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An Assessment of Factors Associated with Damage to Tree Crowns from the 1987 Wildfires in Northern California

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ABSTRACT. Relationships between (1) degree of damage caused by the 1987 fires in northern California and (2) prior management activities, fuelbed characteristics, and site/stand factors were studied on the Hayfork Ranger District of the Shasta-Trinity National Forests. Postfire aerial photography was used to assess scorch and consumption of tree crowns (the selected measure of fire damage), and other data were obtained from existing records. Data were collected and analyzed separately for (1) plantations and (2) uncut and partial-cut stands. Ordinal logistic regression was the primary analytical technique used. Factors significantly related to degree of fire damage in plantations were cover of grasses, cover of forbs, elevation, site preparation method, and level of damage in the adjacent stand. Damage to uncut and partial-cut stands depended on stand treatment, primary tree species, and aspect. The variables that most strongly influenced fire damage tended to be those most directly related to management activities—site preparation method and damage in adjacent stand for plantations, and stand treatment for uncut and partial-cut stands. FOR. SCI. 41(3):430–451.

ADDITIONAL KEY WORDS. Fire damage, plantation protection, site preparation, fuels management, ordinal logistic regression.

SCIENTISTS AND LAND MANAGERS LONG HAVE RECOGNIZED that fuels, topography, and weather are the chief determinants of wildland fire behavior, and that, of these, only fuels can be managed. That understanding, together with awareness of a continuing large-scale fuels buildup associated with human activities (including fire suppression), has prompted numerous calls for improved management of wildland fuels (e.g., Arno and Brown 1989, Countryman 1974, Dodge 1972, Wilson and Dell 1971). Relationships between fuel characteristics and fire behavior associated with the propagating fire front have been defined in a widely applied mathematical fire model (Andrews 1986, Rothermel 1972). Effects of fuels on fire behavior as predicted by the fire model have been tested in a series of experimental fires (Andrews 1980), and are observed and adjusted on a recurring basis by trained fire behavior analysts on actual wildfires (Rothermel 1983).

The Rothermel (1972) fire model has provided the basis for methods of appraising fuels and fuel management alternatives from the standpoint of wildfire hazard (Anderson 1974, Hirsch et al. 1981). A number of simulations have shown the expected influence of fuel treatments and other management activities on

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severity and size of wildfires (e.g., Brown and Johnston 1987, Cohan et al. 1983, Kilgore and Sando 1975, Martin et al. 1989). Several studies have shown reductions in severity of actual wildfires in areas in which prescribed burning had been done previously (Buckley 1992, Cumming 1964, Davis and Cooper 1963, Helms 1979, Moore et al. 1955, Wagle and Eakle 1979), with more recent prescribed burns generally being more effective. Some of these studies also documented reduced suppression difficulty and wildfire size as a result of the prescribed burns. Deeming (1990) reviewed the literature related to cost-effectiveness of prescribed fire for reducing wildfire occurrence and severity. Few studies have attempted to demonstrate effects of fuel conditions or management practices other than prescribed burning on size (Omi 1977, Salazar and Gonzalez-Caban 1987, Wood 1982) or severity (Van Wagner 1968) of actual wildfires. Omi and Kalabokidis (1991) examined tradeoffs between "extensive" and "intensive" management on one of the 1988 Yellowstone fires, but did not quantify the effects of management or fuels on fire severity.

In the wake of the wildfires that burned extensive areas of California forests during late summer and fall of 1987 following a prolonged drought (Reider 1988), we undertook a large-scale study to determine relationships between (1) degree of damage caused by the 1987 wildfires, and (2) prior management activities, fuelbed characteristics, and site/stand factors that might be expected to influence fire behavior and associated fire effects. We attempted neither to evaluate effects of these factors on amount of area burned nor to conduct an economic assessment of costs and benefits of management activities from the standpoint of wildfire hazard.

METHODS

STUDY AREA

The study site on the Hayfork Ranger District of the Shasta-Trinity National Forests, in northwestern California, included an extensive area burned by the 1987 wildfires. At least 20 separate fires, totaling approximately 20,000 ha and covering a wide range of terrain, vegetation, burning conditions, and fire behavior, occurred on the District.

The Hayfork District is located in the Klamath Mountains physiographic province. The burned area is situated in the extensive watershed of the South Fork Trinity River and varies in elevation from approximately 600 to 1500 m. About half the area has slopes greater than 40%. Douglas-fir–Tanoak–Pacific Madrone (SAF forest cover type 234) is the dominant forest type in the western portions of the District, grading to Pacific Ponderosa Pine–Douglas-fir (SAF 244) and Sierra Nevada Mixed Conifer (SAF 243) in the east (Eyre 1980). Additional information about the areas burned was reported by Miles et al. (1989).

Besides fire suppression, management activities having the greatest effect on fuelbeds on the Hayfork District have been timber harvesting, fuel treatment or lack of it, site preparation for regeneration, and plantation establishment and maintenance. Timber harvests began on a significant scale in the 1940s. Until the early 1960s, harvests consisted mostly of partial cuts, prescribed for sanitation salvage and overstory removal, and yarded by tractors on terrain generally less than 40% slope. Many stands were left understocked or dominated by trees in poor condition to respond to release. Virtually no fuel treatment took place following partial cutting during those years. However, within 4 of the 26 management compartments impacted by the 1987 fires, fuel treatments were conducted subsequently in some stands.

In the early 1960s, foresters began to prescribe clearcuts to regenerate understocked or overmature stands. Considerable clearcutting has continued since then, using both cable and tractor yarding. On most tractor-yarded units, slash has been piled by tractors and then burned. On cable-yarded units and on some of the steeper tractor-yarded units, broadcast burning of slash, usually during the fall, has been the site preparation treatment of choice.

In recent years, however, concerns over air pollution from burning and adequate retention of soil cover and large woody debris have led managers to forego site preparation and plant through untreated slash on some units. Depending on the site, clearcut units generally have been planted either with ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) or Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) seedlings, or combinations of the two species. Until the early 1980s, plantations routinely were sprayed with herbicides to release conifer seedlings from a wide variety of competing plant species. Since then, restrictions on use of herbicides have led to fewer plantations being released, and those mostly with hand tools. No recorded precommercial thinning was done in plantations affected by the 1987 fires.

GENERAL APPROACH AND SELECTION OF VARIABLES

The retrospective nature of the study dictated that we derive data from postfire aerial photography and from existing data bases and records. We undertook no field-based verification of these data or collection of new data. To do an adequate job of on-site sampling of the large area and great diversity of conditions included in our study would have required time and resources far beyond those available to us. Furthermore, for some variables and for many locations, data could not have been retrieved on the ground after the fires.

We used two sets of postfire aerial photos, both at a nominal scale of 1:15,840, for assessing fire damage as well as for other purposes related to the study. A set of color photos was taken approximately 1 month after the fires, and a set of color infrared photos was taken 8 months after the fires.

We included in the study all plantations and other (uncut and partial-cut) stands on productive forestland that burned in the major Hayfork fires of 1987. This comprised 246 plantations, totaling approximately 970 ha, and 874 other stands, totaling about 13,000 ha. Data on plantations were collected and analyzed separately from those on uncut and partial-cut stands because stand and fuelbed conditions, susceptibility to fire damage, and nature of the available data varied substantially between these groups.

We selected a measure of fire damage that could be interpreted reasonably consistently on aerial photos—scorch or consumption of tree crowns. Crown scorch is closely associated with fireline intensity (Van Wagner 1973). It also is one of the major determinants of tree damage and mortality (Ryan 1982, Wagener 1961), which, along with canopy opening resulting from crown scorch, affect numerous other ecosystem components and processes. Crown scorch, therefore, also has reasonable relevance to other kinds of fire effects on resources. Percent of trees having substantial crown scorch (at least 50% scorch on individual trees for it to be readily apparent on aerial photos) or crown consumption was the basis for defining the following fire damage classes (FDCs):

0 No burn—used only for plantations in which fire burned to the edge but not through most of the plantation because of fuel conditions in the plantation, not because of barriers such as firelines
1 Light underburn—less than 10% of trees with 50% or more crown scorch
2 Moderate damage—10 to 50% of trees with 50% or more crown scorch
3 Heavy damage—greater than 50% of trees with 50% or more crown scorch, less than 50% of trees with crowns consumed
4 Extreme damage—greater than 50% of trees with crowns consumed

Equivalent fire behavior ranges from a low-intensity surface fire in FDC 1, through a moderate-to-high-intensity surface fire with intermittent torching in FDCs 2 and 3, to extensive torching and crowning in FDC 4. In uncut and partial-cut stands with more than one canopy layer, overstory trees were assessed for crown scorch. Despite the somewhat subjective nature of the classification system, we found few borderline situations: practically all plantations and stands could be rated readily and consistently, even by different observers.

For each of the two groups of stands, a set of independent variables that seemed (1) related to fire damage and (2) probably available from existing records was determined. Some of these original variables subsequently were modified or dropped because available data were inadequate (Table 1). In all cases, data for the independent variables were derived separately and independently from FDCs.

A basic concern was that potential effects of the independent variables on fire damage might be masked by high variability in the data, due largely to unknown weather-related burning conditions. The Hayfork fires burned mostly during September under a wide variety of burning conditions—from strong daytime winds to high-humidity stagnant conditions beneath inversions. Unfortunately, however, those conditions cannot be reconstructed for any given time and place. Much of the area burned during the first few days of the fires, when smoky inversions and shortages of people and equipment [because of numerous concurrent fires in California and Oregon resulting from widespread lightning ignitions (Reider 1988)] prevented knowledge of their location or extent. We attempted to deal with this problem in two ways: First, we assumed that burning conditions may have been more similar among nearby stands than among widely separated stands. Therefore, we took advantage of the management compartments into which plantations and other stands were grouped by using compartments as dummy variables in the analysis with the hope that they might help to explain some of the observed variability. Second, for plantations, we assigned a FDC to the adjacent stand from which the fire apparently came, as well as to the plantation itself. This supplementary rating provided the best available measure of local burning conditions and thus another means of accounting for some of the variability.

DATA COLLECTION FOR PLANTATIONS

We identified plantations located within the 1987 fires initially from maps prepared in connection with postfire plantation surveys, and then verified this list using aerial photos. We used a wide variety of District records, supplemented by

TABLE 1.

Original set of independent variables for plantations and uncut/partial-cut stands. Variables retained in the final data set are indicated. Others were dropped because available data were inadequate.

Variable	Retained in final data set
Plantations	
Compartment	X
Size	X
Elevation	X
Aspect	X
Slope	X
Year logged	X
YUM (yarding unmerchantable material)	X
Year of site preparation	X
Method of site preparation	X
For broadcast burned units:	
Month of burn	
Severity of burn	
Residual fuel loading	
Year planted (most recently if replanted)	X
Species planted	X
Initial density of planted trees	X
Year of release (and rerelease if relevant)	
Method of release (and rerelease if relevant)	
Year of precommercial thinning	
Slash treatment following precommercial thinning	
Vegetation variables:	
Species, cover, and height of dominant woody and herbaceous competing plants[a]	X
Fire damage class for adjacent stand (in direction from which fire apparently came)	X
Uncut/partial-cut stands	
Compartment	X
Size	X
Elevation	X
Aspect	X
Slope	X
Primary tree species (forest type)	X
Secondary tree species	X
Crown size class	X
Density (crown cover)	X
Partial-cut or uncut[b]	X
Year of most recent harvest entry	
YUM (yarding unmerchantable material)	
Method of fuel treatment, if any[b]	X
Year of fuel treatment	
Loading of woody fuels after harvest or, if applicable, after fuel treatment:	
0- to 7.6-cm fuels	X
>7.6-cm fuels	X

[a] On the basis of available data, these variables were converted to the 9 vegetation variables shown in Table 2. Height was dropped for lack of data.

[b] No fuel treatment was done in uncut stands. In the relatively few treated partial-cut stands, method of treatment was found to be unimportant. Therefore, uncut/partial-cut status and fuel treatment were combined into a single variable—stand treatment—with three classes: (1) uncut/untreated, (2) cut/treated, and (3) cut/untreated.

knowledge of present and past District employees, to derive data for the various site and plantation attributes, including management history (Table 1). The nature and apparent quality of information about competing vegetation in plantations varied widely. However, the potential importance of this vegetation with respect to flammability of plantations, and the variety of species or species groups referred to in the records, prompted us to expand our characterization of vegetation beyond the original attributes in Table 1. Nine new vegetation variables were developed by grouping species or species groups for which data were available, according to growth form (herbs, shrubs, hardwoods) and our estimate as to their relative flammability (Table 2). A classification system that indicates cover or abundance of each vegetation variable (Table 2) was defined in both quantitative and qualitative terms to accommodate differing types of information occurring in various records.

A FDC for each plantation was determined using both the color and color infrared aerial photos. Descriptions of fire damage included in postfire surveys were used when available—for approximately 10% of plantations—to check and calibrate the photo-based ratings.

Preliminary study of the aerial photos indicated that the pattern of fire damage

TABLE 2.

Vegetation variables listed in order of increasing estimated flammability within each of three growth forms, and the four cover classes used to characterize the cover or abundance of each vegetation variable.

Variable name	Species or species groups
Herbs	
GRASSES	grasses—both annuals and perennials
FORBS	forbs (including bracken fern), except thistles
CIR	thistles (*Cirsium* Mill. spp.)
Shrubs	
SHR_LOW	deerbrush (*Ceanothus integerrimus* H. & A.) *Ribes* L. spp. *Rubus* L. spp. hazel (*Corylus cornuta* Marsh. var. *californica* [A. DC.] Sharp.)
SHR_MED	whiteleaf manzanita (*Arctostaphylos viscida* Parry.) whitethorn (*Ceanothus cordulatus* Kell.)
SHR_HIGH	greenleaf manzanita (*A. patula* Greene.) snowbrush (*Ceanothus velutinus* Dougl. ex Hook.) buckbrush (*Ceanothus cuneatus* [Hook.] Nutt.)
Hardwoods	
HDW_LOW	canyon live oak (*Quercus chrysolepis* Liebm.) interior live oak (*Q. wislizeni* A. DC.)
HDW_MED	tanoak (*Lithocarpus densiflorus* [Hook. & Arn.] Rehd.) Pacific madrone (*Arbutus menziesii* Pursh) golden chinkapin (*Castanopsis chrysophylla* [Dougl.] A. DC.)
HDW_HIGH	California black oak (*Q. kelloggii* Newb.)
Cover Classes	
0	not listed as present in that plantation
1	1–20% cover, or "light"
2	21–50% cover, or "moderate"
3	51–100% cover, or "heavy"

within plantations varied significantly. Accordingly, an additional dependent variable—uniformity of damage—was used to record whether the damage appeared (1) relatively uniform within the plantation, (2) spotty or patchy, (3) decreasing in severity from the edge inward, or (4) increasing in severity from the edge inward.

The aerial photos also were used to assess the degree of damage in the adjacent stand in the direction from which the fire apparently came. The direction of fire movement in the vicinity of each plantation was estimated using indicators such as topography and patterns of crown scorch.

DATA COLLECTION FOR UNCUT AND PARTIAL-CUT STANDS

We used polygons characterized in the Shasta-Trinity National Forests' Geographic Information System (GIS) to represent uncut and partial-cut stands in this study. The polygons, which were based on timber type maps, provided most of our data related to topography and stand characteristics (Table 1). The GIS contained no information, however, regarding the locations of the 1987 wildfires. We therefore made our own determination, using fire maps and the postfire aerial photos, of stands located within the fires. The following additional criteria were used to select the final set of stands for inclusion in the study: (1) stand was typed as productive timberland, (2) stand had ponderosa pine or Douglas-fir as the primary species (very few stands had other primary species designations), and (3) stand had a crown diameter size class equivalent to 1.8 m or larger (smaller crowns were restricted to plantations, which were studied separately).

Maps were generated from the GIS showing stand location, aspect, and slope class. These maps were overlaid on topographic quads to verify aspect and slope class, and to determine stand elevation. If a stand covered a mixture of aspects or a wide range of elevation, it was split to provide for more uniform conditions within each of the resulting stands.

We used District records and consulted with current and former District employees to acquire data on uncut/partial-cut status of stands, type of fuel treatment, and loading of woody fuels less than and greater than 7.6 cm in diameter (Table 1).

The color and color infrared postfire aerial photos, along with prefire orthophotos, were used to assign the FDC to each stand and, independently, to verify uncut/partial-cut status of the stands.

DATA ANALYSIS

Data for plantations and uncut/partial-cut stands were analyzed separately. Approximately 10% of the records, comprised of 24 plantations and 90 uncut/partial-cut stands, were randomly removed before analysis and set aside for later validation of relationships. Both FDC and uniformity of damage were used as dependent variables for plantations, whereas FDC was the single dependent variable used for uncut/partial-cut stands.

FDC as we defined it is an ordinal (discrete, ordered, semiquantitative) variable. The statistical technique best suited to this kind of dependent variable is ordinal logistic regression (SAS 1990). Multiple linear regression treats the dependent variable as continuous, and discriminant analysis ignores its ordered nature. We explored the data initially using all three of these analysis techniques, including stepwise and other variable elimination procedures appropriate for each (SAS 1988, 1990). We concluded, however, that neither linear regression nor discriminant analysis added anything to an understanding of the relationships involved and have omitted both techniques from further discussion.

A final logistic regression model was selected for each stand type with the help of several tests of model fit applied to analysis and test data sets (Tables 3 and 4). Sensitivity analyses then were conducted for each independent variable comprising the final models. These sensitivity analyses were used to clarify the marginal relationship of each independent variable with FDC—i.e., the rate of change of FDC with respect to the selected independent variable when all other independent variables in the model are held constant. The validity of such analyses depends on the assumption that independent variables are uncorrelated. Low levels of multicollinearity among the independent variables suggested that this assumption is reasonable for our data. The sensitivity analyses were done as follows: for each plantation (for example), each independent variable in the logistic regression model, except for the variable for which the sensitivity analysis was being done, was held constant at its actual value in the data set. The variable being analyzed was assigned several values spanning the entire range assumed by that variable in the plantation data set. The model was used to predict FDC for each of those several values. This procedure was repeated for each independent variable in the model.

Most independent variables were considered continuous variables. A few, however, like site preparation method and stand treatment (Table 1), were treated more appropriately as class variables, and therefore were converted to sets of indicator (dummy) variables in the analyses. Aspect was analyzed both as a continuous (mesic to xeric) and as a class variable, although the latter seemed to be the more useful approach. Compartments were included as dummy variables during initial analyses, but subsequently dropped because they added little to prediction accuracy and lacked usefulness outside the Hayfork District.

RESULTS AND DISCUSSION

CLASSIFICATION ACCURACY OF MODELS

A number of variables were found to be highly significant in terms of their effect on FDC in the logistic regression models (Tables 3 and 4). The models performed relatively poorly, however, in terms of correctly classifying fire damage. The model for plantations (Table 3) correctly classified 37% and 42% of the analysis data set (90% of observations) and test data set (10% of observations), respectively; the model for uncut and partial-cut stands (Table 4) correctly classified 49% of both the analysis and test data sets. The poor performance of the models in terms of predicting actual FDC is not surprising because (1) fire weather variables were unknown and thus not included in the models, and (2) the several FDCs (five for plantations, four for uncut/partial-cut stands) make correct classification inherently more difficult than if fewer classes had been defined. Of considerably greater value, we believe, are the marginal relationships shown by the sensitivity analyses. Readers are referred to the Appendix for a guide to interpreting the sensitivity analyses represented in Figures 3 and 4.

OVERALL DISTRIBUTION OF FIRE DAMAGE CLASSES

FDCs were roughly uniformly distributed among the plantations (Figure 1), while in the uncut/partial-cut stands they were skewed somewhat toward the lower FDCs (Figure 2). A larger proportion of higher FDCs in plantations is to be expected because the smaller trees are more easily damaged. Also, uncut stands, which tended to have lower levels of damage (Figure 4a), comprised 60% of the total number of uncut/partial-cut stands. Aside from this comparison of the overall distribution of FDCs, no direct comparison of wildfire hazard or degree of fire damage *between* plantations and uncut/partial-cut stands is warranted.

Figures 1 and 2 also provide comparisons of actual versus predicted (using logistic regression models) distributions of FDCs for plantations and uncut/partial-cut stands. Not surprisingly, overall distributions of FDCs are predicted better than are FDCs for individual plantations or stands, as discussed in the previous section.

FIRE DAMAGE IN PLANTATIONS

Variables comprising the best logistic regression model for FDC in plantations were GRASSES and FORBS (see Table 2); ELEV (elevation in hundreds of meters); SP_NONE and SP_MP (two of the three dummy variables representing site preparation method—no treatment and machine piling); and DMG_ADJ (FDC for the adjacent stand in the direction from which the fire apparently came). Details of the model, including measures of overall reliability and significance of individual variables, are shown in Table 3.

Grasses

Abundance or cover of grasses was positively related to FDC: more grass was associated with more damage—i.e., with greater proportions of the higher FDCs (Table 3, Figure 3a; see Appendix for further explanation). This relationship is

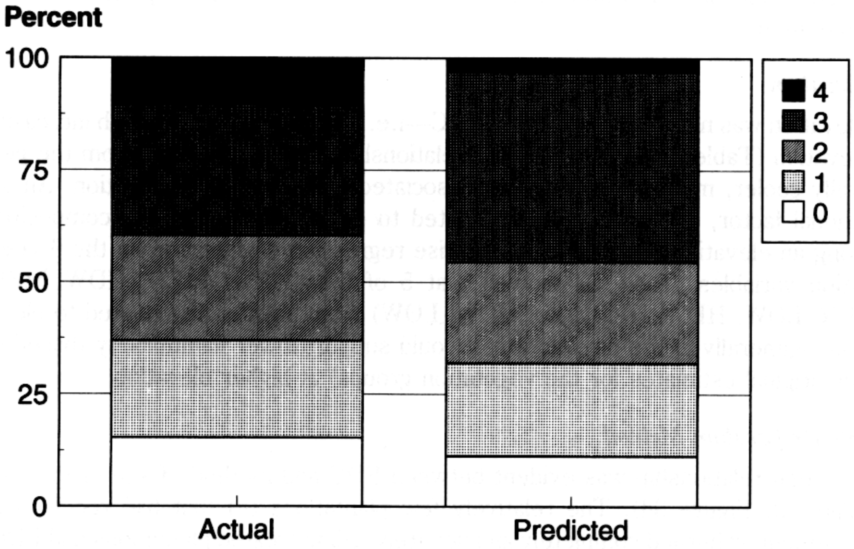

FIGURE 1. Actual and predicted distributions of fire damage classes in plantations.

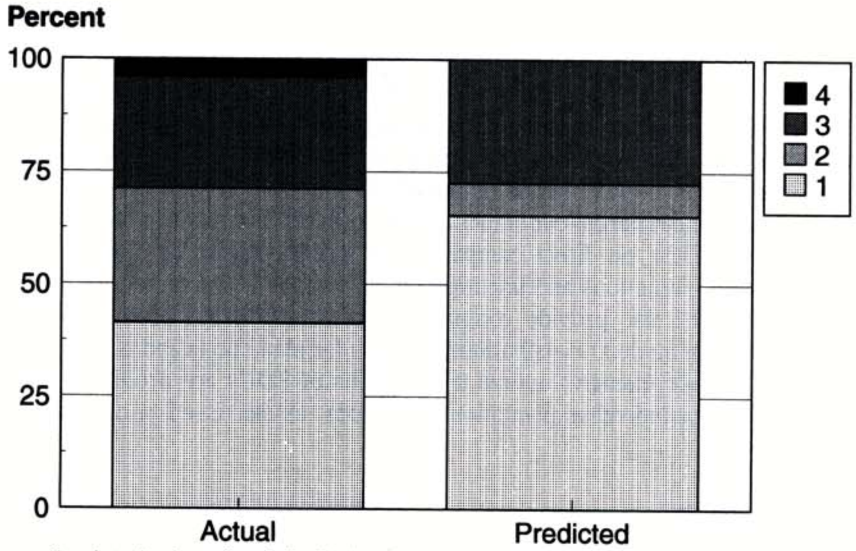

FIGURE 2. Actual and predicted distributions of fire damage classes in uncut and partial-cut stands.

corroborated by observations of a number of people who were on the fires. It also is consistent with the relatively continuous and, at that time of year (September), dry and flashy fuelbed provided by most grasses.

Forbs

Forbs tended to have the opposite effect of grasses on FDC (Table 3, Figure 3b). As compared with grasses, the apparently retarding effects of forbs on fire may have been related to differences in moisture content or other factors affecting flammability, perhaps including degree of curing and relative proportions of annuals and perennials. An additional factor may simply have been an inverse relationship of forbs with more highly flammable (and perhaps unmeasured) vegetation.

Elevation

Elevation was negatively related to FDC—i.e., damage decreased with increasing elevation (Table 3, Figure 3c). This relationship may result partly from the generally cooler, moister environment associated with increasing elevation. An additional factor, however, may be related to changes in vegetation composition along an elevational gradient. A stepwise regression of elevation on the 9 vegetation variables (Table 2) showed that 5 of them (SHR_MED, HDW_MED, SHR_LOW, HDW_HIGH, and HDW_LOW) were significantly related to elevation—generally in the direction that would support lower flammability (based on our original estimates for the vegetation groups) at higher elevation.

Site Preparation Method

A strong relationship was evident between FDC and method of site preparation (Table 3, Figure 3d). The relatively few plantations (8) that had received no treatment all burned completely and severely. All untreated plantations had FDCs of either 3 or 4, both in the actual data set and as predicted by the model.

Broadcast burned units suffered significantly less damage, as evidenced by lower FDCs (about half rated 0 or 1), than did the machine piled units.

The records indicated that on all machine piled units, piles had been burned before the 1987 fires. So the observed differences between machine piled and broadcast burned units evidently cannot be attributed to damage caused by unburned piles. YUM (yarding unmerchantable material) might have contributed to the difference between the two site preparation methods. For our study area, YUM was more common in broadcast burned units than in machine piled units. However, even though it was significant in univariate analyses, YUM probably did not have a major influence on fire damage since (1) the dummy variable for YUM was a very poor substitute for SP_BB (dummy variable for broadcast burning) in multivariate analyses; and (2) the effect of YUM disappeared when all broadcast burn units were taken as a separate data set.

Dissimilar successional patterns following the two site preparation methods may account for much of the difference. Correlations and stepwise regressions of the site preparation dummy variables on the nine vegetation variables indicated significant and usually opposite influences of a number of vegetation groups in broadcast burned units as compared with machine piled units. In general, these relationships are corroborated by the experience of foresters and fuels specialists. Grasses and forbs were significantly associated with site preparation method: more grass occurred on machine piled units than on broadcast burned units, with the reverse being true for forbs. Even though GRASSES and FORBS were themselves predictors of FDC, apparently some additional component of their influence was reflected in the site preparation dummy variables. SHR_LOW (Table 2) was favored on broadcast burned units. Although SHR_LOW did not emerge as a significant variable in the multivariate analyses, in a univariate analysis it was strongly negatively correlated with FDC—a relationship consistent with lower levels of damage in broadcast burned units. Other vegetation variables that were correlated in opposite directions with the two site preparation methods, thereby perhaps contributing to the observed differences in FDC, were CIR, SHR_HIGH, SHR_MED, HDW_LOW, and HDW_MED.

Damage in Adjacent Stand

As might be expected, fire damage to plantations was strongly affected by damage in the adjacent stand in the direction from which the fire apparently came (Table 3, Figure 3e). More damage—i.e., higher intensity—in the adjacent stand generally led to greater damage in the plantation.

One might expect susceptibility of plantations to wildfire damage to be linked to their size and continuity—i.e., a patchwork of small plantations resulting from clearcuts versus larger, more continuous plantations established on earlier wildfires. Virtually all of the fire-affected plantations on the Hayfork District were in the former category (small clearcuts—average 4 ha). Fire damage to larger plantations—those with smaller perimeter-to-area ratios—might be relatively less affected by degree of damage in the adjacent stand.

UNIFORMITY OF DAMAGE IN PLANTATIONS

Site preparation method (as represented by dummy variables) was the only factor related to uniformity of damage, and it was highly significant. Untreated planta-

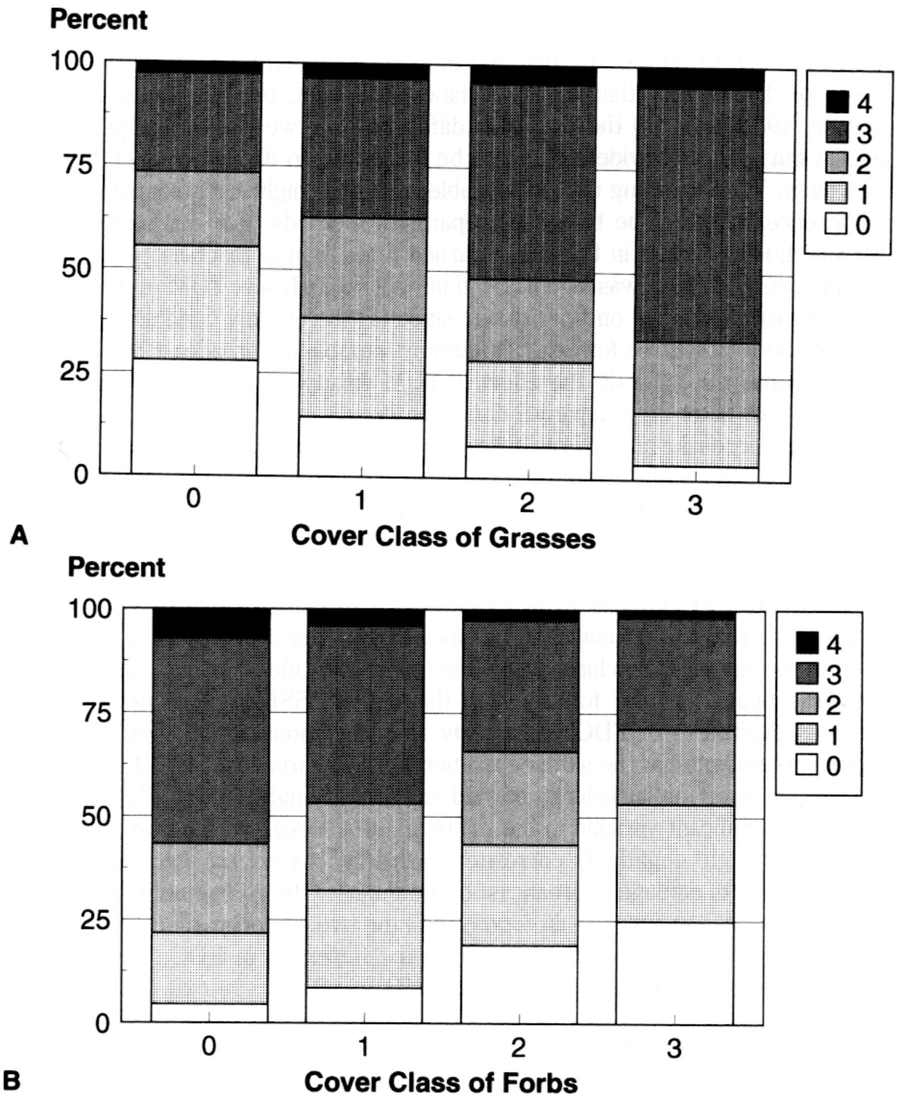

FIGURE 3. Sensitivity analyses showing changes in predicted distributions of fire damage classes as each of the independent variables in the logistic regression model for plantations (Table 3) is varied throughout its range: cover class of grasses (A); cover class of forbs (B); elevation (C); site preparation method (D); and damage class in adjacent stand (E).

tions burned quite uniformly (and severely), and differed markedly from treated units in terms of uniformity of damage. Broadcast burned units showed the greatest tendency for fire damage to decrease from the edge of the unit inward—i.e., for the plantation apparently to retard the spread and intensity of the fire. They differed significantly from machine piled units, which tended more towards a spotty burn pattern. No instances were observed in which fire damage increased from the edge of the plantation inward. Further quantification of results related to uniformity of damage probably is not warranted, given the subjective nature of this variable.

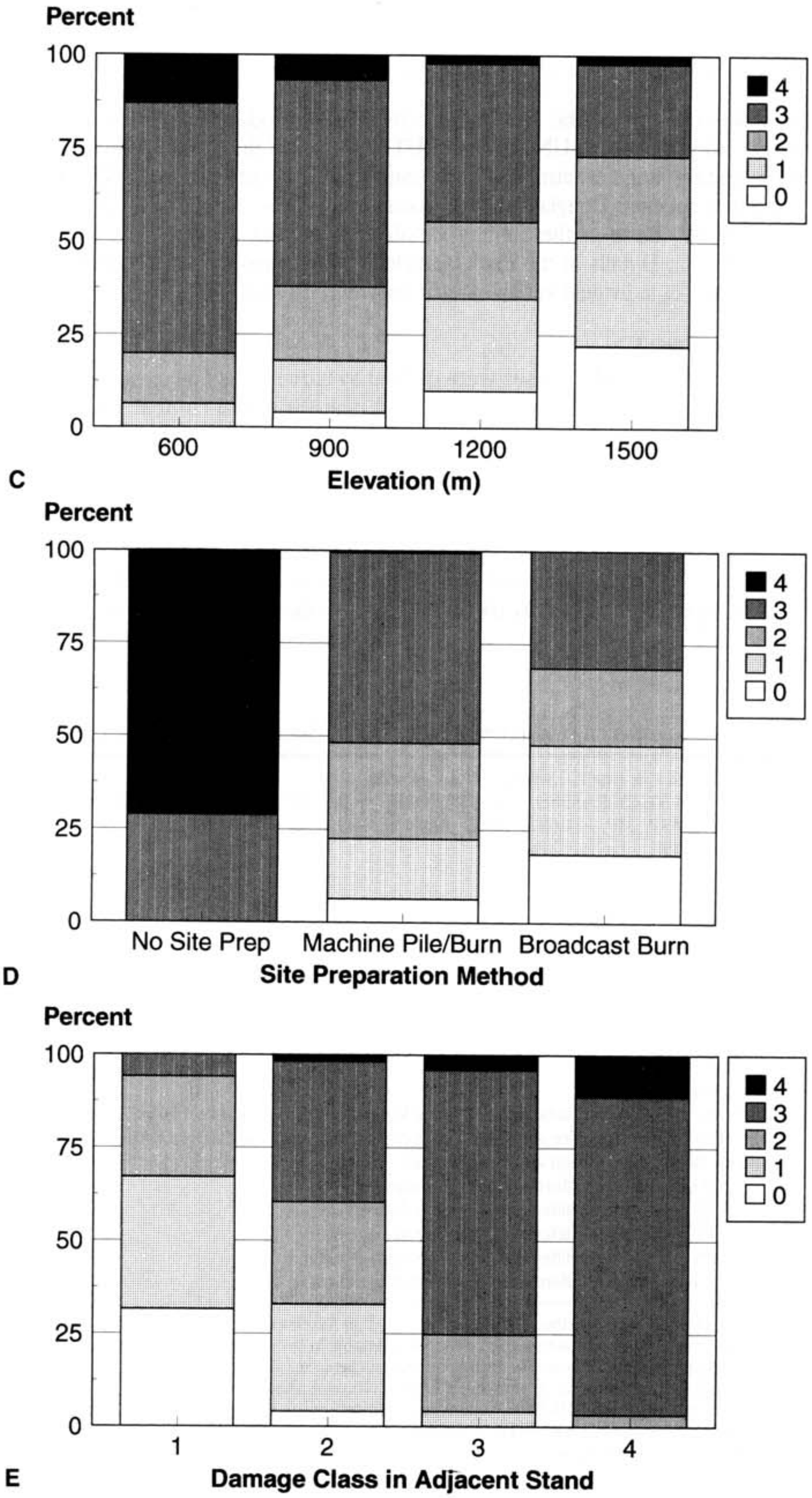

FIGURE 3. (*Continued*)

FIRE DAMAGE IN UNCUT AND PARTIAL-CUT STANDS

Variables comprising the best logistic regression model for FDC in uncut and partial-cut stands were UNCUT and CUT_TR (two of the three dummy variables representing stand treatment—uncut/untreated and cut/treated); PRI_SP (primary tree species: Douglas-fir = 1; ponderosa pine = 2); and ASP_N, ASP_E, and ASP_W (three of the dummy variables for aspect—north, east, and west, respectively). Details of the models, including measures of overall reliability and significance of individual variables, are shown in Table 4.

Stand Treatment

Three stand treatment classes were defined by harvest and fuel treatment status: (1) uncut/untreated, (2) partial-cut/treated, and (3) partial-cut/untreated. Uncut stands suffered the least fire damage, followed by partial-cut stands with fuel treatment; partial-cut stands with no treatment had the most damage (Table 4, Figure 4a).

The occurrence of lower FDCs in uncut stands probably is attributable largely to the absence of activity fuels and to the relatively closed canopy, which reduces insolation, wind movement near the surface, and associated drying of fuels. Conversely, opening the stand by partial cutting adds fuels and creates a microclimate

TABLE 3.

Logistic regression model for predicting fire damage class for plantations.[a]

$P_i = \exp(Y_i)/[1 + \exp(Y_i)]$ where $i = 1$ to 4 and:

$Y_i = K_i - 0.5034*\text{GRASSES} + 0.3958*\text{FORBS} + 0.2148*\text{ELEV} - 4.0968*\text{SP\_NONE} - 0.7722*\text{SP\_MP} - 1.0316*\text{DMG\_ADJ}$[b]

$K_1 = -1.6989$

$K_2 = -0.1739$

$K_3 = 1.2188$

$K_4 = 3.6797$

Chi-square tests of the probability that each coefficient is zero yield:

GRASSES $P < 0.0004$

FORBS $P < 0.0039$

ELEV $P < 0.0017$

SP_NONE $P < 0.0001$

SP_MP $P < 0.0052$

DMG_ADJ $P < 0.0001$

The P_i are cumulative probabilities. In ordinal logistic regression, an observation is assigned to the class (in this case, fire damage class) corresponding to the highest probability—i.e., the largest difference between adjacent P_i. Thus:

If $P_1 - 0$ is the largest difference, then fire damage class = 0.

If $P_2 - P_1$ is the largest difference, then fire damage class = 1.

If $P_3 - P_2$ is the largest difference, then fire damage class = 2.

If $P_4 - P_3$ is the largest difference, then fire damage class = 3.

If $1 - P_4$ is the largest difference, then fire damage class = 4.

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[a] A test of significance of the overall model (−2 Log Likelihood, SAS 1990) gives $P < 0.0001$ (chi-square = 115.2_{6df}). A positive coefficient for a variable in the equation for Y_i indicates a negative marginal relationship of that variable with fire damage class, and vice versa.

[b] GRASSES = cover class of grasses; FORBS = cover class of forbs; ELEV = elevation in hundreds of meters; SP_NONE = dummy variable for no site preparation; SP_MP = dummy variable for machine piling; DMG_ADJ = fire damage class for the adjacent stand in the direction from which the fire apparently came.

TABLE 4.

Logistic regression model for predicting fire damage class for uncut and partial-cut stands.[a]

$P_i = \exp(Y_i)/[1 + \exp(Y_i)]$ where $i = 1$ to 3 and:
$Y_i = K_i + 1.2349$*UNCUT + 0.5807*CUT_TR − 0.8983*PRI_SP + 1.1133*ASP_N + 0.4969*ASP_E + 0.7742*ASP_W[b]
$K_1 = -0.7316$
$K_2 = 0.6913$
$K_3 = 3.0228$
Chi-square tests of the probability that each coefficient is zero yield:
UNCUT $P < 0.0001$
CUT_TR $P < 0.0396$
PRI_SP $P < 0.0001$
ASP_N $P < 0.0001$
ASP_E $P < 0.0059$
ASP_W $P < 0.0001$
The P_i are cumulative probabilities. In ordinal logistic regression, an observation is assigned to the class (in this case, fire damage class) corresponding to the highest probability—i.e., the largest difference between adjacent P_i. Thus:
If $P_1 - 0$ is the largest difference, then fire damage class = 1.
If $P_2 - P_1$ is the largest difference, then fire damage class = 2.
If $P_3 - P_2$ is the largest difference, then fire damage class = 3.
If $1 - P_3$ is the largest difference, then fire damage class = 4.

[a] A test of significance of the overall model (−2 Log Likelihood, SAS 1990) gives $P < 0.0001$ (chi-square = 137.1_{6df}). A positive coefficient for a variable in the equation for Y_i indicates a negative marginal relationship of that variable with fire damage class, and vice versa.

[b] UNCUT = dummy variable for uncut/untreated stands; CUT_TR = dummy variable for cut/treated stands; PRI_SP = primary tree species (Douglas-fir = 1, ponderosa pine = 2); ASP_N = dummy variable for north aspect; ASP_E = dummy variable for east aspect; ASP_W = dummy variable for west aspect.

conducive to increased fire intensities (Countryman 1955). In addition, partial cutting historically has favored removal of larger trees, thereby leaving behind a higher percentage of smaller trees that are more readily scorched by fire. Not surprisingly, partial-cut stands in which some fuel treatment had been done suffered less fire damage than untreated stands. Only 52 of the stands in four compartments had received any kind of fuel treatment, consisting either of lop and scatter or underburning. Lop and scatter had been done by Forest Service crews at the time of partial cutting—mostly 15 or more years before the 1987 fires. The underburns, which occurred 5 to 6 years before the fires, were not planned treatments, but rather burns that were allowed to creep around between clearcut units that had been broadcast burned or away from burned roadside piles. Thus fuel consumption may have been spotty in these areas. Prescribed burning has been shown to reduce damage from subsequent wildfires (Buckley 1992, Cumming 1964, Davis and Cooper 1963, Helms 1979, Moore et al. 1955, Wagle and Eakle 1979). More intensive fuel treatment in our study area, therefore, might well have reduced fire damage further.

Primary Tree Species

Stands in which ponderosa pine was the primary species sustained more damage than stands dominated by Douglas-fir (Table 4, Figure 4b). The most likely ex-

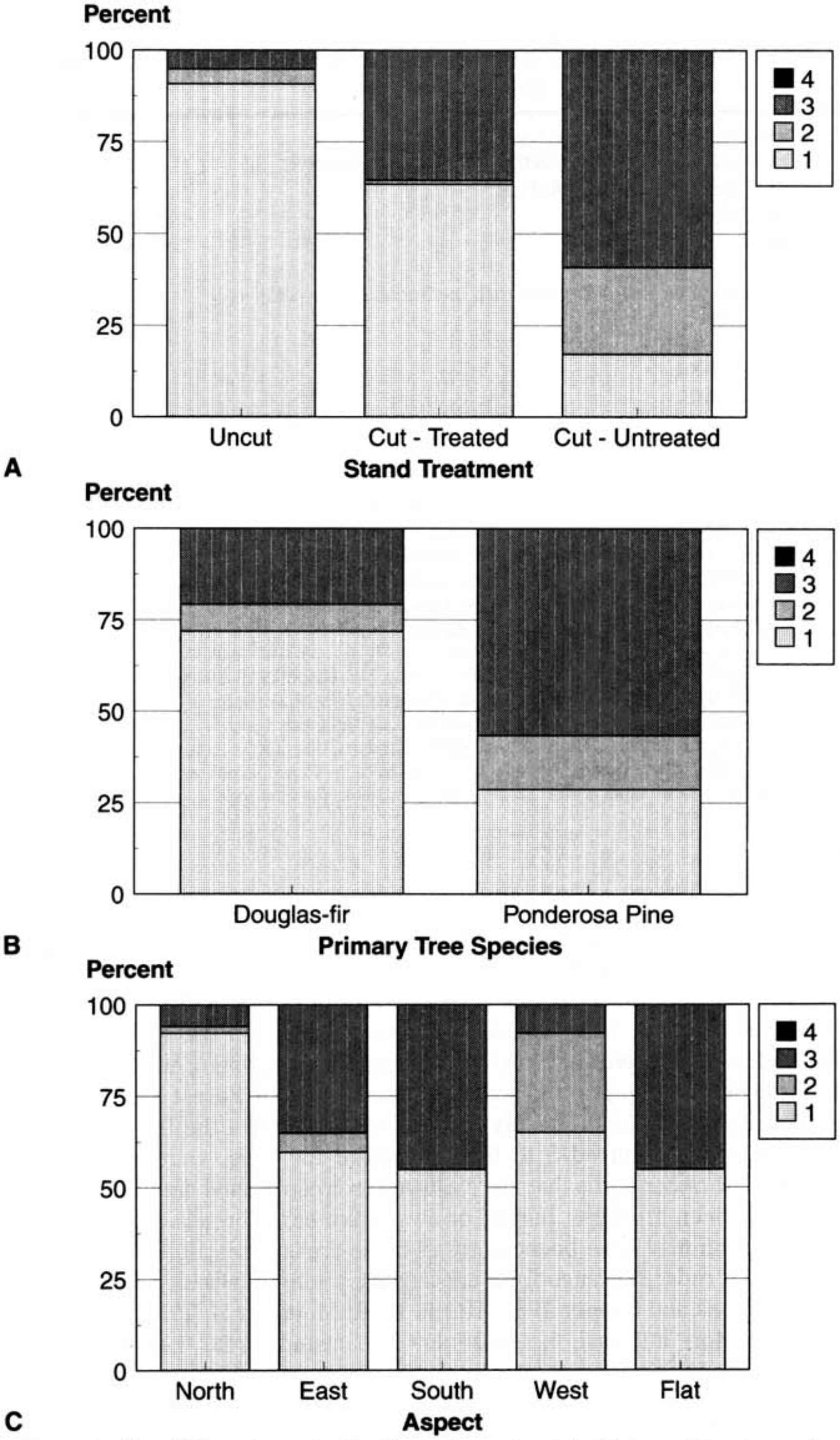

FIGURE 4. Sensitivity analyses showing changes in predicted distributions of fire damage classes as each of the independent variables in the logistic regression model for uncut and partial-cut stands (Table 4) is varied throughout its range: stand treatment (A); primary tree species (B); and aspect (C).

planation may be that the fuelbed, usually warmer and drier sites, and generally more open stand structure of ponderosa pine-dominated stands promote more intense fire. A related consideration is that natural fire regimes for ponderosa pine stands normally involve shorter fire return intervals than those for Douglas-fir. It could be argued, therefore, that fire exclusion policies have eliminated more natural fuel reduction cycles, and so promoted a relatively greater fuel buildup, for ponderosa pine than for Douglas-fir. Note that our FDCs only describe degree of crown scorch and have nothing to do with relative susceptibility of the two species to fire-induced mortality or other damage.

Aspect

FDC was significantly affected by aspect. The logistic regression model (Table 4, Figure 4c) predicted an ordering of aspects, from lowest to highest FDC, of north, west, east, and south/flat (south and flat were not distinguished in the model). We had hypothesized a similar ordering—from mesic to xeric aspects—except that we had expected the order of west and east to be reversed. The relatively low damage class of west aspects may be in part a peculiarity of the Hayfork District: a large proportion of the west aspects within the burned areas fell within a large roadless area, which had generally lower levels of fire damage.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Even though no information was available concerning weather conditions, a number of variables were found to have a highly significant relationship to FDC. The fact that these variables emerged from the "noise" of quite variable burning conditions is a measure of their significance. Had we been able to assign weather variables, the ability of the models to predict actual FDCs undoubtedly would have improved. On the other hand, marginal relationships of the significant site and management variables with FDC may have changed relatively little, since effects of weather conditions should have been more or less independent of effects of the other variables. Thus, these relationships may be useful in evaluating the wildfire hazard implications of alternative management practices.

The measure of fire damage that we used—crown scorch—does not directly account for damage to other parts of trees (boles and roots), and does not solely account for fire-induced tree mortality. Crown scorch is, however, useful in predicting postfire condition of stands and needs for management actions (Ryan 1982, Wagener 1961). Our FDCs 0 and 1 indicate stands with minimal damage (from the standpoint of crown scorch) and little need for further action, whereas FDCs 3 and 4 suggest extensive mortality and probable needs for salvage (if appropriate) and reforestation. FDC 2 denotes marginal areas requiring relatively intensive on-site evaluations in order to make postfire management decisions. Differences in probable tree mortality and canopy opening among the FDCs also suggest a range of effects on other ecosystem components and processes, including soils and vegetation succession. In light of such management interpretations of the FDCs, the magnitude of predicted changes in FDC as a function of individual variables in the models (Tables 3 and 4, Figures 3 and 4) suggests that several of those variables are significant not only statistically, but also from a management standpoint.

Interestingly, the variables spanning the greatest range in FDC, and therefore having the greatest potential management impact, tended to be those most directly related to management activities: site preparation and damage in adjacent stand for plantations; and stand treatment for uncut/partial-cut stands. Although some difference in fire damage was found between machine piled and broadcast burned plantations, a much larger change attributable to site preparation method was that between treatment and no treatment. There has been an increasing tendency recently in some areas for managers to leave clearcut areas untreated for various reasons. From a fire hazard standpoint, the acceptability and cost-effectiveness of foregoing treatment depend on several factors, including cost of treatment, values at risk, frequency of wildfire occurrence, and natural fire regime (Agee 1993, Deeming 1990, Hirsch et al. 1981). We have not attempted an economic analysis of costs and benefits of site preparation or other fuel modification practices. Our results suggest, however, that in short-interval, low- to moderate-severity fire regimes (Agee 1993) such as those on the Hayfork District and widespread elsewhere in the West, nontreatment may represent an undue risk of loss of high-value plantations and related resource values.

In assessing damage to plantations, we used damage in the adjacent stand as an indicator of local burning conditions. Undoubtedly it did reflect burning conditions to a large degree. However, damage in the adjacent stand also is a function of the fuelbed and related conditions in the stand. Thus this factor may have significant management implications for plantation protection: management activities and site/stand conditions that favor reduced fire damage in uncut or partial-cut stands also tend to decrease the severity of damage in adjacent plantations. This finding supports the need for a landscape perspective in managing fuels.

The dominant variable for uncut/partial-cut stands was stand treatment, which was also the variable most directly reflecting management activities. Clearly, stands that had been partial-cut with no subsequent fuel treatment suffered the most fire damage. Even the relatively nominal fuel treatment that had been conducted within four of the compartments substantially reduced damage. The recently renewed interest in uneven-aged management and other forms of partial cutting brings with it new and difficult challenges for fuels management. Our results suggest, for the short-interval, low- to moderate-severity fire regimes studied here, that if the problems are ignored and fuels are left untreated, damage from wildfires could increase significantly. No comparison of wildfire hazard between plantations and uncut/partial-cut stands is provided by this study.

Another group of variables significantly related to FDC and under some degree of management control was species or groups of species of vegetation. Vegetation management activities in plantations—mostly site preparation and release treatments—generally are intended to reduce species that compete severely with conifer seedlings and favor those that are less competitive. Our results suggest that flammability of alternative vegetation complexes and implications for plantation protection also should be considered in vegetation management decision making. In uncut/partial-cut stands, the dominant species in the stand had an influence on FDC. This finding probably should not be interpreted as a suggestion to make major changes in tree species composition for the sake of fire hazard reduction, but rather as a reason for managers to be more sensitive to natural fire regimes and species-related variations in fire hazard in planning fuels management strategies.

Lack of data precluded our being able to address possible effects of some important management activities on fire hazard—e.g., release treatments, precommercial thinning and associated fuel treatment, or other practices in plantations (Wilson 1977); and planned prescribed burning or other fuels management activities in existing stands. Future studies of this type would benefit from the presence of a greater range of fuel-affecting activities. Obviously, complete and accurate records are critical.

The common thread running through most of the foregoing discussion seems to be the nature of fuelbeds. We were surprised, therefore, to find that the two explicit fuel variables for which we had data [(1) loading of woody fuels less than or equal to 7.6 cm and (2) loading of woody fuels greater than 7.6 cm, in uncut/partial-cut stands] were not significant predictors of FDC. We think that the most likely explanation lies in the way the fuels data were developed. Fuel inventories were conducted in a relatively small sample of stands representing the various timber strata on the District. The data then were extrapolated to other stands within the same stratum. Strata designations, however, do not account for differences in stand or treatment history and resulting differences in fuels. Thus the variability of fuels within the strata, and associated variability in fire behavior and fire damage, evidently were sufficient to mask any detectable effect of recorded fuel loadings. If this assumption is correct, it points to a need for more site-specific data on fuels. No relationships between fuels and FDC were found for plantations, either, but for a different reason: fuels were rarely inventoried after site preparation and therefore could not be used as a variable in the analyses.

A large number of plantations and other stands, covering a considerable range of conditions, were included in this study. Results should be at least indicative for an area well beyond the Hayfork District.

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APPENDIX: INTERPRETATIONS OF SENSITIVITY ANALYSES

The sensitivity analysis for each independent variable in the logistic regression models (Tables 3 and 4) is presented as a stacked bar chart (Figures 3 and 4). In Figure 3a, for example, each bar represents the entire analysis data set of 222 plantations. The leftmost bar indicates the distribution of fire damage classes (FDCs) among all these plantations, as predicted by the model, when GRASSES (cover class of grasses; see Tables 2 and 3) is set to 0 for each plantation and all other independent variables in the model retain their actual values. The remaining bars show how the distribution of predicted FDCs changes as GRASSES is increased to values of 1, 2, and 3 (to span the range covered in the data set): increasing numbers of plantations experience higher FDCs and fewer plantations experience lower FDCs. One interpretation of the sensitivity analysis, therefore, relates to an overall change in the distribution of predicted FDCs as the independent variable of interest is changed.

Another useful interpretation involves more specific comparisons of FDCs between two values of the independent variable. One could ask, for example: For those plantations that had no recorded grass (GRASSES = 0) and that incurred a FDC of 0, what FDC(s) would be predicted if those plantations had had heavy grass cover (GRASSES = 3)? This question can be answered by extending horizontal lines from the upper and lower limits of FDC 0 on the leftmost bar (GRASSES = 0) across to the rightmost bar (GRASSES = 3) (Figure 3a). The extended horizontal lines encompass three FDCs on the bar for GRASSES = 3: a small proportion of FDC 0 and roughly equal proportions of FDCs 1 and 2 would be predicted to have occurred if those same plantations had had heavy grass cover. The legitimacy of this kind of interpretation can be seen by examining a matrix of predicted FDCs for GRASSES = 0 and GRASSES = 3 (Table 5). The vertical axis in Table 5 represents GRASSES = 0, and the column of totals for this axis reflects the distribution of FDCs in the corresponding (leftmost) bar of Figure 3a. Similarly, the horizontal axis represents GRASSES = 3, and the row of totals along the bottom of the table corresponds with the rightmost bar of Figure 3a. For the row representing FDC 0 for GRASSES = 0, predicted damage classes for GRASSES = 3 are 8, 28, and 26 plantations in FDCs 0, 1, and 2, respectively. (None are predicted for FDCs 3 or 4.) The corresponding percentages—13, 45, and 42%—match the values that would be determined from a careful measurement of the region encompassed by the extended horizontal lines (Figure 3a) described earlier. One could do a similar projection in the other direction on Figure 3a. For example, extending horizontal lines from the limits of

TABLE 5.

Matrix of predicted fire damage classes for two values of GRASSES.[a]

Fire damage classes for GRASSES = 0	Fire damage classes for GRASSES = 3					
	0	1	2	3	4	TOTAL
0	8	28	26	0	0	62
1	0	0	13	48	0	61
2	0	0	0	40	0	40
3	0	0	0	48	5	53
4	0	0	0	0	6	6
TOTAL	8	28	39	136	11	222

[a] Using the logistic regression model for plantations (Table 3), two predictions of fire damage class were made for each of the 222 plantations in the analysis data set—one with GRASSES (cover class of grasses; see Tables 2 and 3) set to 0 and the other with GRASSES set to 3. In both cases, the other independent variables in the model retained their actual values. Values in the table are the joint frequencies of fire damage classes resulting from these two sets of predictions. For example, the value of 13 in row 2, column 3 of the table indicates that, for 13 of the 222 plantations, a fire damage class of 1 was predicted when GRASSES was set to 0 *and* a fire damage class of 2 was predicted when GRASSES was set to 3.

FDC 2 on the bar for GRASSES = 3 indicates a split between predicted FDCs 0 and 1 on the bar for GRASSES = 0. The corresponding values in Table 5 are 26 and 13 (67 and 33%) for FDCs 0 and 1, respectively. The same kind of assessment can be made for any other pair of bars in Figure 3a or in any of the other stacked bar charts representing independent variables in the logistic regression models (Figures 3 and 4).

An alternative interpretation of the data cited in the previous paragraph (Figure 3a, Table 5) is that, for a given plantation with no grass cover that experienced a FDC of 0, the probabilities would be 13, 45, and 42% that that plantation would have experienced FDCs of 0, 1, and 2, respectively, if it had had heavy grass cover.

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