Landscape modeling of wildfire severity based on topography of Douglas-fir regions in the central-western Cascade Range.

by

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I. Introduction

At present, much research in ecosystem management is being done in the Pacific Northwest. Agencies and research institutions have joined forces in developing means to preserve biodiversity, for the sake of maintaining the integrity of ecosystems, and because they recognize there is much to be learned about ecosystem processes. The U.S. Forest Service and Oregon State University (OSU), for example, cooperate on many forest research topics at the OSU Forest Sciences Laboratory, and in the field. Also, the National Science Foundation provides scholarships to undergraduates to gain experience in research activities (REU program). As a student in the REU program at the H.J. Andrews Experimental Forest, I became involved in modeling studies of wildfire severity. This and other studies are being used to develop ecosystem management strategies for the future.

There is a concensus today that the forestry practices of our era have resulted in spatial and temporal variation of forest succession that is outside the range of historic conditions (Swanson, Jones, Wallin, Cissel, 1993). One strategy of ecosystem management that has been proposed is the approximation of landscape conditions of the Pacific

Northwest, to within a range of natural variability (Swanson, et. al., 1993). As the structure and composition of virgin forests have evolved under the natural disturbance regimes of the Holocene, so too have the constituent fauna of the biome (Swanson, et. al., 1993). Under this premise, natural disturbance regimes should be incorporated as templates for forest management for the sake of preserving biodiversity (Connelly and Kertis, 1992; Swanson, et. al., 1993).

Attempts to characterize the range of natural variability are being made at the OSU forest sciences laboratory. One approach is the quantification of wildfire severity as a function of topography. The natural disturbance regime related to wildfire (fire regimes) may provide clues about the landscape dynamics of the presettlement era, that could be used in ecosystem management (Swanson, et. al., 1993; Wallin, Marks, Cissel, Kertis, in review). The reconstruction of presettlement fire regimes is facilitated by the sampling of fire scar and tree origin data visible among the growth rings of stump faces found in clearcuts.

Much work in determining the fire history of the central-western Cascade Range has been completed (Teensma, 1987; Morrison and Swanson, 1990; Connelly and Kertis, 1992). These studies contain analyses of fire frequency and fire regimes for their particular landscapes. This project takes a step furthur by providing a conceptualization of fire severity in an effort to characterize its dependency on topographic factors. Simple methods of quantifying severity were used, based on fire history data collected in the field. This data was combined with remotely sensed topographic data into a regression analysis. The goal is to produce a prediction equation that can be used to identify fire severity potential based on topography at the landscape scale. Discussion of the various themes that contribute to the conceptualization of fire severity follow.

II. Background

Ecological Development of Douglas-fir Forests

Particular growth habits of the Douglas-fir are useful in the interpretation of forest succession. First, the species is fire resistant, due in part to the thick corky bark of its lower bole and main roots. This enables it to survive its less fire resistant associates; however, all but the most ancient trees are susceptible to high severity fire. Second, the species requires full sunlight beyond the first years growth for successful establishment (Hermann and Lavender, 1990). Establishment is therefore dependent upon light gaps created by events such as wildfire.

These two features affect succession under different fire regimes. For example, catastrophic events often result in the removal of continuous Douglas-fir canopy which affords the wholesale ~~release~~ establishment of seedlings over widespread areas. This is termed regeneration. Less severe fires remove less canopy and suppression is increased. In such fires Douglas-fir may only sustain scarring. Both regeneration and scarring are environmental responses influenced by fire regimes.

Fire Regimes

Fire regimes are characterized in terms of fire severity; low, moderate, and high. The occurrence of any particular fire regime is dependent upon climate, fuels, and of interest here, topography (Swanson, et. al., 1988; Agee 1993). Consider the difference in fire return intervals between aspects (Agee, 1993). South aspects exhibit lower severity fires and shorter fire return intervals because fuels are often reduced. This is caused mainly by increased insolation and fuels are more prone to ignition before they build up; these slopes sustain less damage when fire occurs. North aspects are more mesic and less prone to burn or be ignited. These slopes have longer fire return intervals and the fires are more severe when they do occur. This phenomenon directly influences the age class distribution of the forest. In the context of sampling Douglas-fir in clearcuts, stumps of many age classes indicates a low to moderate severity fire regime for that location. In contrast, a more even-age distribution indicates the past occurrence of a high severity fire which few trees may have survived. The degree of dependence between topography and fire regimes is therefore manifested in the age class distribution of trees (stumps), governed by the successional pattern of the species, and has been quantified as wildfire severity for this paper.

Location

The field work for this study took place in the Augusta Creek study area of the Blue River ranger district of the Willamette National Forest, Oregon (fig. 1). Three sections of the watershed were sampled:

A. The upper drainages of Grasshopper and Augusta Creeks.

B. The lower tongue of the Chucksney Mountain spine.

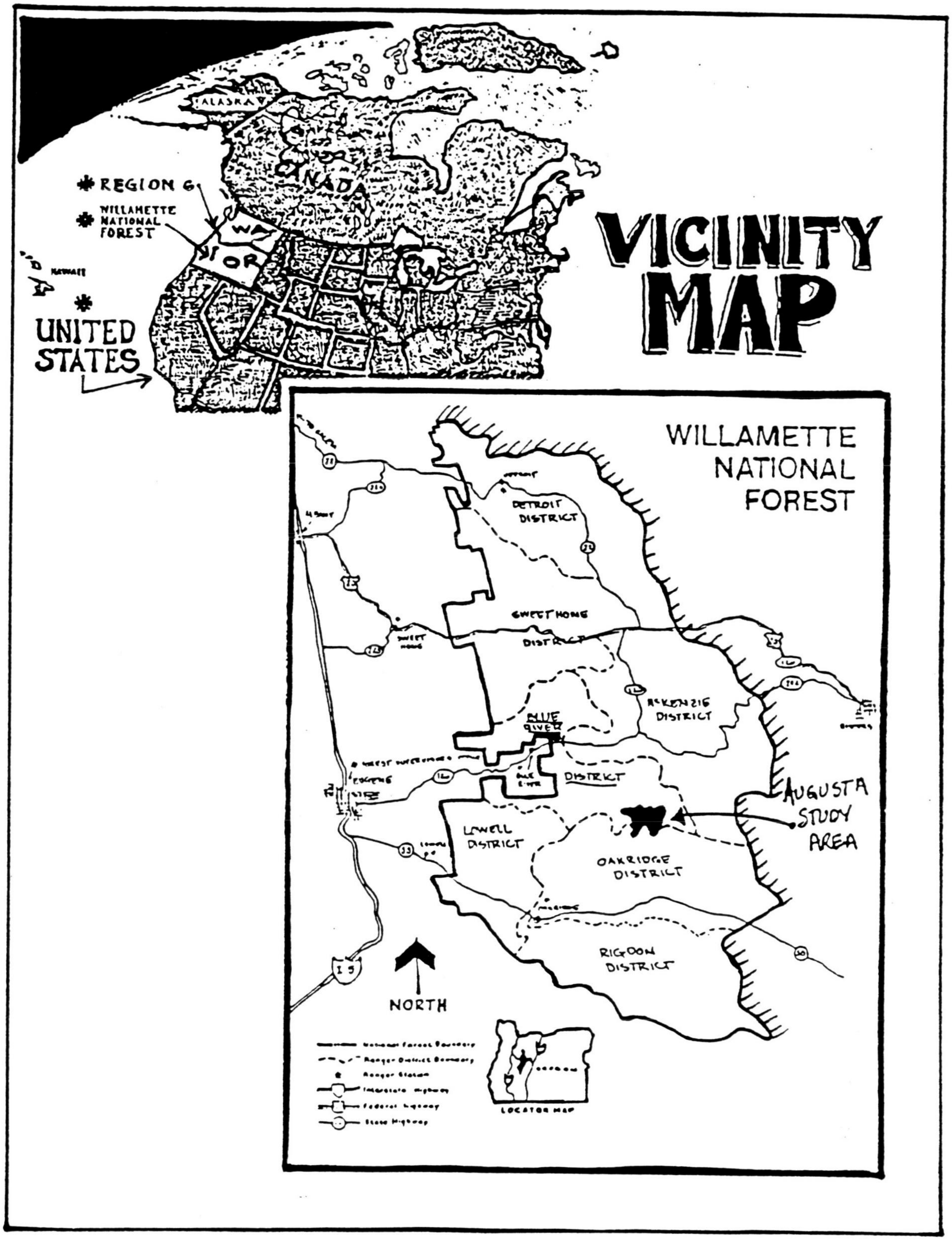
C. South of the South Fork of the McKenzie River along the North face of the Chucksney Ridge.

These areas were outlined by Connelly and Kertis (1992), based upon uniformity in stand-age structure, and differences in fire frequency and fire intensity (severity) between these and six other sections comprising the rest of the watershed. These sections were chosen because of their apparently contrasting fire regimes; A is an area of low frequency, high severity fires, while B & C are areas of high frequency, low severity fires (Connelly and Kertis, 1992). Thus, by sampling these three sections it is possible to model fire severity across the entire range of fire regimes.

Fire Episodes

Fire Severity as conceptualized here, is the relative frequency, for each sample plot, of trees having origin or scar ages that coincide with a particular fire episode. As mentioned, the proportion of trees with scars or those which constitute regeneration after a fire, is a function of how

Figure 1. Vicinity map of Augusta Creek watershed study area. (Connelly and Kertis, 1992)



severe the fire was. These frequencies are considered indices of fire severity (Wallin, 1994).

According to Connelly and Kertis (1992) 21 fire episodes have occurred in the Augusta Creek Watershed between 1469 and the present, based on substantial evidence in the form of both scars and regeneration patterns. The approach to selecting a fire episode was to seek out the greatest frequency of regeneration and scarring, for each watershed section, over the 600 year period for which the fire chronology has been determined (sample, table 1). Thus, for section A most of the ages for regeneration and scarring coincide with the fire episode of mean year 1790 (1784-1795). The evidence in section B coincides with the fire episode of 1835 (1830-1839). A previously unknown fire episode in 1751 (1742-1760) was affirmed for section C under rules set forth by Morrison and Swanson (1990).

Severity index intervals were established to select the precise origin and scar age data to be used to calculate the severity indices. These intervals are based on ring count reliabilities to accomodate for error in the aging of scars. For any given section, the scar index interval was widened by +/- 10 years from the mean fire episode year. The regeneration index interval was widened in a similar fashion, yet was extended 20 years to account for succession, or until the following fire episode, whichever came first.

Table 1: Sample regeneration and scar age chronology for section A-upper drainages of Grasshopper and Augusta creeks.

Date classes	origin	scar
--		
1469	8	1
1470	0	0
1491	3	0
1492	0	0
1500	1	1
1501	0	0
1514	6	0
1515	0	0
1529	5	0
1530	0	0
1531	1	0
1545	11	0
1546	0	0
1560	7	1
1561	1	0
1578	14	1
1579	0	0
1586	8	1
1587	1	0
1596	3	0
1597	0	0
1631	11	4
1632	0	0
1640	5	0
1641	0	0
1726	14	8
1727	0	0
1741	2	5
1742	0	1
1760	0	8
1761	1	0
1776	8	8
1777	0	1
1784	14	7
1795	12	14
1796	5	2
1801	14	3
1802	3	0
1817	22	8
1818	5	0
1819	0	0
1820	1	0
1828	3	2
1829	0	0
1830	1	0
1839	3	2
1840	0	0
1848	1	2
1849	0	0
1853	0	0
1854	0	1
1856	0	2
1857	0	0
1860	0	0
1861	0	0
1862	0	0
1871	0	1
1872	0	0
1879	0	2
1880	0	0
1892	0	1
1893	0	1
1900	0	0

Thus, the intervals are as follows:

Severity Index Intervals

	Mean year	Scar	Regeneration
Section A =	1790	1780-1800	1780-1820
Section B =	1835	1825-1845	1825-1856
Section C =	1751	1741-1761	1741-1781

Fire Severity Indices

For each plot, four fire severity indices were calculated for one of the fire episodes listed above depending on the watershed section they were located in. These indices were calculated as follows (tables 2a & 2b):

i. Regeneration Index = number of regeneration trees / number of trees predating the fire episode + regeneration

ii. Scar Index = number of scar trees / total number of trees that predate the fire episode

iii. Extended scar Index

Scar years which did not fall within the designated scar interval for an episode yet which had scar age count reliabilities of +/- 10 to 20 years were accounted for in the same manner as number 2 above if the intervals created by the extended reliability count overlapped the scar interval.

iv. Scar and regeneration index combined

The sum of both scar and origin trees as divided by the sum of all trees sampled at the site, again excluding trees which post-date the regeneration interval.

Table 2a: Key to sites of fire severity vs. topographic variables (30m DEM) compiled for section A- Upper drainages of Grasshopper and Augusta creeks.

Site	Cut unit #	Plot #	Aspect-azimuth	TCI scaleless	Slope %	Elevation m.	Accum. drainage ha.	Regen index 1780-1820	Scar index 1780-1800	Extended scar index	Regen+ scar index
1	56	1	254	1	39	1394	0.09	0.45	0	0	0.45
2	56	2	224	1.92	44	1388	0.27	0	1	0	1
3	56	3	328	1.05	69	1399	0.18	0.67	0.33	0	1
4	55	1	269	2.82	18	1198	0.27	1	0	0	1
5	55	2	256	2.68	7	1200	0.09	0.71	1	0	1
6	55	3	290	1.43	24	1236	0.09	0.76	0	0	0.76
7	182	1	281	4.17	48	1303	2.79	0.4	0.33	0	0.6
8	182	2	334	1	78	1273	0.18	0	0	0	0
9	182	3	332	1	82	1295	0.18	0	0.11	0	0.11
10	63	1	298	1	73	1233	0.09	0.95	1	0	1
11	63	2	309	2.85	75	1134	1.17	0	0.2	0.4	0.2
12	63	3	311	5.8	37	1031	10.89	0	0	0	0
13	227	1	82	1	57	1142	0.09	0.91	0	0	0.91
14	227	2	84	1	42	1049	0.09	1	0	0	1
15	227	3	54	3.52	53	1037	1.62	0	0.43	0.57	0.43
16	101	1	98	1.38	25	1403	0.09	0	0	0.33	0
17	101	2	67	1.37	25	1335	0.09	0	0	0	0
18	119	1	331	1.66	38	1297	0.18	0.33	0.5	0.75	0.67
19	119	2	291	3.14	26	1276	0.54	0.67	0.67	1	0.89
20	119	3	321	5.37	37	1213	7.20	0	0	0	0
21	81	1	17	2.33	48	1195	0.45	0	0	0.33	0
22	81	2	43	2.4	45	1273	0.45	0	0	0	0
23	96	1	138	1.53	65	1320	0.27	0	0.125	0	0.125
24	96	2	96	1	53	1333	0.09	0.17	0.2	0.6	0.33
25	96	3	35	1.31	54	1373	0.18	0	0	0.125	0
26	91	1	221	2.41	45	1186	0.45	0	0	0.14	0
27	91	2	347	2.81	72	1205	1.08	0	0.14	0	0.14
28	71	1	56	2.49	41	1454	0.45	0.167	0	0.4	0.167

Table 2b: Key to sites of fire severity vs. topographic variables (30m DEM) compiled for
section B- lower tongue of Chucksney Mountain spine.
section C- S. of the south fork of the Mckenzie River along the N. face of the Chucksney ridge.

Site	Cut unit #	Plot #	Aspect-azimuth	TCI scaleless	Slope %	Elevation m.	Accum. drainage ha.	Regen index note 1	Scar index note 2	Extended scar index	Regen+ scar index
29	136	1	241	2.93	21	937	0.36	0.87	0	0	0.87
30	160	2	243	3.06	23	924	0.45	0.7	0	0	0.7
31	160	3	225	3.2	49	767	1.08	0.17	0	0	0.17
32	103	1	28	1.05	69	919	0.18	0.4	0	0	0.4
33	103	2	345	1	48	864	0.09	0.9	0	0	0.9
34	103	3	62	2.94	53	726	0.9	0	0.125	0	0.125
35	103	4	63	2.7	34	801	0.45	1	0	0	1
36	10	5	285	1.01	73	708	0.18	0.67	0	0	0.67
37	101	6	70	2.2	22	754	0.18	1	0	0	1
38	94	7	67	1.76	52	747	0.27	1	0	0	1
39	96	8	80	1	52	774	0.09	0.92	1	0	1
40	83	9	25	3.53	38	889	1.17	0.29	0	0	0.29
41	83	10	65	2.07	63	1021	0.45	0.83	0	0	0.83
42	5	11	359	4.34	31	790	2.16	0.44	0	0	0.44
43	107	12	46	2.88	22	861	0.36	0.83	0	0	0.83
44	109	13	358	1.7	18	910	0.09	0.73	0	0.67	0.73
45	112	14	34	2.6	44	953	0.54	0.67	0	0.5	0.67
46	110	15	5	1	55	892	0.09	0.5	1	0	1
47	111	16	37	2.33	48	951	0.45	0.25	0	0	0.25

Note 1: sites 29-39 (section B) = 1835 f.e. (1825-1856)
sites 40-47 (section C) = 1751 f.e. (1741-1781)

Note 2: sites 29-39 (section B) = 1835 f.e. (1825-1845)
sites 40-47 (section C) = 1751 f.e. (1741-1761)

III. Methods

Sample Plots

Pseudotsuga menziesii var. menziesii, the green variety of Douglas-fir was the experimental unit. Sampling took place in mesic to dry Douglas-fir/Western Hemlock forest cover. Stumps of Douglas-fir are abundant in clearcuts of the study area. Selection of clearcuts to sample in was performed on the basis of maintaining an even distribution of sample plots throughout the watershed sections and to encompass the full range of topographic positions (Wallin, 1994). One to three plots were placed in each clearcut depending on its size and topographic complexity. Overall sampling density was about three plots per 100 hectares. The plots were distributed to sample as many of the topographic variables a clearcut had to offer.

For each plot a stump was selected to serve as the center point for two plots with radii of 17.8 m and 25.2 m, delineated with flagging. The plots formed areas of 0.1 & 0.25 hectares, respectively. Within these two concentric plots, the diameter (to the nearest 10 cm) and species of each stump was recorded. Only stumps of diameter 30 cm or greater for the inner plot and 50 cm or more in the outer plot were inventoried. The inventory serves to characterize the structure and composition of the plot (for future reference). Though all species were inventoried, only Douglas-fir stumps were examined for evidence of past fires. All Douglas-fir stumps in the smaller plot were examined, while those in the outer ring were examined if a minimum of 5 were not available from the inner plot. Because many plots were common to particular clearcuts, all have been ordered numerically with site numbers for easier reference to topographic and severity values (tables 2a & 2b).

Data Collection

Once the plot was set and inventoried, the sampling of individual stumps was begun. The first step is to find a path on the stump face in which the rings can be counted most easily and reliably. Often the stumps are covered with pitch and/or the rings have been blurred by decomposition. Paint scrapers were used to remove pitch, and both fine and course wire brushes helped to remove the more easily decayed softwood from the rings, thus creating readily countable ridges. The rings were then counted from the bark inward using a dissecting probe and hand lens, while pins were used to mark off ages from 75 yrs to 150, 200, 250, and so on to the origin age, in case one lost count. The actual scars and pitch rings (a type of scar), described in Morrison and Swanson (1990), were aged in the same manner. Origin age was not corrected for stump height, though various diameter tape measurements were taken for future reference. Origin and scar years were later calculated using harvest dates provided for each plot by the ranger district.

Topographic Variables

After plot locations were selected in the field, the locations were marked on 1 : 12,000 aerial photographs. The photographs were later used to digitize the location of each plot using Arc/Info software (Wallin, 1994). These digitized points were then used to extract topographic information for each plot via a Digital Elevation Model (DEM) developed by the U.S. Geological Survey. Elevation was extracted directly from the DEM, and Arc/Info software was again used to develop data layers for aspect, slope, accumulated drainage area, and topographic convergence index (TCI); a total of 5 factors (tables 2a & 2b). These last two are related in that they are both used to distinguish between dry and mesic locations. Specifically, TCI is a scaleless index of soil moisture which indicates the likelihood of encountering saturated soils during storm events (Beven and Kirkby, 1979; Beven and Wood, 1983). TCI was calculated for each plot by using the accumulated area drained by a given point (α, in hectares), and the slope at that point (β, in radians) in the formula $\ln(\alpha/\tan\beta)$.

For each plot, two sets of topographic variables were developed to investigate whether fire regimes are defined by fine or coarse-scale topographic features. A fine-scale DEM provided elevational data for grid points that are 30m apart

(30m), while a coarse-scale DEM provided data based on a 60m x 90m grid (90m). Fire severity was modeled for these databases separately.

Modeling

SPSS/PC+ was used to perform the stepwise regression routines used to screen out any severity indices (the response variables) for which no topographic variables (factors) contribute information for their prediction. Stepwise was applied to each of the four severity indices for the two topographic databases; a total of 8 routines. The p-values specified were 0.05 to enter topographic variables into the model, and 0.10 to remove them; no quadratic or interaction terms were tested.

A residual analysis for the model assumptions has been included here for two reasons. First, because the sample plots were selected by the analyst the topographic factor-level combinations for each plot were non-random. Second, not enough is known about the probability distribution of fire severity as a function of topography (Wallin, 1994). The residual analysis will help determine whether the assumptions for ANOVA hold true for our purposes here and whether transformation of the response variable is necessary (McClave and Dietrich, 1988, p.697).

Scattergraphs

Only variables from the significant topographic databases and severity indices were plotted against one another. Trends were examined in these graphs and compared to expected fire regimes associated with the topography of the sites, based on a survey of the literature. A comparison as such helps to reveal the accuracy of the response variables as quantified, and therefore the model itself.

IV. Results

Statistical Analysis

To begin, none of the 90m database topographic variables were significant with respect to any of the severity indices. Discrepancies were observed between the data derived from the 90m DEM and corresponding sites on the aerial photos. Apparently, the database used by the digital elevation model to generate the topographic data reflected inaccurate positions of plots on the landscape. Thus, the four routines based on the 90m database were automatically eliminated from evaluation.

Of the four routines based on the 30m database, only a model for severity as a function of regeneration frequency could be produced, and then using only three of the topographic variables. Stepwise could not produce a model for the three scar-related indices possibly because there were too few proportions qreater than zero to support any relationships; there were likely too few samples from which to draw scar data. The stepwise results for the regeneration severity model are printed in an SPSS/PC+ format in figure 2 (appendix A).

The hypothesis test for model usefulness is outlined below:

i. Ho: $\beta 1 = \beta 2 = \beta 3 = 0$ (elev., slope, TCI, respectively)

Ha: At least one of the coefficients is non-zero.

ii. $\alpha = 0.05$ to enter

$\alpha = 0.10$ to remove

iii. Global F = MSR/MSE = 11.51

iv. $F > F\alpha = 2.84$ with 3 num. d.f. and 43 denom. d.f. (actually tabulated under 40 denom. d.f.; McClave and Dietrich, 1988)

v. Reject Ho.

vi. Conclusion: According to the hypothesis test, the model is useful for predicting high severity fires provided the independent variables fall within the range of the topographic values used to create the least squares equation (McClave and Dietrich, 1988, p. 825). The model should only be applied to landscapes with similar plant association criteria. The low R-square value suggests more factors are needed and/or the indvidual factor correlations need improvement. Questions regarding the assumptions about the probability distribution of the random error term are addressed as follows.

Residual Analysis

The distribution of residuals was plotted separately for each factor in the model, for clarity (fig. 3). In the

Figure 3. Residual plots for regeneration severity model terms.

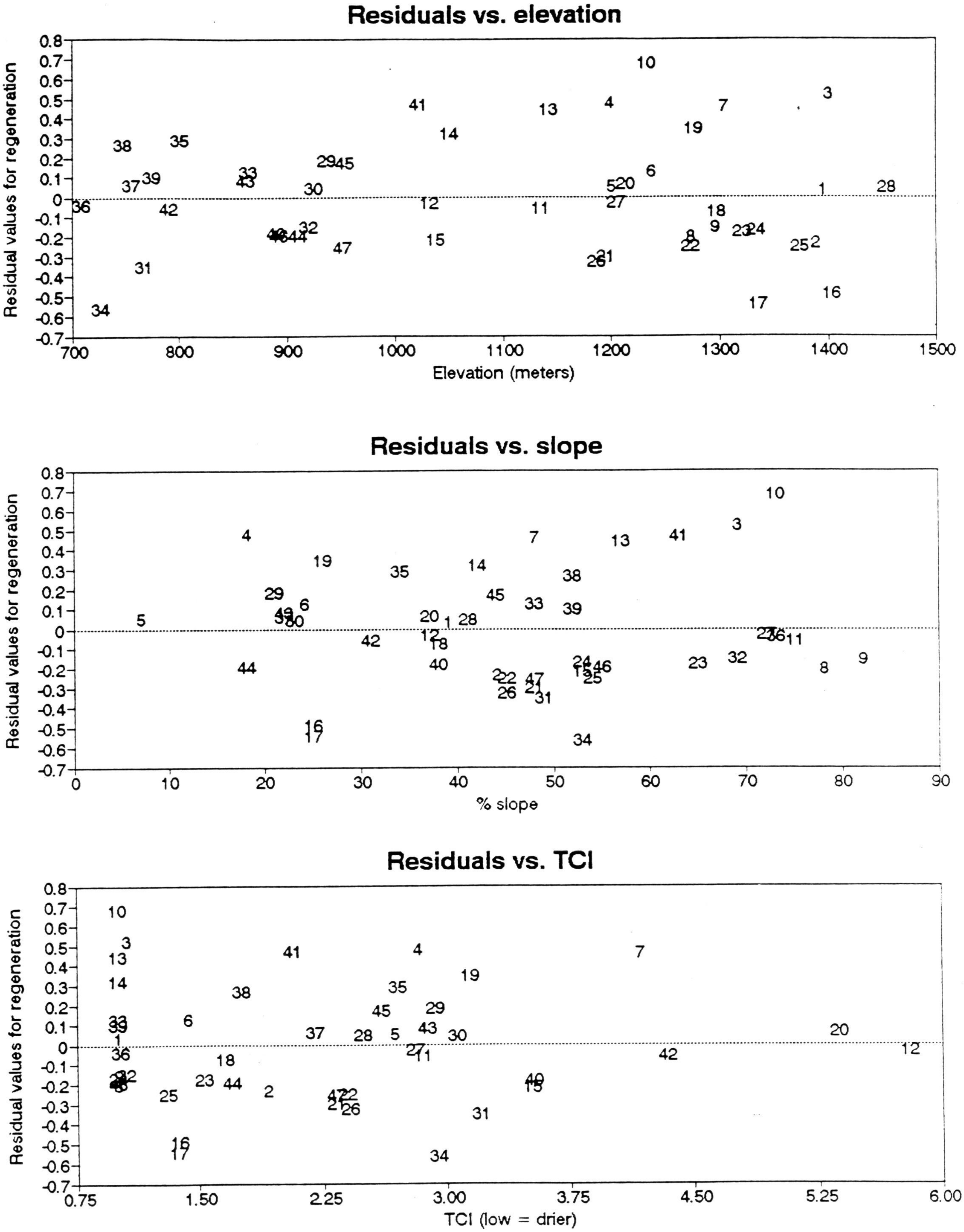
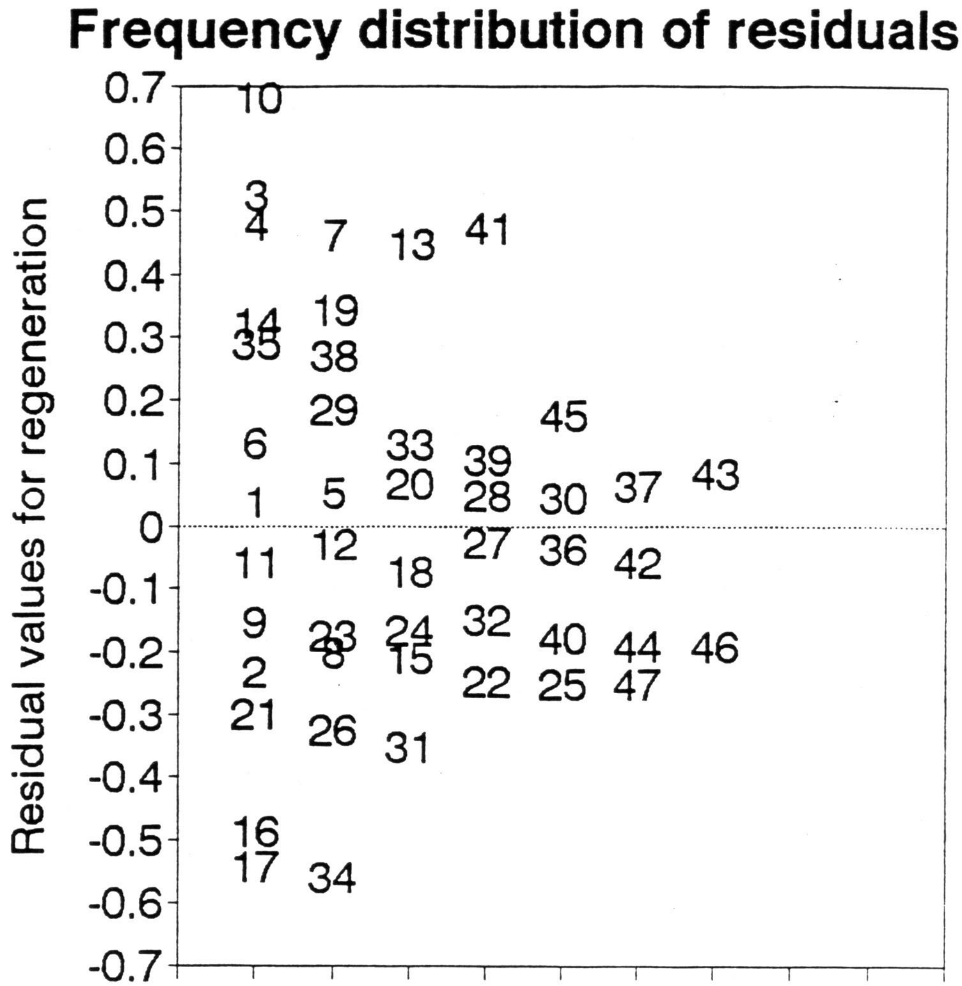


Figure 4. Frequency distribution of residual values for severity observations.

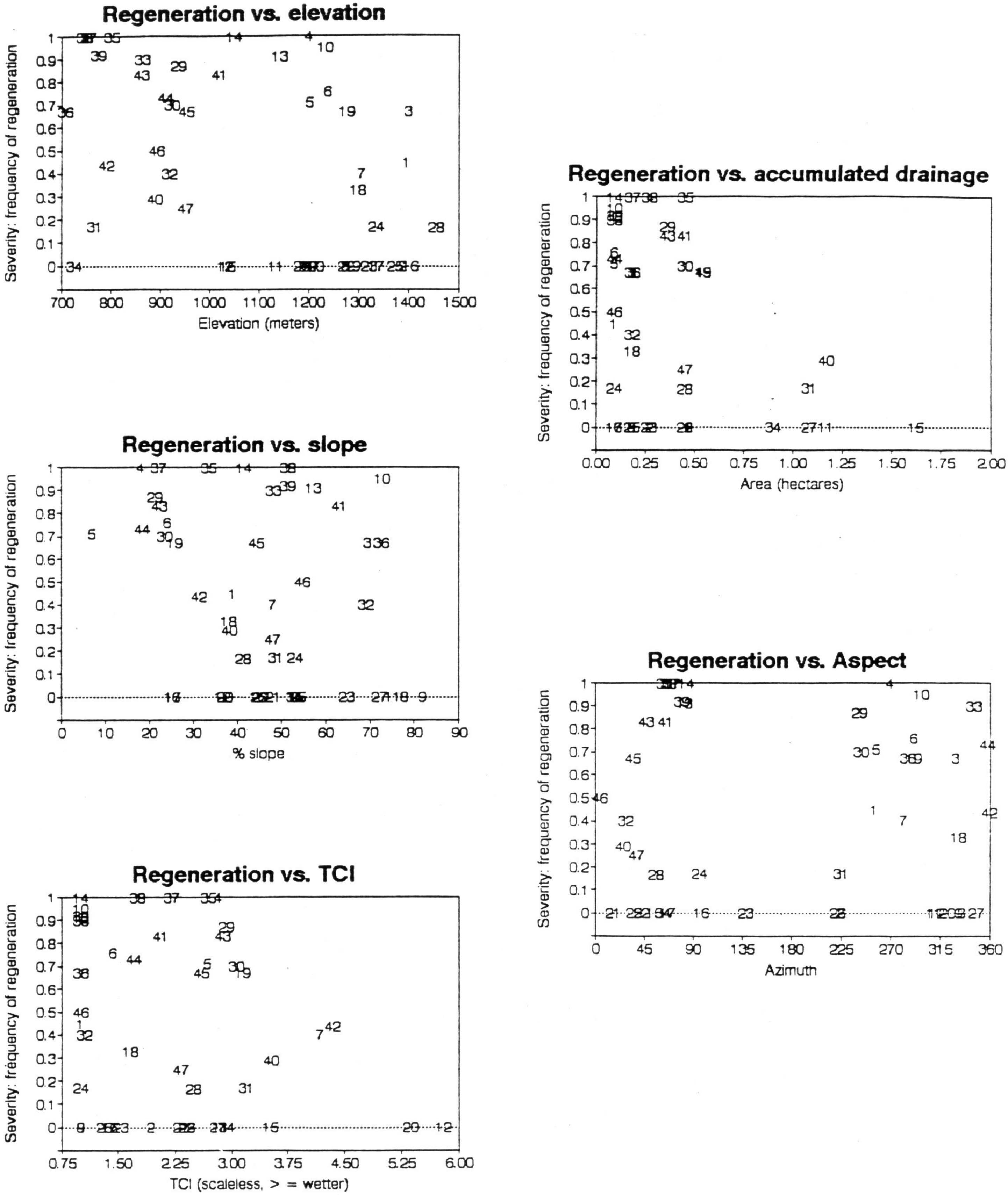


plots, site numbers were used in place of symbols to aide in interpretation. More than 95% of the residuals fall within 2 standard deviations (2s) of the 0 line and there are no outliers (residuals beyond 3s). Of the three factors, elevation appears to have a weak non-random (mound) pattern; a quadratic elevation term would probably remove the curvature (McClave and Dietrich, 1988). The frequency distribution of the residuals (fig. 4) portrays no obvious departure from normality. These criteria indicate that the assumptions regarding the relative frequency distribution of the error component of the model have been satisfied (except as noted) and arcsine transformation of the regeneration severity index proportions is not necessary (Sokal and Rohlf, 1969; McClave and Dietrich, 1988, p.814). The calculations of the residual values for the severity observations are listed in table 3 (appendix A).

Trends in severity

Scattergraphs of the regeneration index versus the significant and excluded topographic factors of the model are shown in figure 5. An evaluation of the trends they present reveals whether the severity index as conceptualized is true to the expected fire regimes for the ranges of topography in which sampling took place. As in the residual plots, site numbers were used in place of symbols to aide in cross referencing trends to the data in tables 2a & 2b.

Figure 5. Scattergraphs for regeneration model terms - significant & excluded.



At first glance, the scattergraphs for both significant and excluded terms of the model reveal two potential pitfalls with the conceptualization of fire severity used here. The first is that 54% of the sites (1-28) from watershed section A have index values of zero. Recall section A has a low frequency-high severity fire regime. Such an occurrence is not out of the ordinary since not all tree origin data coincided with the selected fire episodes to calculate a proportion for these sites. Yet for particular topographic factors, the zero values may contribute misleading information for model development if their distribution is not true to expected values of severity for any given topographic position.

A second pitfall concerns sites 29-47, 67% of which had higher severity values than expected of the fire regime for their location (watershed sections B & C). This implies that one or more factors (topographic or otherwise) was particularly influential to cause the deviations. If the factor is not a component of the equation, the model will not provide accurate predictions. The graphs will be reviewed here therefore, to determine which factor influences the anomalous severe low elevation sites, and whether the non regenerative sites interfere with modeling accuracy.

Regeneration vs. elevation portrays an inverse relationship as evidenced by the abundance of higher severity sites below 1000 m and a decrease of such sites above 1200m.

When compared to an analysis of fire history for two other areas (within the Willamette N.F.) by Morrison and Swanson (1990), the results here are the opposite of what is expected for the range. Their study determined that the more severe fires resulting in increased regeneration occurred above 1067 m, while below this elevation fire return intervals dropped off markedly implying lower severity regimes. For the Augusta watershed, the severe low elevation sites indicate that another factor is influencing their response since they are not true to elevation. While all of the sites above 1000 m belong to watershed section A, for which greater severity is expected, over half of these are non-regenerative. These zero values are not true either and contribute to the inverse relationship.

For slope, the distribution of sites is relatively accurate. A threshold is apparent between 25-35% slope, below which greater regeneration was most prominent. The inverse correlation of slope and fire severity could be attributed to the gravitational gradient of water (Agee and Huff, 1987; Swanson, Kratz, Caine, and Woodmansee, 1988) which on gentle slopes serves to inhibit ignitions due to increased surface saturation. The result is an extension of the fire return interval, and severe fire conditions when ignition occurs. Slope is possibly an influencing factor of the severe low elevation sites. The wide variation of severe sites over the range of slopes, however, implies a dependency on additional factors such as accumulated drainage area, the hydraulic conductivity of the soil, and the distribution of fuels (Beven and Wood, 1983; Agee and Huff, 1987). It is unclear what effect positive values for the non-regenerative sites would have considering these interactions.

TCI, the index of moisture, is partially a function of accumulated drainage area and they are quite visibly correlated with one another. The latter was likely screened out because of multicollinearity. Both graphs impart an inverse relationship between severity, and moisture potential which increases with catchment size. It appears that moisture in not limiting in sites with less than .5 hectares accumulated drainage or a TCI value below 3.5. Accordingly, the variation in severity is widest below these points, where the majority of sites for all watershed sections fall (including most non-regenerative sites). TCI has little or no influence for sites below the thresholds and therefore offers little predictive value overall. Only sites 20, 12, and 15 were perhaps most influenced by either factor. As with slope, moisture interacts with other factors when conditions are drier, before it becomes limiting of severity on its own.

Aspect was likely screened out as a potential factor because of the wide variation in severity for all directions sampled. Azimuth possibly needs to be transformed into a linear scale for statistical purposes as well (Lienkaemper, 1994). Though there was no significant correlation, there is a trend which is not readily apparent. The trend is the clustering of sites with indices above .65 largely on north facing slopes (the severe low elevation sites account for 60% of sites above this index). Evidence suggests that northern aspects exhibit mostly greater regeneration for this region (Morrison and Swanson, 1990). If the non regenerative sites are presumed to imply high severity potential this would further support the trend. The distribution of sites for aspect is more accurate than the preceding factors. For this reason aspect is likely responsible for the distribution of severity values overall, especially with regard to elevation. Unfortunately, there were too few sites sampled from due E. south to due W. to examine how this trend might continue and to support a correlation for an aspect term in the model.

To summarize, the developed model is clearly inadequate as the distribution of high severity sites is dependent on a factor (aspect) not included in the model. The model is also limited by the ineffectiveness of the TCI term and the conceptual problem of non-regenerative sites and their effect on modeling elevation. Slope is the only accurate term in the model, yet the wide variation of severe sites over the range indicates that interaction is occurring that has not been accounted for. Let us now turn to a discussion of possible methods of improving the model.

V. Discussion

An analysis of the trends has revealed that the modeling effort here is only as good as the accuracy of the response variables and the completeness of the factors used to model them. Three improvements for modeling are suggested below for application to existing and future fire severity databases from the Augusta Creek watershed. The intricacies of scales in the wildland fire context (Simard, 1991) are then discussed to determine the accuracy of measurement scales for both severity and topography.

Modeling improvements

While fire severity as conceptualized appears to be accurate for more than half of the sites, it needs to be expanded to offer more accurate representation of non-regenerative sites. As quantified, the zero values are inaccurate with regard to modeling elevation; positive values would also improve other factor terms. Additional fire episodes could be used to calculate regeneration frequencies for sites which tree origin ages did not coincide with the designated intervals. If multiple fire episodes are used for a single watershed section, time series analysis might be necessary if the resulting observations are correlated over time (McClave and Dietrich, 1988). To do otherwise would violate the ANOVA assumption of independent errors. Further investigation is warranted depending on the sampling scenario.

Next, the design of the experiment requires more complete sampling across the range of the topographic factors to strengthen the correlations of each. Terms such as aspect would benefit greatly. Third, more investigative modeling of terms needs to be performed. These might include adding curvature (with quadratic terms) to reflect thresholds of severity response to topography. The correlation between slope, accumulated drainage area, and other factors related to moisture could be studied more closely through interactive modeling to determine the dependence of severity on soil surface saturation governed by these factors. Any multicollinear interactive terms could then be screened out using stepwise, rather than removing factors entirely from the model; this would enhance understanding of dependent factors and also increase the R-square value of the model.

Focus on Scale

Simard (1991) proposes that fire severity is a higher level process belonging to a synoptic scale class. This class is part of a hierarchy of processes hypothesized by Simard on the basis of symmetry with space and time and which follow a natural progression (table 4). According to this hierarchy, the conceptualization of fire severity used here is based upon the processes of fire behavior and

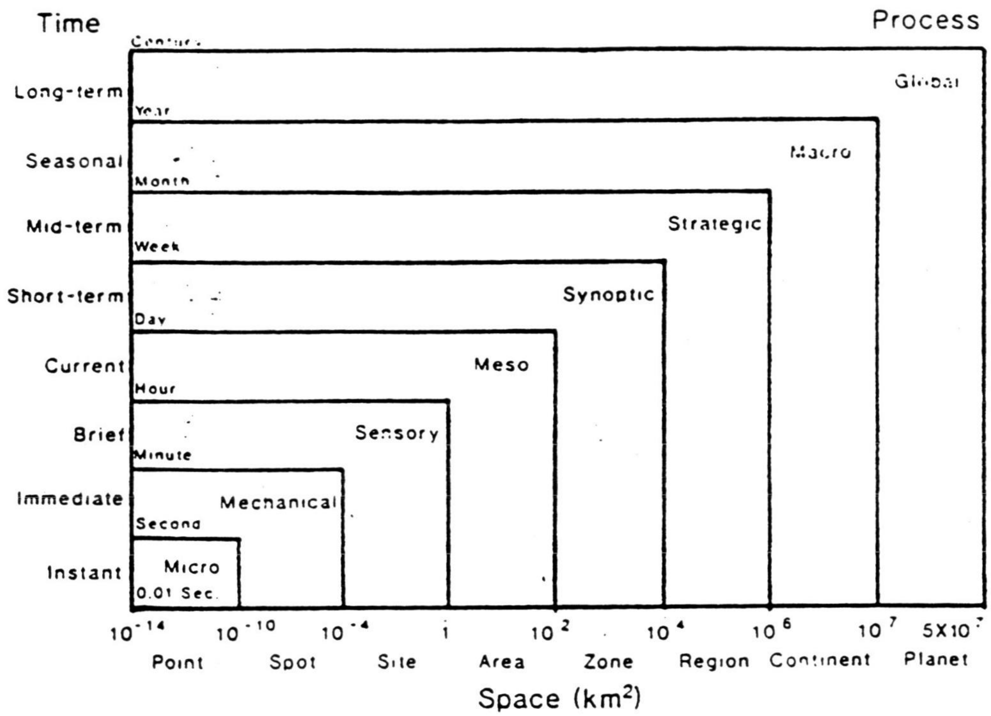
Table 4. Process scale class hierarchy for wildland fire. (Simard, 1991)

Name	Examples
Micro	Energy flux, pyrolysis, personal attitude
Mechanical	Temperature, radiation, ignition, individual behavior
Sensory	Weather observation, fire behavior, suppression, human activity
Meso	Thunderstorm, fire danger, dispatch, supervision
Synoptic	Cold front, fire severity, mobilization, production
Strategic	Drought, fire season, fire planning, organizational budget
Macro	Climate, fire ecology, fire policy, government
Global	Climate change, fire history, treaty

biology which represent sensory and mechanical scale classes respectively. In terms of space, these scale classes do not exceed 1 km^2 (.1 ha.), and .001 km^2 (.0001 ha.) respectively (fig. 6). In contrast, the synoptic scale represents a zone of between 1000 to 100,000 km^2. The process of fire severity can then be viewed as an aggregation of processes from the scale classes beneath it whose grouping generates the phenomena (Simard, 1991).

Simard (1991) maintains that severity as a synoptic process is poorly understood and that modeling lower scale (sensory) phenomena is a poor substitute with which to interpret it. This is based on two assumptions: first, we cannot directly model properties of the synoptic phenomena because our current lack of understanding does not allow us to readily observe or measure them. Second, the degree to which a model represents the real world is inversely proportional to the "conceptual distance" between the scale at which a response occurs, and that for the causative process being used to model the response (Simard, 1991). The conceptualization of severity used here has violated these assumptions because the scale at which severity was quantified (0.1 ha.) was used to represent a process that occurs over at least a 1000 km^2 (100 ha.) area, and that is not a direct function of topography. Thus, the measurement scale of the response variable (regeneration) was inaccurate for the purpose of characterizing severity.

Figure 6. A space/time/process taxonomy for wildland fire. (Simard, 1991)



Simard (1991) does not offer any practical solutions for quantifying severity at the hypothesized landscape resolution, but rather presents concepts of fire severity to facilitate new modeling strategies. These concepts are beyond the scope here, but their measures are pertinent. Of these, the ecosystem measure of fire severity validates the use of tree mortality and regeneration data in modeling. In this light, if the regeneration severity index were to be recognized as a fire behavior index, then the response variables could in turn be used to derive a severity quantity for each <u>section</u> of the Augusta watershed that meet the minimum size requirement (100 ha). There is sufficient land in the Augusta project area (8100 ha.) for model development at this scale. The 'true' index would be used to model severity based on factors which influence the response at the larger scale (i.e. weather systems as opposed to topography). Topographic factors such as used here would be reserved to evaluate the accuracy of the fire behavior response.

Conclusion

No satisfactory fire severity prediction model could be produced for the Augusta Creek watershed with the statistical methods and severity conceptualization used here. However, suggestions have been made that set the stage for further study and experimentation in the Augusta project area. These address modeling strategies, scale of the data, and the concept of fire severity itself. Swanson (et.al.,

1993) reminds us that physical and biological thresholds perceived in our observations are not necessarily common ecosystem behaviour. This thought is compounded by the fact that interpretations of the environment and its processes are equally diverse. In this light, we must strive for complete understanding of ecosystems, and accuracy in our models before our hypotheses are put to use. To do otherwise would be to compromise our efforts to preserve the environment. In the spirit of ecosystem management, until we have achieved this, ecological forestry alternatives to the management of forest ecosystems based on natural disturbance regimes deserve attention (Twight, 1973).

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VIII. Appendix A

Figure 2. SPSS/PC+ printout for regeneration prediction model based on 30m DEM topogrphic database. (Wallin, 1994)

Multiple R	.66739
R Square	.44540
Adjusted R Square	.40671
Standard Error	.29858

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	3	3.07863	1.02621
Residual	43	3.83338	.08915

F = 11.51125 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
ELEV	-8.35608E-04	1.98024E-04	-.486468	-4.220	.0001
SLOPE	-1.089371	.312395	-.420708	-3.487	.0011
TCI	-.148243	.040238	-.449736	-3.684	.0006
(Constant)	2.130942	.293621		7.257	.0000

------------- Variables not in the Equation -------------

Variable	Beta In	Partial	Min Toler	T	Sig T
ASP	.188253	.242083	.825695	1.617	.1134
ACC_AREA	.013750	.011166	.318047	.072	.9427

End Block Number 1 PIN = .050 Limits reached.

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1 Dependent Variable.. ORIG

Residuals Statistics:

	Min	Max	Mean	Std Dev	N
*PRED	-.0681	.9374	.4331	.2587	47
*RESID	-.5582	.6823	.0000	.2887	47
*ZPRED	-1.9373	1.9492	.0000	1.0000	47
*ZRESID	-1.8694	2.2851	.0000	.9668	47

Total Cases = 47

Durbin-Watson Test = 1.77686

Table 3: Residual analysis for the developed model.
Residual = response - (2.130942 - .000835608*elev - 1.089371*slope - .148243*TCI)

Site	Elevation m.	Slope %	Slope radians	TCI-scaleless	Regen obs.	Y-hat	Residual
--	--	--	--	--	--	--	--
1	1394	39	0.3721	1	0.45	0.412506	0.037494
2	1388	44	0.4162	1.92	0	0.233095	-0.2331
3	1399	69	0.6071	1.05	0.67	0.144914	0.525086
4	1198	18	0.1773	2.82	1	0.518693	0.481307
5	1200	7	0.0686	2.68	0.71	0.65619	0.05381
6	1236	24	0.2354	1.43	0.76	0.629705	0.130295
7	1303	48	0.4466	4.17	0.4	-0.06254	0.462542
8	1273	78	0.6605	1	0	0.19944	-0.19944
9	1295	82	0.6858	1	0	0.153496	-0.1535
10	1233	73	0.6285	1	0.95	0.267725	0.682275
11	1134	75	0.6449	2.85	0	0.058335	-0.05833
12	1031	37	0.3509	5.8	0	0.02736	-0.02736
13	1142	57	0.5201	1	0.91	0.461853	0.448147
14	1049	42	0.3934	1	1	0.677588	0.322412
15	1037	53	0.4880	3.52	0	0.210988	-0.21099
16	1403	25	0.2470	1.38	0	0.484934	-0.48493
17	1335	25	0.2486	1.37	0	0.541495	-0.54149
18	1297	38	0.3653	1.66	0.33	0.403128	-0.07313
19	1276	26	0.2529	3.14	0.67	0.323721	0.346279
20	1213	37	0.3574	5.37	0	-0.06806	0.068057
21	1195	48	0.4495	2.33	0	0.297312	-0.29731
22	1273	45	0.4262	2.4	0	0.24714	-0.24714
23	1320	65	0.5757	1.53	0	0.173977	-0.17398
24	1333	53	0.4888	1	0.17	0.336349	-0.16635
25	1373	54	0.4940	1.31	0	0.251305	-0.2513
26	1186	45	0.4218	2.41	0	0.323149	-0.32315
27	1205	72	0.6257	2.81	0	0.025852	-0.02585
28	1454	41	0.3922	2.49	0.167	0.119592	0.047408
29	937	21	0.2112	2.93	0.87	0.68355	0.18645
30	924	23	0.2306	3.06	0.7	0.654008	0.045992
31	767	49	0.4549	3.2	0.17	0.520098	-0.3501
32	919	69	0.6049	1.05	0.4	0.548403	-0.1484
33	864	48	0.4500	1	0.9	0.770517	0.129483
34	726	53	0.4868	2.94	0	0.55815	-0.55815
35	801	34	0.3236	2.7	1	0.708843	0.291157
36	708	73	0.6278	1.01	0.67	0.705699	-0.0357
37	754	22	0.2179	2.2	1	0.937385	0.062615
38	747	52	0.4758	1.76	1	0.727512	0.272488
39	774	52	0.4767	1	0.92	0.816635	0.103365
40	889	38	0.3649	3.53	0.29	0.467277	-0.17728
41	1021	63	0.5634	2.07	0.83	0.357172	0.472828
42	790	31	0.3029	4.34	0.44	0.497467	-0.05747
43	861	22	0.2203	2.88	0.83	0.744555	0.085445
44	910	18	0.1815	1.7	0.73	0.920805	-0.1908
45	953	44	0.4176	2.6	0.67	0.494254	0.175746
46	892	55	0.5011	1	0.5	0.691453	-0.19145
47	951	48	0.4488	2.33	0.25	0.501963	-0.25196
						Sum of residuals=	0.00201