIG, which means that the model is designed to simulate a site (model grid) at any elevation or topographic position (slope, aspect). The model corrects climate internally for topography using locally estimated lapse rates and established models. Thus, ZELIG requires as input data, mean monthly minimum and maximum temperature, precipitation, and the interannual variability (standard deviation) in these. Lapse rates are used to adjust temperatures and precipitation for elevation (Running *et al*. 1987, Daly *et al*. 1994), and temperature is used to fractionate precipitation into snow *versus* rain. Temperatures and precipitation are used in conjunction with latitude, slope, and aspect, and elevation to predict solar radiation (Bonan 1989, Nikolov and Zeller 1992). Soils are defined in terms water-holding capacity for each of any number of layers; water-holding capacity is itself estimated from the depth and texture of each layer (Cosby *et al*. 1984).

The species driver file includes parameters that define potential growth rates, environmental tolerances, and allometric relationships of each species. In contrast to early gap models which estimated some of these parameters without data, ZELIG is rather data-intensive: Sierran allometries are based on hundreds to tens of thousands of individual trees. Growth rates are calibrated to local tree growth measurements where available, or adjusted to stand-level data as necessary for data-poor species. Parameters are constrained to be consistent with known autecology (Minore 1979) and local data.

The Soil Water Balance. Much of our effort to date has focused on the soil water balance as a primary constraint on forests directly, and indirectly through its effect on the fire regime. The current model simulates the water balance as the difference in water demand (energy supply) and water supply. Water demand depends on radiation and temperature, using a Priestley-Taylor estimate of potential evapotranspiration (PET; Bonan 1989). Demand thus varies with elevation (via temperature lapse rates) and topographic position (relative radiation). Water supply depends on water input (precipitation plus snowmelt) and water storage (mostly a function of soil depth for these sandy soils). The forest canopy influences the water balance though interception and by effecting the depth distribution of transpiration (which depends on fine root density per soil layer). Thus, the water balance is responsive to static (*in situ*) constraints such as topography and soil, as well as to dynamic constraints that might be expected to change under greenhouse scenarios, especially temperature and precipitation. Importantly, we have taken special care to ensure that this model can simulate water relations under a broad range of environmental conditions, both within the Sierra and at other study sites in other parts of the country.

The Fire Regime. The ZELIG fire model represents a new advance in fire modeling as it integrates fire, climate and forest pattern. Although other gap models have incorporated fire, this model is unique because it simulates a climatically sensitive fire regime and a spatially heterogeneous fuel bed. A schematic of the fire model is shown in Figure 2.

Climate is coupled to the fire regime through ZELIG's soil water balance, from which a proxy for fuel moisture is computed. Thus, fuel moisture is dynamic; it changes from year to year, throughout the fire season, and reflects current canopy conditions. This approach provides a means for investigating the influence of climate on the fire regime, and is a critical improvement over other gap models where fuel moisture is treated as a constant parameter.

Fuel loads are coupled to tree-level information, and therefore reflect current plot conditions. Whereas other gap models have assumed a constant accumulation rate for a given forest type (Kercher and Axelrod 1984, Keane et al. 1990), our model accumulates fuels according to tree-level allometries, with annual rates calibrated to data from a long-term fuel

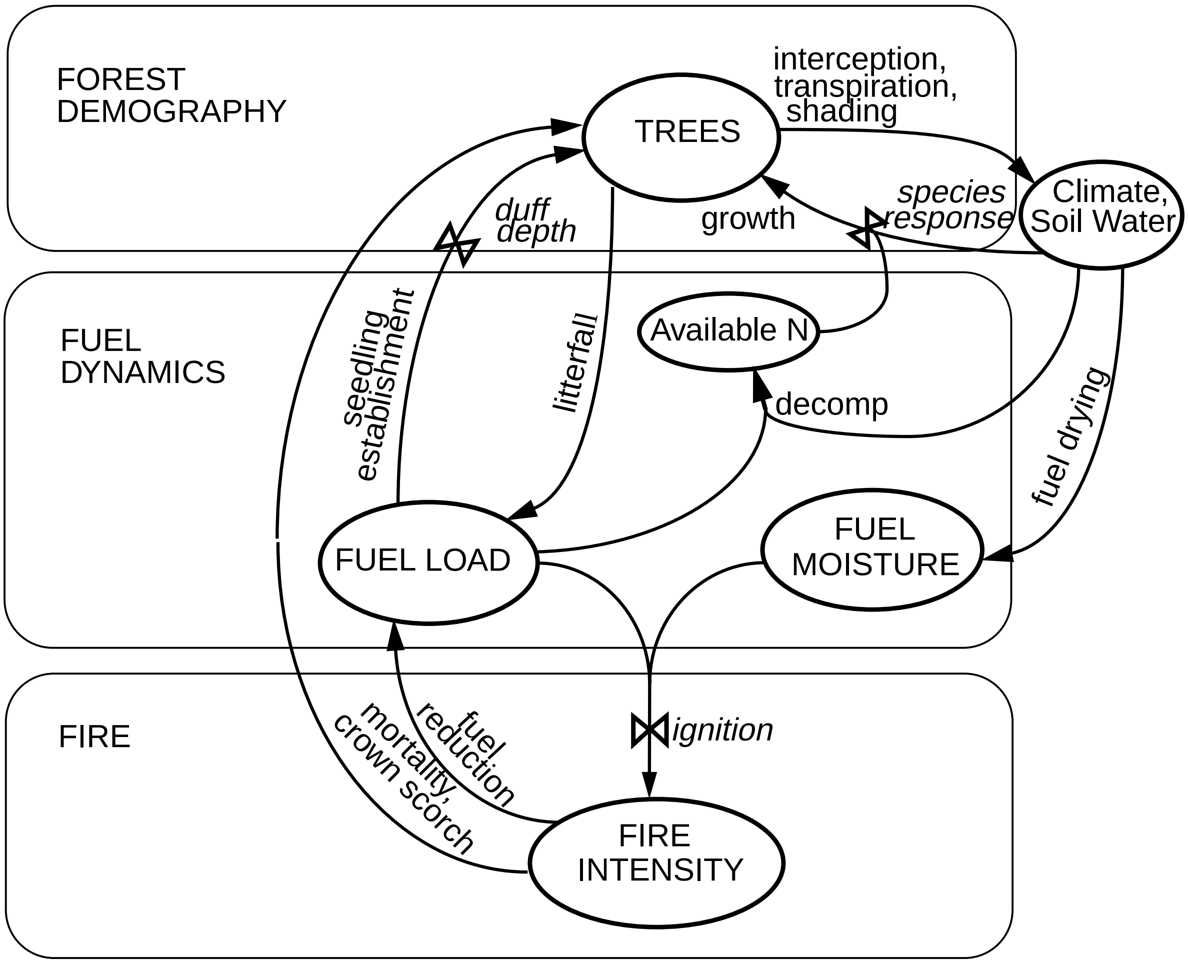

Figure 2. Schematic of the fire model in ZELIG version 3. Fuel loads relfect forest condition because litterfall is a function of tree-level allometries. Fuel moisture is computed from the soil water balance, thus coupling fire with climate. Fire frequency is internally generated by the model, with fire occurrence and fire intensity being functions of fuel moisture and fuel load. Implementation of the model on a raster grid enables the generation of spatial heterogeneity within the simulated stand.

study (van Wagtendonk, National Biological Service, *unpub. data*). A portion of each tree's foliage and branches fall each year as litterfall. Also, when a tree dies, its biomass is added to the fuel bed. Thus, the fuel loading on each plot reflects the size and species of trees on that plot, is sensitive to temporal changes in forest structure and composition, and is not constrained by an assumed accumulation rate for a particular "forest type."

Fuel loads and fuel moisture act together to define the intensity, severity, size and frequency of fires. First, the year and month of a potential fire event are determined probabilistically from user inputs. Fire intensity is then calculated (Rothermel 1972) for each plot, according to both the fuel load and fuel moisture on that plot. For those plots (if any) where the computed fire intensity exceeds an assumed threshold, fire effects (fuel reduction, crown scorch, tree mortality) are calculated according to known regression equations (Brown *et al*. 1985, Ryan and Reinhardt 1988, Van Wagner 1973). In addition to these direct fire effects, an important influence of fire in the model is its indirect effect on seedling establishment and species composition. Establishment success for some species is constrained by the depth of the forest floor, or duff layer; this layer is substantially reduced when a fire occurs.

The spread of fire is not explicitly simulated; fire does not travel from cell to cell in a contagious fashion (this feature may be included in a future version, however). Even so, the spatial structure of the model allows fire to affect only those plots that are "burnable" (*i.e.*, those plots that are both dry enough and have sufficient fuel loading). From this, fire size can be estimated as the number of burnable plots. Note that at wet sites, potential fire starts may be common, but burnable plots, and therefore actual fires, will be rare. In this way, climatic factors can influence fire frequency.

Capabilities and Domain of Applicability

The benchmarked version of the Sierran model does an adequate job of reproducing the gross distribution of the major tree species with respect to environmental gradients (Figure 3). This version is less satisfactory in reproducing successional trends in species abundance; we are currently working to improve this aspect of the model. We have not yet attempted to apply the model to subalpine forests or sites near treeline, as we are not confident that our model can simulate the extreme physical regimes of these sites. The model also does not apply to low-elevation savannah and chaparral, nor to grass- or shrub-dominated vegetation. While these latter cases are perhaps within the realm of possibility for gap models (Burton and Urban 1989, Coffin and Urban 1993), we feel these are beyond the scope of our Sierran project.

Within the scope of our efforts, both the water balance and fire model seem remarkably robust. The soil moisture model behaves well over an elevation gradient spanning 4000 m relief (Figure 4); the model also responds appropriately to variations in soil properties and topographic exposure. We are currently working to improve the manner in which the model distinguishes topsoil from deep-soil water relations, a concern borne of our interest in the role of topsoil moisture in governing seedling dynamics.

The fire model successfully reproduces empirical relationships among fire frequency, fire magnitude, and fire severity as these are governed by fuel loads and fuel moisture (*e.g.*, Figure 5). The model also reproduces elevational trends in the fire regime as inferred from fire-scar data. One of the model's greatest potentials is its ability to generate a dynamic and detailed "map" of fuels that can be used to interface with a landscape fire spread model such as FARSITE (Finney 1994). In contrast to models such as FARSITE, which rely on homogeneous "average" fuelbed conditions assigned by forest cover type, our fire model can provide information on the spatial heterogeneity of fuels as generated by gap dynamics. Currently, the model only treats dead and down fuels, and so is best suited for simulating low intensity surface fire regimes. We plan to add live fuels to augment the model's ability to simulate other types of fire regimes.

Our preliminary testing of the model in Sequoia National Park, as well as initial tests in other study sites suggests that there are no algorithmic limits to implementing this model throughout the Sierra Nevada and into the Cascade Range. For example, we feel the fire model should be applicable to other forest ecosystems, and we plan to extend the model northward from the Sierra along this latitudinal gradient. Between the Sierran and Pacific Northwestern versions of ZELIG, we currently have preliminary species parameters for all common western conifer tree species. The physical submodels (radiation, water balance) are sufficiently general to span this area as well. Some aspects of the model still require site-specific data for implementation; necessary data include soil depth and texture (which vary at all spatial scales) as well as species silvics and growth rates (which differ regionally in response to genetic variation). We suspect that species data could be collated through a concerted effort, especially focusing on Forest Service data used to calibrate local variants of the FVS model (WESSIN). Data on soils are typically not available at a level of resolution appropriate to our modeling efforts, but some simple assignments might be made from coarse-resolution soils maps such as the STATSGO database. Finally, our modeling effort would require stand-level data for local verification of the simulator--a data requirement not restricted to gap models but required for any model that is to be used for predictive applications.

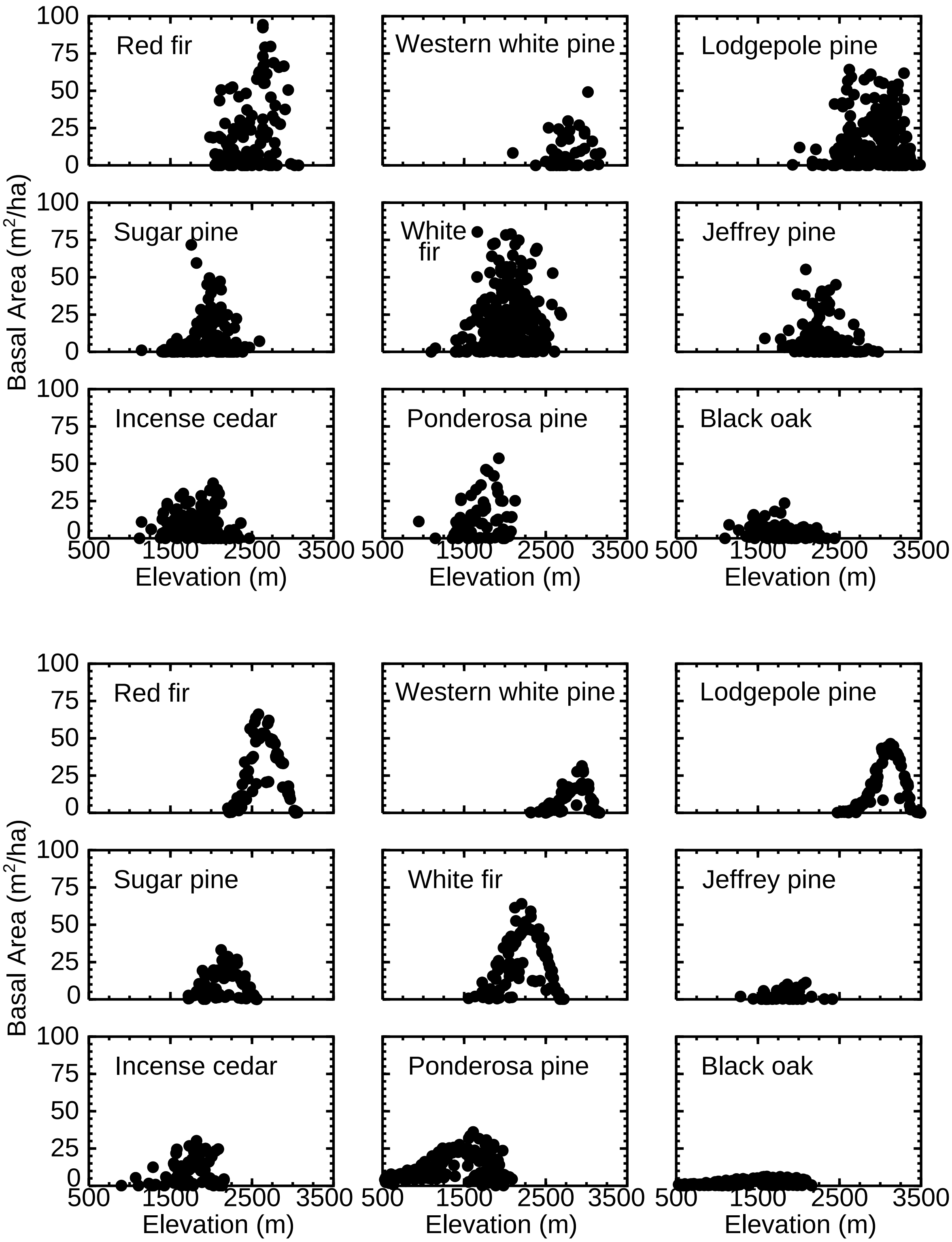

Figure 3. Distributions of common trees species, based on 599 sample quadrats (top panels) and as simulated with the Sierran version of ZELIG (bottom panels; as 300 100-plot grids).

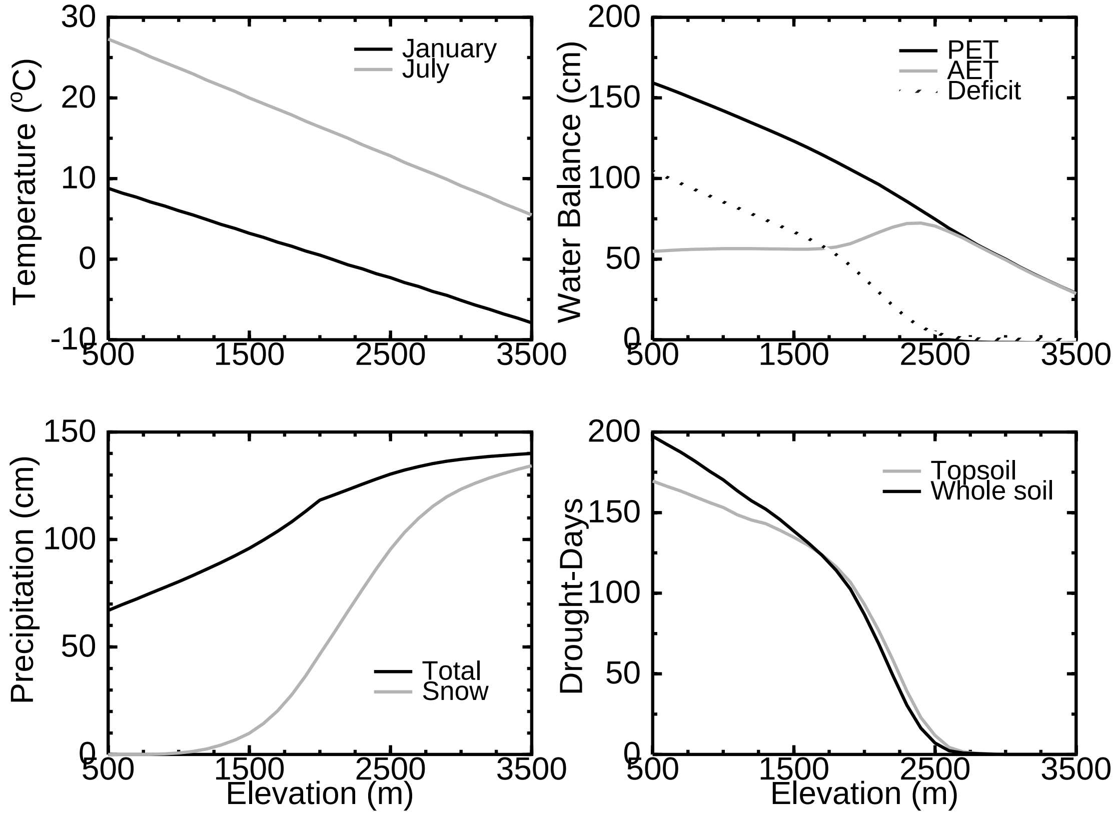

Figure 4. Components of the water balance in Sequoia National Park (39.6°N, 115.6°W, as simulated with the soil moisture model in ZELIG version 3.

Prospectus

The ZELIG family of models was designed to be general while retaining the flexibility for application-specific extensions. An especially pertinent example of this has been the modification of the PNW version of ZELIG for applications concerned with timber management (Garman *et al*. 1992; Hansen *et al*. 1993, 1995). This extension involved incorporating empirical equations to estimate timber volume (ZELIG already includes local taper equations, so this was rather straightforward), and more substantially, adding a user interface that allows extremely sophisticated timber management tactics via an "event scheduler." This interface (Garman *et al*. 1992) was specifically designed to examine alternative silvicultural practices such as green-tree retention and highly selective cuts specified as any combination of diameter limits and species selection. Because ZELIG simulates individual trees on a grid of model plots, this approach is especially appropriate for exploring single-tree or small-group selection strategies. The model is configured to respond to the removal of single trees on a given plot or groups of trees from multiple grid cells (adjacent or otherwise). The PNW version of the model has also been extended to make predictions about wildlife habitat availability, by incorporating statistical (discriminant function) models that assign each grid cell as "habitat" or "not habitat" for a suite of forest birds; this model has been used to examine trade-offs between alternative silvicultural options (retention level and rotation length) and wildlife habitat diversity (Hansen *et al.* 1995).

The ZELIG model also gains flexibility from its modular structure. Thus, if a specific application argues for an alternative model formulation, this new function can simply be substituted into the code. For example, the model now uses allometric relationships that do not

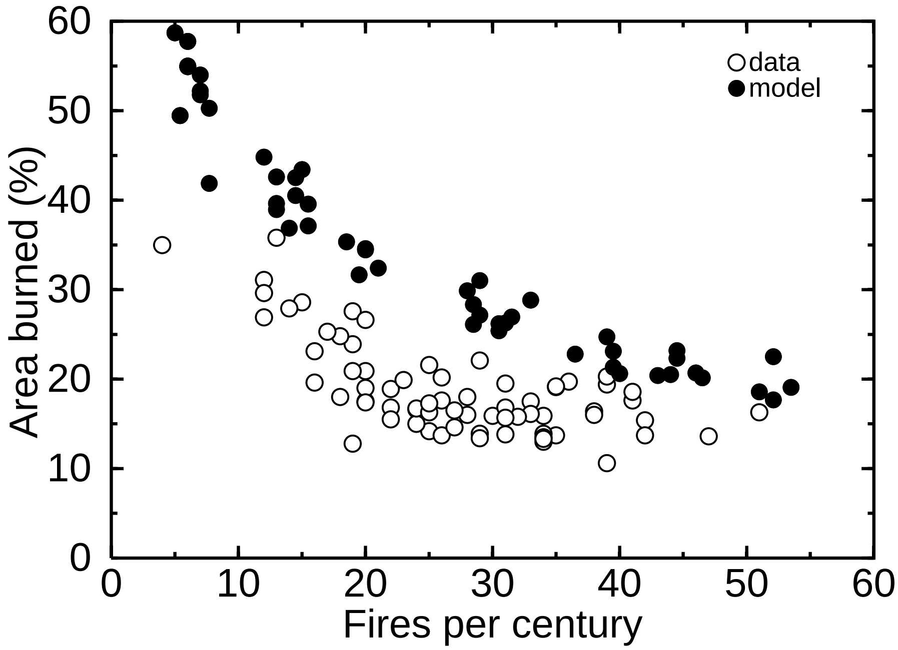

Figure 5. Average area burned related to fire frequency. Open circles represent mean values from fire scar data from five giant dequoia groves; area burned is the percent of sample trees within a site that recorded the same fire (Swetnam 1993). Filled circles are mean values from simulations usiong site descriptions from the fire scar study; area burned is the percent of model plots that had fire intensities greater than 90 kWm^{-1}. Fire magnitude tends to be underestimated by fire scars and overestimated by the logic used in the model (which does not simulate contagion effects), and so the discrepancy between model output and data is as expected.

vary across sites. In particular, trees do not grow taller on more mesic sites (or in thinner stands) as data typically show. Yet it would be a simple change to the code to substitute a function that included soil moisture as an additional argument to influence tree height (see Harrison and Shugart 1991 for an example of site-dependent allometries in a gap model). At a larger scale, Garman *et al.* (1995) have calculated allometries for western tree species, with the allometries adjusted for different regions of each species range (*e.g.*, Coast Range *versus* the Cascades); these allometries are now used in the PNW version of ZELIG (Hansen *et al.* 1995).

The flexibility of the ZELIG model greatly facilitates any efforts to reconcile the gap model with other modeling approaches. For example, the gap model could be parameterized (and perhaps incorporate alternative functions) to make it empirically consistent with FVS models, simply by using the same data to estimate parameters for each model. The two approaches would remain conceptually different, but at least in this case discrepancies in output from the two models could be attributed to these more fundamental differences instead of to data problems.

Conclusion

With respect to the mission of SNEP, one inescapable conclusion emerges: there is no model currently available that meets the needs of SNEP. Because it was designed to address many of the same issues as SNEP faces, the Sierran version of ZELIG clearly would meet many of these needs. Moreover, other extensions to the model concerned with forest management could be extended to Sierran systems, increasing the model’s utility even further. But the model is still under testing and it would be premature to attempt to apply it in predictive applications under conditions outside its current domain.

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