Long-Term Forest Ecosystem Planning at Pacific Lumber

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In 1995, the Pacific Lumber Company contracted with VESTRA Resources to develop a 120-year, 12-period forest-ecosystem management plan for its properties to meet new California Board of Forestry wildlife, fisheries, and timber resource requirements and to optimize its timberland operations and profitability. VESTRA Resources developed the ecosystem-planning express model, Ep(x), which seamlessly integrates geographic information systems with a database resource capability model and a policy-alternative model, providing the inputs to a linear program. The Ep(x) model uses an underlying adaptive management approach that also maximizes the knowledge base of the ecosystem through detailed sensitivity analyses. The model increased present net worth by over $398 million and generated a more optimal mix of wildlife habitat acres, including spotted-owl-nesting habitat.

The Pacific Lumber Company (PALCO) is a large timber-holding company with headquarters in Scotia, California. The company has over 200,000 acres of highly productive forest lands that support five mills located in Humboldt County in northern California. This land is zoned exclusively for commercial timber production. Since 1869, PALCO has been growing trees, making wood products, employing people, and taking care of the forest.

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Early on, the owners of PALCO realized that the lands they held included some of the most spectacular redwood groves on earth. They have given or sold at low cost nearly 20,000 acres of the most accessible and beautiful redwood groves to the public to be preserved as parks. PALCO manages the remaining land intensively for timber production, subject to strong forest practice laws. In many cases, company policy is even more protective of the forest, streams, and wildlife than state and federal law requires. On the average, PALCO plants 500,000 seedlings a year, and it is committed to operating for sustained yield, balancing harvest with forest growth.

Pacific Lumber has over 200,000 acres of highly productive forest lands.

PALCO's forests are home to many species of wildlife, including spotted owls, marbled murrelets, bear, deer, chinook salmon, and steelhead trout. In 1973, the federal Endangered Species Act became law, requiring private citizens and government entities to protect endangered and threatened species and their habitats. In 1982, Congress added the Habitat Conservation Plan (HCP) to the Endangered Species Act. This process was designed to integrate human activities with endangered species protection. Specifically, the HCP focuses on the potential impact (referred to as a "take") of operations (that is, logging) on threatened or endangered species, proposes measures to minimize and mitigate the effects of the take, and authorizes the incidental take of certain listed species in connection with otherwise lawful activities [PALCO]. PALCO can now coordinate both its long- and short-term forestry activities with the protection of wildlife and is currently working with the US Fish and Wildlife Service and other federal and state agencies to develop a multispecies HCP for its lands that will provide long-term protection to wildlife while ensuring that the company can continue growing and harvesting trees.

The forest-products industry can no longer rely on a continuous supply of trees from state and national forest lands because the allowable levels of timber harvest on public lands have decreased substantially during the last 10 years. Coinciding with this reduction in public timber sales has been an increase in public concern for wildlife habitat and landscape stability. Public awareness and concern has prompted stringent laws and regulations governing the activities on private timberlands. As a result, approval to harvest timber on tracts as small as three acres requires participation by the landowner, state and federal agencies, and a host of special interest groups and individuals. PALCO is at the forefront of the industry in developing the technology and methodology it needs to remain profitable while meeting or exceeding the many environmental and sociopolitical constraints on the forest ecosystem.

Prior to contracting with VESTRA Resources in 1995, PALCO managed its lands at the individual-timber-sale level (20 to 500 acres) using classical forest-management practices [Davis and Johnson 1987] coupled with local forester expertise. This classical approach involves setting annual-harvest-flow and area-control objectives and maintaining the forest structure necessary to sustain this schedule. Wildlife and watershed requirements and policies, at both federal and state levels, were often ambiguous and poorly enforced. These government policies and the company's planning methods often resulted in nonoptimal harvesting regimes, inadequate levels of wildlife habitat, supply problems to the mills, nonoptimal mixes of tree species harvested, and antagonistic social and political encounters with other stakeholders—government agencies, special interest groups, and the general public.

In California, forest practices are governed by the California Forest Practice Rules [California 1997] as adopted by the California Board of Forestry and enforced by the California Department of Forestry and Fire Protection (CDF). In 1994, the Board of Forestry approved a measure to allow large landowners, those with holdings over 50,000 acres, to submit a single sustained yield plan (SYP) for the entire landholding, as opposed to submitting sale-by-sale timber harvesting plans (THPs). The intent of the SYP was to address the long-term health and management of the entire forest ecosystem rather than just the local effects generated by individual timber sales. The THP is typically a cumbersome and complicated document that must be filed by a registered professional forester and approved by the CDF prior to the start of harvesting activities in the timber-sale unit. The current THP format places the onus on the landowner to anticipate the cumulative effects of the timber sale on the watershed and wildlife, in concert with other THPs being filed by other landowners in the area. This has proved to be very expensive to the landowner and does not adequately address the overall health of the forest. Under the California Forest Practice Rules, once the California Board of Forestry has approved the SYP the landowner is still required to submit individual THPs; however, the approval process is expedited if the THP conforms to the management and resource policies outlined and approved in the SYP.

In 1995, PALCO contracted with VESTRA Resources to develop a 120-year, 12-period, long-term forest ecosystem management plan for its properties to meet the new SYP requirements. The task was to develop a workable model that addressed the wildlife, fisheries, and timber resource constraints imposed by the SYP and other federal and state laws and regulations and also optimized the company's overall timberland operations and profitability after it had met those constraints. The emphasis was on "workable" since the company could not realize the model results and savings unless the local foresters and logging personnel could physically implement the solution assignments on the landscape.

The Ep(x) Model

In the classical forest-management approach that PALCO used prior to 1995, the harvest-flow constraint is meant to ensure a continuous supply of wood to the mills, while the area-control constraint is designed to maintain the forest structure. The state did not allow harvesting in wildlife habitat areas or within stream buffers. When the California Board of Forestry adopted the SYP, however, and introduced more complex wildlife habitat requirements, PALCO had to develop a new methodology to accommodate the new constraint sets within the concept of total ecosystem management. In constructing the Ep(x) model, we included harvest-flow constraints but chose maximizing present net worth (PNW) as the objective function. If we had used maximizing harvest as the objective function, the linear program (LP) would not distinguish between the low-value hardwoods and the high-value conifers (evergreen trees—primarily pine, fir, and redwood species). As a result, although it would maximize harvest volumes, the resulting timber sent to the mills would not be the optimal mix of quality logs needed to optimize mill operations. Maximizing PNW ensures this quality mix.

It is impossible to establish habitat objectives for every wildlife species.

The classical measure of allowing only the no-harvest option in wildlife habitat areas and stream buffers also fell short of providing the required habitat levels within the time frame specified in the SYP. The primary challenge in managing a forest ecosystem is to provide good wildlife habitat while optimizing PNW or harvest volumes. Many of the species of concern, the spotted owl, for instance, require mature and dense conifer stands for their primary habitat—the same stands that provide the highest contribution to PNW or to the mills. Using the Ep(x) model, we can perform detailed sensitivity analyses on particular wildlife habitat structures and determine the optimal mix of habitat types within each of the individual watersheds.

We begin a run of the Ep(x) model by delineating the management unit—the entire 200,000-acre expanse of PALCO's landholdings. This management unit falls within five watershed assessment areas (WAAs), which are defined in terms of common drainages and the natural ecosystem. The management unit is further divided into large homogeneous polygons called strata types (STs), each having the same vegetation type (tree species) and site class (or site quality). Site class is an indicator of growth potential and is the sum of many environmental factors: soil depth, soil texture, profile characteristics, mineral composition, steepness of slope, aspect, microclimate, species, and others [Daniel et al. 1979]. There are 406 such distinct STs over the management unit numbered ST1 through ST406. It is the ST units on which we conduct growth and yield simulations (an ST need not be continuous and may be an accumulation of disjoint polygons homogeneous in their vegetation and site class combinations).

Using geographic information systems (GIS) overlays showing areas of special use and concern, we further delineated the STs into 7,837 land types (LTs), which then became the primary units of the LP decision variables (Figure 1). All LTs within a specific ST thus have the same growth and yield characteristics and differ only by the combinations of special-concern area overlays that characterize them. And similar to the ST, an individual LT within a particular ST need not be continuous but may be an accumulation of

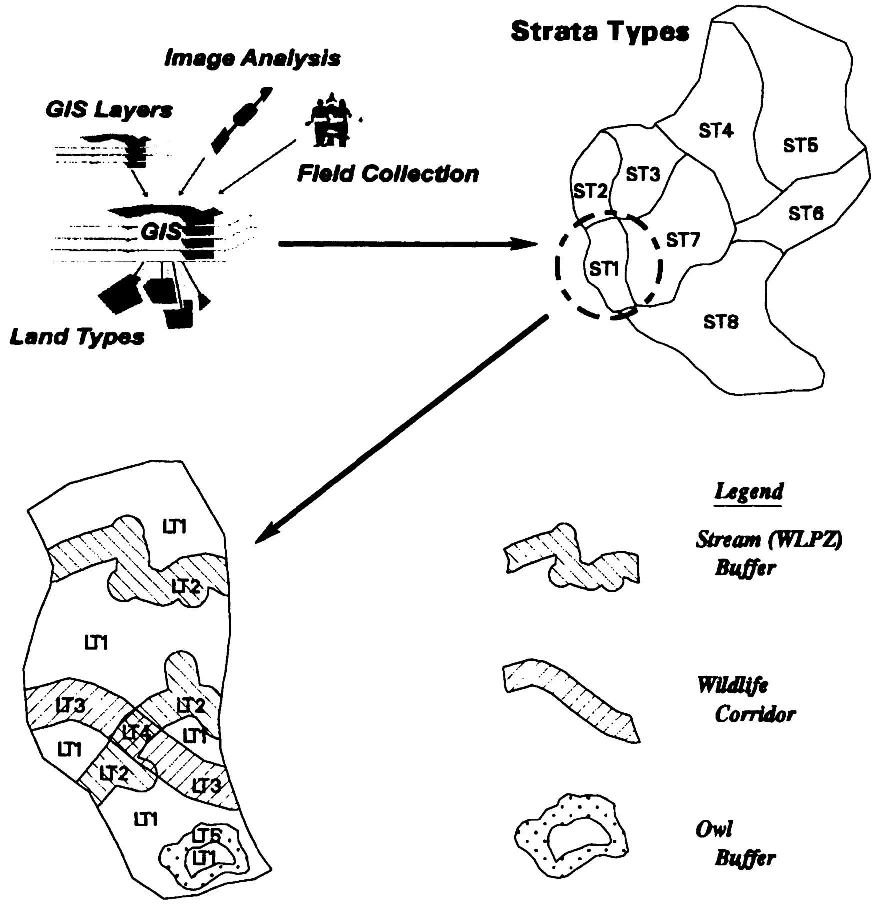

Figure 1: Geographic information systems (GIS) vegetation and site-class overlays create the strata types (ST) over the management unit. Additional special-concern-area GIS overlays on the ST, such as stream buffers, wildlife corridors, and owl-habitat buffers, delineate the distinct land-type (LT) decision-variable set.

disjoint polygons homogeneous in their combinations of special-concern-area overlays. Examples of areas of special use and concern within PALCO's management unit include watercourse-and-lake-protection zones (WLPZs), wildlife corridors, viewsheds, parks and recreation areas, buffer zones surrounding endangered species, and buffers adjacent to neighboring properties. We then constructed the land-type table. It is composed of individual LTs as record sets and special-concern areas as defining attribute fields. We developed silvicultural prescription (RX) sets (biologic- and economic-management treatments) and ran all allowable ST-RX combinations through the growth-and-yield simulation model.

We linked the yield results from the simulation to individual LTs within the resource capability model (RCM) database, and the RCM Query creates the LT_jRX_k decision variable set (Figure 2). We developed the RCM by defining the LT_jRX_k de-

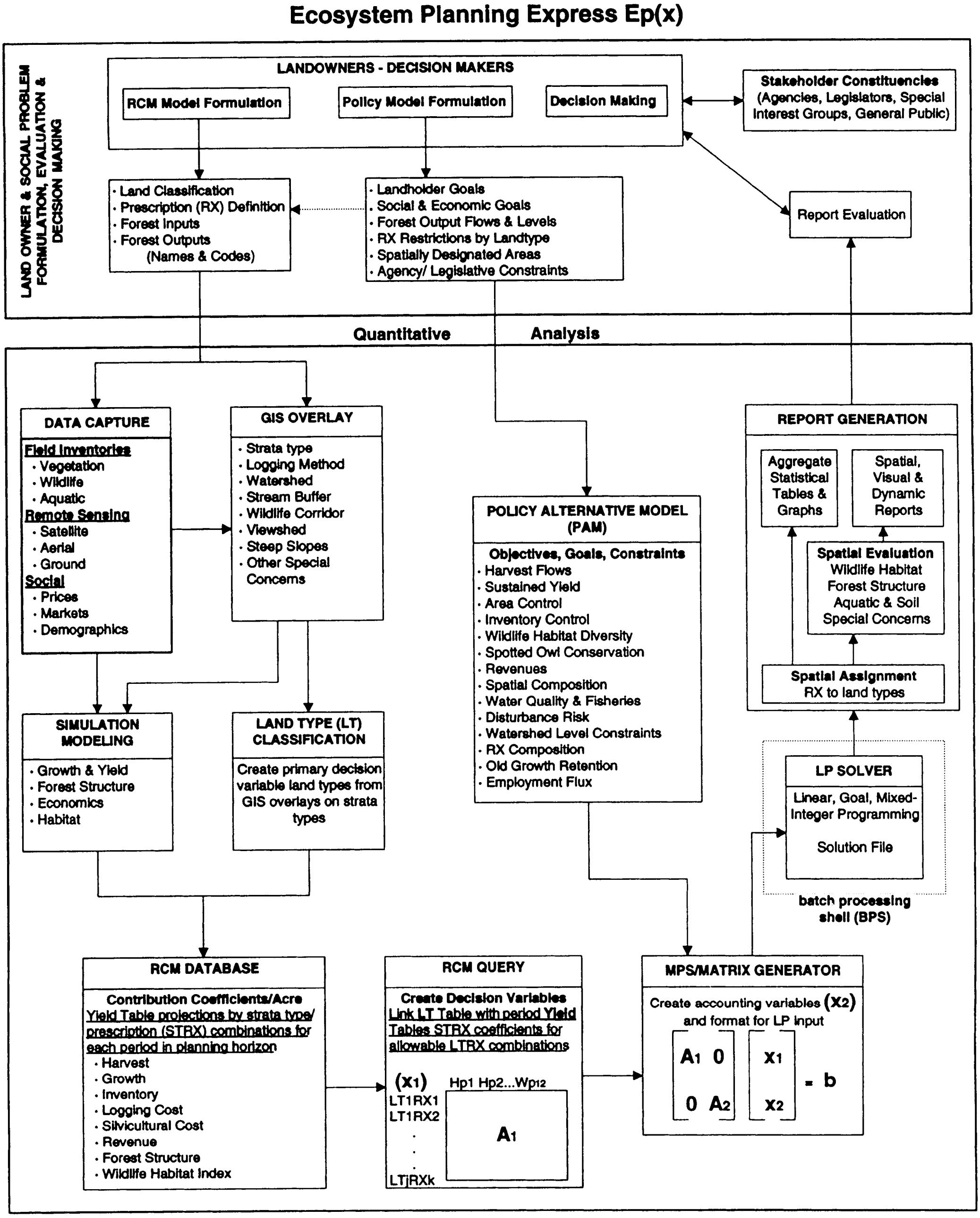

Figure 2: The Ep(x) planning process is circular and begins with identification and delineation of the biological resources and policy formulations. Biological data for the management unit are captured and processed through yield simulations over the planning horizon. These yield tables, along with the land-type delineations, are reformulated into a database structure (RCM), and the RCM Query generates the LP decision-variable set and associated yield coefficients per acre. Objectives, goals, and constraints are developed within the policy alternative model (PAM) and are input into the MPS generator along with the results of the RCM Query. LP outputs are then evaluated by the landowner and stakeholders, and additional LP runs are formulated and evaluated until convergence on the "preferred alternative" is achieved.

Harvest yield stream in thousand board feet per acre (mbf/acre)

STName	RXNum	HV01	HV02	HV03	HV04	HV05	HV06	HV07	HV08	HV09	HV10	HV11	HV12
ST1	1	0	0	0	0	0	0	0	0	0	0	0	0
ST1	51	22.54	0	0	0	0	41.85	0	0	0	0	43.45	0
ST1	63	0	0	41.91	0	0	0	0	10.72	43.55	0	0	0
ST1	93	0	0	30.15	0	13.66	0	11.45	0	10.13	0	9.95	0
ST1	102	0	16.62	5.57	6.92	5.83	5.51	6.98	5.54	5.20	4.99	5.00	5.02
ST1	123	0	0	5.68	0	13.03	0	14.2	0	14.06	0	14.93	0
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—	—	—	—	—	—	—	—	—	—	—	—	—	—
ST406	204	0	0	0	25.76	0	13.87	0	2.85	0	10.42	0	14.89

Growth yield stream in thousand board feet per acre (mbf/acre)

STName	RXNum	GR01	GR02	GR03	GR04	GR05	GR06	GR07	GR08	GR09	GR10	GR11	GR12
ST1	1	7.59	10.06	11.24	11.86	12.20	12.59	12.81	12.88	12.82	12.65	12.41	12.15
ST1	51	3.73	2.44	10.74	11.01	11.69	5.97	2.51	11.35	11.38	12.05	6.16	2.50
ST1	63	7.59	10.06	5.45	3.14	11.32	11.11	11.79	11.40	5.49	3.17	11.37	11.17
ST1	93	7.59	10.06	8.56	6.49	5.49	6.79	5.98	6.20	5.59	6.19	5.04	6.26
ST1	102	7.59	8.64	8.18	7.08	6.51	7.67	7.03	6.64	6.03	6.54	6.10	6.04
ST1	123	7.59	10.06	10.57	10.53	10.24	10.50	9.78	9.54	9.52	9.27	8.95	8.66
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ST406	204	7.59	10.06	11.24	9.41	7.38	7.30	7.61	8.1	8.09	7.47	7.20	7.23

Gross revenue yield stream in dollars per acre ($/acre)

STName	RXNum	RV01	RV02	RV03	RV04	RV05	RV06	RV07	RV08	RV09	RV10	RV11	RV12
ST1	1	0	0	0	0	0	0	0	0	0	0	0	0
ST1	51	13,530	0	0	0	0	22,974	0	0	0	0	23,931	0
ST1	63	0	0	24,981	0	0	0	0	5,816	24,239	0	0	0
ST1	93	0	0	18,442	0	8,092	0	6,712	0	4,684	0	4,734	0
ST1	102	0	10,430	3,203	4,040	3,406	3,372	4,193	3,231	3,154	2,624	2,682	2,766
ST1	123	0	0	3,562	0	7,445	0	8,645	0	8,709	0	8,982	0
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ST406	204	0	0	0	15,411	0	8,428	0	664	0	6,196	0	9,653

Table 1 continues on next page

cision variables with respect to their contribution to the biological attributes of interest and used it to determine the biological capability of the management unit over the planning horizon. We constructed the policy-alternative model (PAM) by compiling the political and environmental constraints imposed by the landowner and the regulatory agencies. The PAM and RCM are joined within the MPS generator that provides the input format to the LP. We ensured complete traceability by using

Wildlife habitat relationships (WHR) stages per acre

STName	RXNum	WH01	WH02	WH03	WH04	WH05	WH06	WH07	WH08	WH09	WH10	WH11	WH12
ST1	1	4D	4D	6D	6D	6D	6D	6D	6D	6D	6D	6D	6D
ST1	51	1	2D	3D	4D	4D	1	2D	3D	4D	4D	1	2D
ST1	63	4D	4D	1	2D	3D	4D	4D	4D	1	2D	3D	4D
ST1	93	4D	4D	3D	4D	3D	4D	3D	4D	4D	4D	4M	4D
ST1	102	4D	3D	4D	4D	4D	4D	4D	4D	4D	4D	4D	4D
ST1	123	4D	4D	6D	6D	6D	6D	6D	6D	6D	6D	6D	6D
—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	—	—	—
ST406	204	4D	4D	6D	6D	6D	6D	6D	6D	6D	6D	6D	6D

LEGEND for RXNum: RX1 = no harvest. **RX51** = clearcut start period 1, 50-year rotation, no commercial thin, regeneration plant. **RX63** = clearcut start period 3, 60-year rotation, thin age 50 to 200 ft^2 residual basal area (RBA), natural regeneration. **RX93** = single tree selection to 150 ft^2 RBA, start period 3, 20-year cutting cycle. **RX102** = single tree selection to 200 ft^2 RBA, start period 2, 10-year cutting cycle. **RX123** = selection to 300 ft^2 RBA, start period 3, 20-year cutting cycle, leave three largest trees/acre—late-seral emphasis. **RX204** = selection to 240 ft^2 RBA, start period 4, 20-year cutting cycle, leave four largest trees/acre—late-seral emphasis.

Table 1: Harvest, growth, gross revenue, and WHR are some of the yield streams generated in the simulation modeling stage and converted to database tables, with contribution coefficients developed for all strata/silvicultural prescription combinations (only partial recordsets are shown). The land type table is joined to the respective yield tables by the STName, and the RCM Query generates decision variables for all allowable LT_jRX_k combinations.

this glass box approach.

Management Through Silviculture

Silviculture is a branch of forestry concerned with controlling the establishment, growth, composition, and quality of forest vegetation [Daniel et al. 1979]. To achieve a specific goal or objective within the management unit, we must establish a specific vegetative structure that will provide the particular goods (harvest volumes), conditions (wildlife habitat), or services (recreation) called for. We achieve this vegetative structure by designing a set of silvicultural prescriptions, which, when physically applied to the landscape, will provide the desired outputs over the planning horizon. RXs designate the periodic activities (treatments) applied to the landscape to manipulate the biologic and economic structure of the particular landscape unit (ST or LT), the particular WAA, or the overall management unit. To maximize PNW, for instance, we must develop a set of available RXs that will provide a continuous supply of merchantable trees for harvest. To provide for stream (WLPZ) buffers, we must develop a set of RXs that will allow for harvesting only a few selected merchantable trees per acre in order to minimize sedimentation and to protect water quality. And, to provide for spotted-owl habitat in the earliest planning periods, we need growth-enhancing RXs that allow selective removal of various-size trees (commercial size or not), resulting in a continuous structure of large-diameter trees with 40 to 100 percent canopy (tree crown) closure. We developed the following RX groups to achieve the PALCO objectives and constraint sets: no harvest

(No_H), clearcut (CC), selection (SEL), late-seral emphasis (LSL), commercial thin-seed tree (CTST), and shelterwood (SHL). These groups comprise 204 individual RXs.

The No_H group has only one member: the no-harvest RX. This code is generally used to preclude entry into areas with landslide potential and recreation areas, or, until we developed the LSL group, to preclude entry into stream zones and most other areas of special concern. The CC group is used for tree species that grow best in even-aged tracts, and clearcutting generally contributes higher revenues per acre than other RX groups, since all trees are harvested. Even-aged species do not grow well in the shade of an overstory of larger trees. Thus, to optimize growth of these species, PALCO harvests these stands and immediately applies some method of regeneration. Variations in RXs within this group include length of rotation, timing of the initial harvest period, timing of commercial thinnings, and method of regeneration (Table 1). Rotation is the length of time between clearcuts, and it may vary between 50 and 120 years (in the West). Intermediate commercial thinning of the less productive and smaller trees encourages the growth of the larger trees and provides revenues. PALCO generally assigns this RX group to areas with no special-concern restrictions. The CC group is also one of the more controversial harvesting methods, since it destroys the visual aesthetics of the area and can cause soil runoff. PALCO has worked closely with various stakeholder groups in planning the size, shape, and location of these cuts to minimize their negative impact on the viewshed and the soil profile.

For shade-tolerant tree species, PALCO can employ either the CC or SEL group RXs. Management using a selection RX group is called uneven-aged management. These species tolerate shade well; and when harvesting trees in the overstory creates open areas on the forest floor, new seedlings soon occupy this space. Individual trees or small groups of trees can be harvested within the LT: the variables include the cutting cycle, the initial harvest period, commercial thin, and residual basal area (RBA). The cutting cycle determines the time between cutting selected trees, generally 10 years (normal cutting cycle) or 20 (long cutting cycle). RBA is a measure of stand density and equals the cross-sectional area of the trees in a stand in square feet per acre based on measuring the diameters of trees at breast height (dbh is 4.5 feet above the average ground level) [Davis and Johnson 1987]. Individual SEL policies range from cutting from above (high-grading—cutting the largest trees) to cutting from below (cutting the smallest merchantable trees) to reach the specific RBAs. PALCO's harvest policy and its simulation modeling of growth and yield reflect harvesting the average merchantable dbh.

The late-seral emphasis RXs are variations on the SEL RXs but are designed to generate specific forest structures to provide for spotted-owl and late-seral habitats. PALCO uses the California Wildlife Habitat Relationships (WHR) system [Mayer and Laudenslayer 1988] to classify its forest structures (Table 2). The WHR system couples the tree-size class with the crown-canopy closure to develop codes for the various wildlife habitat stages. The term *late seral* refers to any stand (LT) of trees having a dbh greater than 24 inches and a canopy closure greater than 40 percent. Alternatively, a late-seral stand may be multilayered with an understory of trees having a dbh greater than six inches and an overall canopy closure greater than 60 percent. Variables in the LSL group include the cutting cycle, the initial harvest period, commercial thin, RBA, and the number of large trees per acre (tpa) remaining after harvest. Commercial thinning is generally done from below (that is, harvesting the smaller trees) and may vary by the period of entry. During the cutting cycle entry period, PALCO leaves a specified number of the largest trees per acre. This ensures that the tract will achieve or be maintained in the late-seral habitat stage (WHR codes 5D, 5M, and 6D—Table 2).

PALCO also uses seed-tree and shelterwood RXs as even-aged management tools. In the seed-tree method, the LT is clearcut, but enough well-spaced trees are left to provide the seed necessary for natural regeneration. Once regeneration is established, the LT is reentered and the seed trees are harvested. The essential purpose of the shelterwood method is to accomplish the regeneration of the site under the shade and protection of the final crop trees [Daniel et al. 1979]. This involves an initial seed cut followed by one or more removal steps after regeneration has occurred.

The LT_jRX_k combination creates the LP decision variable. The company makes this assignment only once, and LT_j remains under RX_k management for every period in the planning horizon. This is a Model I type LP formulation [Johnson and

	Standards for tree size				Standards for canopy closure		
WHR	WHR size class	Conifer crown diameter	Hardwood crown diameter	dbh	WHR	WHR closure class	Ground cover (canopy closure)
1	Seedling tree	n/a	n/a	<1″	S	Sparse Cover	10–24%
2	Sapling tree	n/a	<15′	1″–6″	O	Open Cover	25–39%
3	Pole tree	<12′	15′–30′	6″–11″	M	Moderate Cover	40–59%
4	Small tree	12′–24′	30′–45′	11″–24″	D	Dense Cover	60–100%
5	Medium/large tree	>24′	>45′	>24″	PALCO crosswalk to habitat stage		
6	Multilayered tree	Size class 5 trees over a distinct layer of size class 4 or 3 trees, total tree canopy exceeds 60% closure			Open		1
					Young		2S-2D, 3S-3D
					Midsuccessional		4S-4D, 5S,5P
					Late Seral		5D, 5M, 6D

Table 2: PALCO designates habitat stages using the California Wildlife Habitat Relationships (WHR) system, combining WHR Size Class (1–6) codes with WHR Closure Class (S, O, M, D) codes. For example, a combined WHR code 4M represents a small-tree-size class having a moderate cover-canopy closure. This 4M code then falls within PALCO's midsuccessional habitat stage. Land types within the management unit achieve the respective stages by period as they progress through the growth-and-yield simulation.

Scheurman 1977] in which the LT remains intact throughout the planning horizon. This contrasts to the Model II formulation that allows the redelineation of LTs from period to period as those acres are regeneration harvested. Subsequent period yield streams (contribution coefficients), in units per acre, reflect the activities associated with RX_k (Table 1). The company generates these yield streams for all ST-RX combinations in the growth-and-yield simulation model (Figure 2), and it constructs associated database tables for overall and individual tree species for harvest, growth, gross revenue, logging costs (cable, tractor, helicopter), silvicultural costs, starting and midperiod inventory, and forest structure. It then joins the land type table to the respective yield tables, using the ST name as the primary key, and the RCM Query generates decision variables and contribution coefficients for all allowable LT_jRX_k combinations.

Wildlife- and Fisheries-Habitat Conservation and Enhancement

It is impossible to establish habitat objectives for every wildlife species that occupies or is likely to occupy the management unit. This would be a combinatorial nightmare, and also different wildlife species often compete for the same resource base. Instead, we manage for one or several indicator species under the assumption that habitat suitable for the indicator species will also be suitable for associated species. One such species is the northern spotted owl (*Strix occidentalis caurina*), for which the Endangered Species Acts also mandate specific management. Spotted owls like large trees in dense stands, as do many predator bird species. This habitat provides ideal nesting sites, protective cover, and elevated perches from which to search for prey. Unfortunately, this is the same habitat that provides the most valuable logs. Thus, it is imperative that all stakeholders—landowners, planners, special interest groups, and agencies—understand the environmental and economic effects of designing a particular wildlife-habitat objective or constraint.

Habitat modeling begins with the definition and delineation of habitat types, or stages. PALCO has adopted the California WHR system and has synthesized these stages into four modeling stages: open, young, midsuccessional, and late seral (Table 2). Grasslands and areas with small seedlings characterize the open stage. Small-prey species occupy these areas and provide a food source for predator bird species. The young stage consists of sapling and pole trees less than 11 inches dbh, while the midsuccessional stage comprises small-to-medium trees in dense stands that are greater than 11 inches dbh. The late-seral stage is characterized by stands greater than 24 inches dbh with high-canopy closure. We developed these modeling stages and specified percentages of retention or development in each stage to provide for spotted owl and other mammal and bird species. The model addresses the spotted-owl habitat primarily through constraints on late-seral-stage development (appendix). In addition to the late-seral stage, spotted owl also like WHR stages 4M and 4D, which we classified in the midsuccessional modeling stage.

Initially, we modeled owl habitat separately and constrained on late seral as well. After detailed sensitivity analyses and LP runs, we determined—with the approval of the CDF—that constraining on the four synthesized stages alone best provided overall for owl habitat and for habitat for other wildlife species, present or potentially present, in the management unit. In the "preferred alternative" LP scenario, which we used in the SYP we submitted to the CDF, our objectives were to maintain or develop a minimum of five percent of the area within each WAA in the first three stages (open, young, and midsuccessional) and 10 percent in the late-seral stage.

Constraining on the four synthesized stages alone best provided overall for owl habitat.

Wildlife habitat is dynamic in both the real ecosystem and the Ep(x) modeling environment. A 20,000-acre requirement of late-seral habitat per period does not mean that those identical acres have to be preserved from period to period. We do, however, provide in the RCM model for buffer zones around the known nesting sites of endangered species, such as the spotted owl and the marbled murrelet (*Brachyramphus marmoratus*). We perform spatial integration of wildlife habitat analysis within the long-term planning model in the GIS after the LP solution has been mapped. Wildlife biologists analyze the spatial distribution of the various habitat types for each period to determine reasonableness with respect to fragmentation, edge effect (the fractal properties of the perimeters of habitat polygons), and probabilistic distribution over the WAAs and management unit [Davis and Barrett 1992].

To illustrate the cost of providing late-seral habitat, the difference between 10 percent and zero percent to the present net worth (at a six-percent discount rate) is $55 million for the management unit. Ten percent of the management unit is 20,000 acres. A spotted owl has an average home range—the area an individual animal uses during its usual and seasonal activities [Zeiner et al. 1988]—of 450 acres. Twenty thousand acres provides for approximately 44 individuals, or 22 nesting pairs. This equals about $2.5 million per pair—and goes to the heart of the spotted-owl controversy.

PALCO's management unit is on high-site-productivity land, and because of responsible past forest management and logging practices, its lands currently exceed the 10 percent of late-seral stage habitat required at the overall management-unit level. Several of the individual WAAs, however, are not at this level and must be brought into conformance at the earliest-possible time period. Because of this need and because of the high cost of providing this late-seral-habitat type, we developed the LSL prescription group. We wanted to test the hypothesis that designing the LSL prescription group and applying it to the landscape would result in greater acreages of late-seral habitat being created and maintained than would be realized if no harvesting were allowed over the same areas. To test this hypothesis and to determine the maximum levels of late-seral-habitat acres that PALCO could generate in the overall management unit over the planning horizon, we first performed a database query to determine the number of acres of late-seral habitat in each period. We could do this because each LT had only one assignment possibility, namely LT_jRX_l (no harvest). We then designed an LP run with the objective function maximizing discounted late-seral-habitat acres. The only constraint we imposed was on sustained yield production, and we did not specify individual WAA late-seral levels. We allowed only the No_H and all LSL RX group prescriptions in the LT_jRX_k formulations. The results were phenomenal (although not unexpected), and for every period the LSL RX group acres exceeded the No_H acres (Figure 3). Several of the later No_H run periods showed decreases in this habitat. This is due to the mortality of older trees and subsequent influx of seedlings, which pushes down the average dbh, which in turn lowers the habitat-stage classification to midsuccessional. And since the No_H was the only allowable RX, this condition was not manageable under this scenario. We reran the LSL group run with a nondeclining constraint to show that PALCO could also manage for this condition and create more late-seral acres.

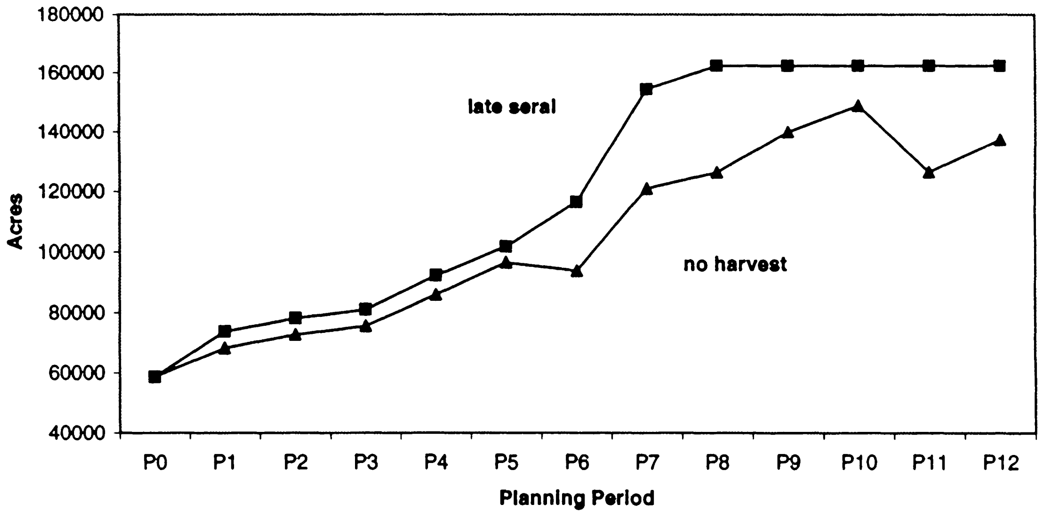
We also wanted to see the effect on PNW of allowing the LSL RX group into the WLPZ buffers, as opposed to just allowing No_H there. There are approximately 28,000 acres within the management unit classified as WLPZ. We ran the preferred alternative with all constraint set limits as submitted to the CDF, maximizing PNW at six-percent discount, with only No_H allowed in WLPZs (scenario 1), and again with No_H plus LSL group in the WLPZs (scenario 2). The difference in PNW over the management unit was equally phenomenal: $105 million.

CDF considered VESTRA to be the only firm in California qualified to conduct all phases of the planning effort.

The Forest Practice Rules require timberland owners to meet certain standards for water quality to protect fish species. We addressed this in the model by attempting to minimize potential sedimentation from both inside and outside the WLPZs. We did this by limiting harvesting within the WLPZs to the LSL RX group, as explained above, and by developing and constraining on the disturbance index (DI). The DI reflects the contribution of the LT_jRX_k and the logging method to potential sedimentation. We developed a contribution coefficient (≤ 1) per acre for each such combination and determined the total cumulative acres by summing the individual indices of each of the harvested acres for that period. We limited the maximum level of such disturbance acres to 25 percent of the individual WAA acres. In addition, we set constraints (generally at a maximum of 10 percent) on the allowable percentage of acres harvested using the clearcut RX group both at the management-unit and WAA levels. These constraints precluded large bare tracts of land contributing to excessive runoff and sedimentation.

Assessments and Benefits

We began developing Ep(x) in 1995 and implemented it at PALCO late that year. PNW (at six-percent discount over the 120-year planning horizon) has been in-



	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
late seral	58673	73742	78121	80990	92182	101686	116429	154322	162324	162324	162324	162324	162324
no harvest	58673	68293	72726	75596	85904	96469	93695	120993	126330	139943	148833	126454	137382

Figure 3: Potential late-seral acres can be achieved over the planning horizon in earlier periods and in larger expanses using the late-seral silvicultural prescription group (LSL) and maximizing nondeclining discounted late-seral-habitat acres. In addition, significant revenues can be simultaneously attained. The acres in the no-harvest condition decrease periodically because of the mortality of older trees and subsequent influx of seedlings.

creased by over $398 million due primarily to the shift from predominantly selection management to predominantly even-aged management, based on the model outputs, and from the development and implementation of the LSL RX set in stream zones ($105 million alone). Average annual net revenues have increased by over $29 million in 1996 and 1997 and sustained-yield annual-harvest levels by 56 million board feet (the board-foot unit of measurement is a board having the dimensions 12 in. by 12 in. by 1 in.). This increase in harvest levels has also resulted in uncalculated but significant increases in economic and social benefits to the local mill communities. Short-term harvest strategies at PALCO have also been improved, since local foresters now have first-decade harvest maps from which to implement their individual timber-harvest plans.

We anticipate that PALCO will realize increased revenues of this magnitude annually. The sustained yield plan, however, is dynamic and subject to many forces. Market supply and demand—at local, regional, and global levels—will continue to fluctuate and render prior solutions obsolete. Logging costs and changes in environmental regulations will have similar effects. For each significant change in an input factor, PALCO performs many alternative LP runs to assess the impact on earnings and the environment. As a result, the firm will continually revisit its short-, mid-, and long-term strategies. But while changes in input factors will require constant sensitivity analyses, the Ep(x) methodology endorsing sustained yield management and maintenance and enhancement of primary wildlife habitats will drive the revised plans. Thus while earnings may fluctuate, the forest ecosystem itself will remain under sound ecological management as approved in the original SYP, which must be resubmitted every 10 years.

PALCO has also used the Ep(x) model in appraising and acquiring land. Running the model solely on the potential acquisition, and, again, combined with the existing management unit, allows it to properly appraise the synergistic contribution of the new property. PALCO is also using the model results at the corporate level to better explain to commercial banks the nature of PALCO's business, and we believe it will secure better loan terms than it might without a long-term plan.

Since approving PALCO's use of the LSL RX group prescriptions in WLPZs, and since PALCO submitted its sustained yield plan, the CDF has contracted with VESTRA Resources to use the Ep(x) model to conduct the long-term planning efforts for California's Jackson Demonstration State Forest. It considered VESTRA to be the only firm in California qualified to conduct all phases of the planning effort. Success in this endeavor could result in a blueprint for the management of all state forestlands. VESTRA has used Ep(x) to plan the management of Louisiana-Pacific and Hearst Corporation timberlands with results similar to PALCO's. In addition, we have developed an academic version of Ep(x), which is currently undergoing beta testing at Northern Arizona University. This abbreviated model allows future foresters and wildlife biologists to design the management actions to manage the forests of the future and to become familiar at the analytical level with the sets of constraint and objectives that they will face in real-world planning.

By developing and implementing Ep(x) and the LSL silvicultural prescriptions for accelerated generation of wildlife habitat, particularly the spotted owl, we have shown that the forest products industries can coexist with wildlife and contribute to their habitats. We have shown this not only in generating PALCO's sustained-yield plan but also in analyzing the management of the state forest and the other companies' timberlands. In all cases, we have been able to increase and control wildlife-habitat acreages better than the models our customers previously used.

Ep(x) is not limited to implementation on forestlands in the West or Pacific-Northwest. It can readily accommodate all strata types and land types, and we can readily adapt the wildlife-habitat coding and constraint-set generation to endangered or indicator species at regional, national, or global levels. We can also modify the silvicultural management technology and strategies used to increase wildlife habitats on PALCO lands to accommodate most other wildlife species throughout the globe. How much is the additional wildlife that will occupy these new niches worth? What are the additional social and environmental benefits worth? These questions cannot be answered in terms of dollars, but rather in terms of increased quality of life for future generations.

Acknowledgments

We thank Lawrence S. Davis, professor emeritus of forest ecosystem management at the University of California at Berkeley, for his contribution to the initial design concept of the Ep(x) model and for constructing data sets for the demonstration software. Larry has been both a mentor and friend to most of us and has produced many of the leading scientists, analysts, and managers in the field today. We also thank the professional forestry staff at PALCO, and CEO John Campbell for his wisdom and insight in pursuing and funding the Ep(x) technology.

We greatly appreciate the continued support of the staff at Ketron Management Science, in particular Tom Dehne, in helping us to fully utilize the MPSIII, C-WHIZ LP solver. As our problems increased in size and complexity over the years, they continued to develop the new features and provide the support we needed to solve these large-scale problems rapidly. We also thank the professional staff and managers at the California Department of Forestry and Fire Protection for their evaluation of PALCO's SYP. And we appreciate the input of all the special interest groups and concerned citizens who have taken time from their private lives to participate in the SYP public hearing process.

APPENDIX

Resource Capability Model Constraints

Certain RCM constraints, whether biological or policy constraints, either can be accommodated directly in the RCM Query (Figure 2) or can be handled as any other constraint within the LP model formulation. For instance, one policy-related constraint specifies that for LTs on steep slopes only RX_l (no harvest) is allowed. This is not mandated by law; however, PALCO has adopted this policy to minimize sedimentation and to preserve viewshed aesthetics. For each such LT, the logical and most efficient way to handle this constraint is to filter out all LT_jRX_k decision variables except LT_jRX_l within the RCM Query, excluding them from the LP model formulation. If, however, we anticipate wanting to lift this restriction occasionally in our sensitivity analyses—for instance, if we want to see the effect on PNW with and without this restriction—we can bring all otherwise allowable LT_jRX_k decision variables into the LP model formulation and define an accounting variable and associated constraint as follows:

Data: $SLPINST(u)$ = unstable slope code $(u) = 1$, else 0.

Accounting variable: $SLOPE_i = \Sigma LT_jRX_k$ $\forall i$, $\forall j$ where $SLPINST = 1$ for LT_j, and $\forall k \neq 1$.

Constraint: $SLOPE_i = 0\ \forall_i$, when we want to constrain harvesting on steep slopes within the LP.

By creating $SLOPE_i$, we avoid having to run the RCM Query and the MPS/MATRIX generator a second time to evaluate the effect on PNW.

Other such RCM constraints that are handled in the RCM Query but could be brought into the LP formulation by using accounting variables are the following:

—WLPZ buffer LTs are allowed only No_H, LSL, and SEL RX groups,

—Wildlife corridor LTs are allowed only No_H, LSL, and SEL RX groups,

—Viewshed LTs are allowed only No_H, LSL, and SEL RX groups,

—Grasslands (on grassland soil types) are to remain as such with No_H,

—Parks, recreation, and archeological sites are allowed only No_H,

—Yarding methods are restricted on unstable soils,

—Buffer zones surrounding known endangered wildlife species are allowed only No_H.

Data for the Growth-and-Yield Simulation

HC_{ijk} = harvest-yield contribution in mbf per acre of LT_jRX_k combination in period i, where mbf = 1,000 board feet,

GC_{ijk} = growth-yield contribution in mbf per acre of LT_jRX_k combination in period i,

IC_{ijk} = standing-inventory-yield contribution in mbf per acre of LT_jRX_k combination in period i,

RC_{ijk} = net-revenue-yield contribution in dollars per acre of LT_jRX_k combination in period $i = GR_{ijk} - LC_{ijk} - SC_{ijk}$,

GR_{ijk} = gross-revenue-yield contribution in dollars per acre of LT_jRX_k combination in period i,

LC_{ijk} = logging-cost contribution in dollars per acre of LT_jRX_k combination in period i,

SC_{ijk} = silviculture-cost contribution in dollars per acre of LT_jRX_k combination in period i,

DX_{pijk} = disturbance-index contribution ($\leq$1) per acre of LT_jRX_k combination in WAA_p in period i,

$MAIC_{jk}$ = mean annual increment contribution of growth in mbf per acre of LT_jRX_k combination,

A_j = area in acres of each LT_j,

$TA = \sum_{j \in J} A_j$ = total acres in management unit,

WA_p = total acres in WAA_p,

$WHROWL(n)$ = wildlife-habitat-relationships (WHR) codes (n) designating owl-habitat types in each period i for each LT_jRX_k combination, where $n = N$ for nesting, R for roosting, and F for foraging,

$WHRSER(s)$ = WHR codes (s) designating seral stages in each period i for each LT_jRX_k combination, where $s = O$ for open, Y for young, M for midsuccessional, and L for late seral,

$OWLN_{pijk}$ = 1 per acre of LT_jRX_k combination in WAA_p in period i if $WHROWL(n)$ code = N,

$SERO_{pijk}$ = 1 per acre of LT_jRX_k combination in WAA_p in period i if $WHRSER(s)$ code = O,

$SERY_{pijk}$ = 1 per acre of LT_jRX_k combination in WAA_p in period i if $WHRSER(s)$ code = Y,

$SERM_{pijk}$ = 1 per acre of LT_jRX_k combination in WAA_p in period i if $WHRSER(s)$ code = M,

$SERL_{pijk}$ = 1 per acre of LT_jRX_k combination in WAA_p in period i if $WHRSER(s)$ code = L,

$RNoH_{pijk}$, $RLSL_{pijk}$, $RSEL_{pijk}$, RCC_{pijk}, $RCTST_{pijk}$, and $RSHL_{pijk}$ = silvicultural prescription groups "no harvest," "late-seral emphasis," "selection," "clearcut," "commercial thin/seed tree," and "shelterwood" = 1 per acre of LT_jRX_k combination in WAA_p in period i if RX_k falls within group,

$MMSTAND(t)$ = marbled murrelet codes (t) where t = 1 designates initial old growth LTs, else 0, OG = total initial old-growth acres, where $MMSTAND(t)$ = 1.

Policy Data

dr_i, dh_i, do_i, ds_i = revenue, harvest, owl-habitat, and late-seral discount-rate coefficients in period i,

ow = minimum percent of total management unit and WAA acres to be maintained in owl-nesting habitat, WHROWL(N),

sl = minimum percent of total management unit and WAA acres to be maintained in late-seral-habitat stage, WHRSER(L),

sr = minimum percent of total management unit and WAA acres to be maintained in open, young, and midsuccessional seral-habitat stages, WHRSER(O, Y, M),

h = percent allowable increase or decrease of harvest levels between periods,

iv = percent allowable increase or decrease of inventory levels between periods,

$old1$ = maximum percent of old-growth acres that can be harvested in period 1,

$old2$ = maximum percent of old-growth acres that can be harvested in periods 1 + 2,

dix = maximum percent of total management unit and WAA that can be in disturbance acres,

ccx = maximum percent of total management unit and WAA acres to be harvested using the clearcut (CC) RX group,

I = number of planning periods,

J = number of land types,

K = set of silvicultural prescriptions,

P = set of WAAs,

$Hmin$ = minimum harvest-volume level per period i, in mbf,

$Hmax$ = maximum harvest-volume level per period i, in mbf,

$Imin$ = minimum inventory level per period i, in mbf,

$Imax$ = maximum inventory level per period i, in mbf,

$Rmin$ = minimum nondiscounted net revenue per period i, in dollars.

Decision Variables

LT_jRX_k = Acres of land type j under silvicultural prescription k. This assignment is made only once, and LT_j remains under RX_k management for every period in the planning horizon. Subsequent period yield streams reflect the activities associated with RX_k.

Accounting Variables

$PNW = \sum_{i \in I} dr_i R_i$ = present net worth—total discounted period net revenue in dollars,

$H_i = \sum_{j \in J} \sum_{k \in K} HC_{ijk} LT_j RX_k \ \forall i$ = harvest in period i in mbf,

$G_i = \sum_{j \in J} \sum_{k \in K} GC_{ijk} LT_j RX_k \ \forall i$ = growth in period i in mbf,

$IN_i = \sum_{j \in J} \sum_{k \in K} IC_{ijk} LT_j RX_k \ \forall i$ = standing inventory in period i in mbf,

$MAI = \sum_{j \in J} \sum_{k \in K} MAIC_{jk} LT_j RX_k$ = total mean annual increment in mbf,

$R_i = \sum_{j \in J} \sum_{k \in K} RC_{ijk} LT_j RX_k \ \forall i$ = net revenue in period i in dollars,

$W_pDI_i = \sum_{j \in J} \sum_{k \in K} DX_{pijk} LT_j RX_k \ \forall p, i$ = cumulative disturbance acres in WAA_p in period i,

$DI_i = \sum_{p \in P} W_pDI_i \ \forall i$ = cumulative disturbance acres in period i at overall management unit,

HOG_i = old-growth acres harvested in period i,

$W_pOWL_i = \sum_{j \in J} \sum_{k \in K} OWLN_{pijk} LT_j RX_k \ \forall p, i$ = owl-nesting habitat in WAA_p in period i in acres,

$OWL_i = \sum_{p \in P} W_pOWL_i \ \forall i$ = owl-nesting habitat in period i at overall management unit in acres,

$W_pO_i, \ W_pY_i, \ W_pM_i, \ W_pL_i = \sum_{j \in J} \sum_{k \in K} SERO_{pijk} LT_j RX_k, \ldots, \sum_{j \in J} \sum_{k \in K} SERL_{pijk} LT_j RX_k \ \forall p, i$ = seral stages in WAA_p in period i in acres,

$O_i, Y_i, M_i, L_i, = \sum_{p \in P} W_pO_i, \ldots, \sum_{p \in P} W_pL_i \ \forall i$ = seral stages in period i at overall management unit in acres,

$W_pNoH_i, W_pLSL_i, W_pSEL_i, W_pCC_i, W_pCTST_i, W_pSHL_i = \sum_{j \in J} \sum_{k \in K} RNoH_{pijk} LT_j RX_k, \ldots, \sum_{j \in J} \sum_{k \in K} RSHL_{pijk} LT_j RX_k \ \forall p, i$ = silvicultural-prescription groups in WAA_p in period i in acres,

$NoH_i, LSL_i, SEL_i, CC_i, CTST_i, SHL_i = \sum_{p \in P}$

$W_pNoH_i, \ldots, \quad \sum_{p \in P} W_pSHL_i \quad \forall i$ = silvicultural-prescription groups in period i at overall management unit in acres.

Objective Functions

We have run the model with each of the following objective functions:

Maximize present net worth (PNW)

$$Z = PNW. \tag{1}$$

Maximize harvest volume

$$Z = dh_iH_i \quad \forall i, \tag{2}$$

$$Z = H1. \tag{3}$$

Maximize wildlife habitat

$$Z = do_iOWL_i \quad \forall i, \tag{4}$$

$$Z = ds_iL_i \quad \forall i. \tag{5}$$

Timber-Resource Constraints

Harvest flow

$$H_{i+1} \geqslant (1 - h)^*Hi, \quad i = 1, 2, \ldots, I - 1, \tag{6}$$

$$H_{i+1} \leqslant (1 + h)^*Hi, \quad i = 1, 2, \ldots, I - 1, \tag{7}$$

$$H_i \geqslant Hmin, \quad \forall i, \tag{8}$$

$$H_i \leqslant Hmax, \quad \forall i, \tag{9}$$

$$H_i \leqslant MAI, \quad \forall i, \tag{10}$$

$$H_i \leqslant G_i, \quad \forall i. \tag{11}$$

Inventory control

$$IN_{i+1} \geqslant (1 - iv)^*INi, \quad i = 1, 2, \ldots, I - 1, \tag{12}$$

$$IN_{i+1} \leqslant (1 + iv)^*INi, \quad i = 1, 2, \ldots, I - 1, \tag{13}$$

$$IN_i \geqslant Imin, \quad \forall i, \tag{14}$$

$$IN_i \leqslant Imax, \quad \forall i, \tag{15}$$

$$IN_I \geqslant IN_1. \tag{16}$$

Cash flow

$$R_i \geqslant Rmin, \quad \forall i. \tag{17}$$

Area accounting

$$\sum_{k \in K} LT_jRX_k = A_j, \quad \text{for each } j. \tag{18}$$

Wildlife-Resource Constraints

$$\mathrm{OWL}_i \geqslant \mathrm{ow}^*\mathrm{TA}, \quad \forall i \text{ feasible}, \tag{19}$$

$$\mathrm{OWL}_i \geqslant \mathrm{OWL}_{i-1}, \quad \forall i \text{ infeasible in (19)}, \text{ where } \mathrm{OWL}_0 \text{ is initial condition}, \tag{20}$$

$$\mathrm{W}_p\mathrm{OWL}_i \geqslant \mathrm{ow}^*\mathrm{WA}_p, \quad \forall p, \text{ and } \forall i \text{ feasible}, \tag{21}$$

$$\mathrm{W}_p\mathrm{OWL}_i \geqslant \mathrm{W}_p\mathrm{OWL}_{i-1}, \quad \forall p, \text{ and } \forall i \text{ infeasible in (21)}, \tag{22}$$

$$\mathrm{O}_i \geqslant \mathrm{sr}^*\mathrm{TA}, \quad \forall i, \tag{23}$$

$$\mathrm{Y}_i \geqslant \mathrm{sr}^*\mathrm{TA}, \quad \forall i, \tag{24}$$

$$\mathrm{M}_i \geqslant \mathrm{sr}^*\mathrm{TA}, \quad \forall i, \tag{25}$$

$$\mathrm{W}_p\mathrm{O}_i \geqslant \mathrm{sr}^*\mathrm{WA}_p, \quad \forall i, p, \tag{26}$$

$$\mathrm{W}_p\mathrm{Y}_i \geqslant \mathrm{sr}^*\mathrm{WA}_p, \quad \forall i, p, \tag{27}$$

$$\mathrm{W}_p\mathrm{M}_i \geqslant \mathrm{sr}^*\mathrm{WA}_p, \quad \forall i, p, \tag{28}$$

$$\mathrm{L}_i \geqslant \mathrm{sl}^*\mathrm{TA}, \quad \forall i \text{ feasible}, \tag{29}$$

$$\mathrm{L}_i \geqslant \mathrm{L}_{i-1}, \quad \forall i \text{ infeasible in (29)}, \text{ where } \mathrm{L}_0 \text{ is initial condition}, \tag{30}$$

$$\mathrm{L}_i \geqslant \mathrm{L}_{i-1}, \quad \forall i, \tag{31}$$

$$\mathrm{W}_p\mathrm{L}_i \geqslant \mathrm{sl}^*\mathrm{WA}_p, \quad \forall p, \text{ and } \forall i \text{ feasible}, \tag{32}$$

$$\mathrm{W}_p\mathrm{L}_i \geqslant \mathrm{W}_p\mathrm{L}_{i-1}, \quad \forall p, \text{ and } \forall i \text{ infeasible in (32)}, \tag{33}$$

$$\mathrm{HOG}_1 \leqslant \mathrm{old1*OG}, \qquad (34)$$

$$\mathrm{HOG}_2 \leqslant \mathrm{old2*OG}. \qquad (35)$$

Watershed and Fisheries Constraints

$$\mathrm{CC}_i \leqslant \mathrm{ccx*TA}, \quad \forall i, \qquad (36)$$

$$\mathrm{W}_p\mathrm{CC}_i \leqslant \mathrm{ccx*WA}_p, \quad \forall i, p, \qquad (37)$$

$$\mathrm{DI}_i \leqslant \mathrm{dix*TA}, \quad \forall i, \qquad (38)$$

$$\mathrm{W}_p\mathrm{DI}_i \leqslant \mathrm{dix*WA}_p, \quad \forall i, p \qquad (39)$$

We formulated most alternatives using the first objective function, maximize present net worth, with a six-percent-discount rate. Objective functions (2) through (5) are used individually to determine the maximum capacity of the management unit with respect to harvest volumes, owl habitat, and late-seral structure. Objective functions (4) and (5) can also be formulated at the WAA level to determine how fast that WAA can be brought up to the minimum acceptable levels.

Constraints (6) and (7) specify minimum and maximum percent changes in harvest levels from one period to the next. These, coupled with the minimum and maximum discrete levels of harvest volumes in constraints (8) and (9), ensure that supply of raw logs to the mill(s) is consistent with mill demand. And along with the cash-flow constraint (17) they all serve to provide stability to the regional economy, since these mills are generally a primary employer to the community.

Constraints (10) and (11) in conjunction with (6) through (9) ensure that the forest will be maintained under sustained-yield management, with harvests flowing from the land in perpetuity. Constraint (10) states that period harvest must be less than the MAI for any period, while (11) states that individual period harvests must also not exceed growth within the same period.

As with the harvest-constraint set, inventory-level percentage increases and decreases, and discrete levels of standing inventories are maintained by constraints (12) through (15). Constraint (16) ensures that ending inventory is greater than starting inventory—another safeguard for ensuring sustained yield. Although constraints (6) through (11) may appear to render constraints (12) through (16) redundant, wildly fluctuating or nondeclining inventory levels can indicate potential problems in the growth-and-yield simulations or in the RCM or PAM models, or can indicate a need to reevaluate various constraint sets. Alternative LP formulations are frequently run initially without constraints (12) through (16) to see if any of these anomalies exist. In sensitivity analyses, inventory levels or percent changes that are at the lower or upper limit for any period are investigated.

The area accounting constraint (18) ensures that for all RX codes assigned to a particular LT, the cumulative assigned acreages do not exceed the area of the LT. This constraint generates the bulk of the rows and greatly increases the density of the LP matrix, since each LT has this constraint (there are over 7,800 LTs in the PALCO management unit). We frequently formulate this constraint as an inequality ($\leqslant$) during sensitivity analyses to evaluate why certain LTs are not assigned any RX code. This indicates unprofitable LTs or potential problems in the growth-and-yield simulations.

Constraints (19) through (22) address owl-nesting habitat at the overall management-unit and individual-WAA levels and specify the minimum desirable acreages in that habitat type over all periods. These levels are not always achievable in the earlier periods, and constraints (20) and (22) state that for all such infeasible periods the level of owl habitat shall be nondeclining until the desired level is reached. Prior to running the final optimization alternative (1), we initially run a nesting alternative as a goal program with severe penalties in the objective function for not attaining the desired levels in the earlier periods. This tells us the earliest time period in which the management unit or WAA can biologically achieve the desired level as well as the maximum attainable levels up to that period. Thus it is known prior to the final optimization run which WAAs cannot achieve the desired levels in which periods.

Constraints (23) through (33) define the structure of the management unit in terms of the diversity of wildlife habitats. While the spotted owl and marbled murrelets, both endangered species, are specifically constrained on, this constraint set addresses maintaining suitable habitats for a variety of other wildlife species in the community. Thus the landscape will generally be required to provide for a minimum of five percent of the acreage in open areas, five percent in young forest areas, five percent in midsuccessional areas, and 10 percent in late seral. This mix ensures a biodiversity that is well distributed across the landscape. Since late-seral habitat, which is similar to owl-nesting habitat, may not be present in certain WAAs in the earlier periods, constraints (30) and (33) serve a purpose similar to (20) and (22). Constraint (31) is generally used with objective function (5).

Constraints (34) and (35) spread out the harvest of PALCO's old-growth stands over the first three periods.

Constraints (36) and (37) limit the percentage of acres within the WAAs and management unit that can be clearcut in any period. Constraints (38) and (39) limit the percentage of acres that can be disturbed, as measured by the interaction of the logging method and the RX on the LT soil properties. Both constraint types limit sedimentation deposits to stream zones, reductions in soil properties, shock to wildlife populations resulting from large harvest areas, and reductions in viewshed aesthetics.

The LP problem size is approximately 8,500 rows and 353,000 columns—a formidable production problem, although we have solved similar problems with almost double the number of rows. The LP solver we use is the MPSIII, C-WHIZ solver by Ketron Management Science. Approximately 50 mb of RAM is required for processing, with a solution time of just over 45 minutes on a 128 mb RAM PC on Windows NT (version 4). The MPS file is approximately 350 mb in size and takes just over 1.5 hours to formulate using the VESTRA-developed MPS generator. Most of the sensitivity analyses are performed using a VESTRA-developed batch-processing shell utility, which makes changes directly to the ACTFILE (Ketron's version of the input matrix in binary form) using the C-WHIZ utility, MPSIN, and starting the next LP run on an advanced basis. These two utilities preclude having to rerun the MPS file for every sensitivity run, and they allow for batch processing of these run sets.

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