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Remote Sensing of Vegetation Responses During the First 20 Years Following the 1980 Eruption of Mount St. Helens: A Spatially and Temporally Stratified Analysis

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8.1 Introduction

The variety of disturbance mechanisms involved in the 1980 eruption of Mount St. Helens (e.g., heat, burial, and impact force) and the resulting diversity of vegetation responses have provided abundant opportunities for disturbance-zone-specific research (Frenzen 1992; Frenzen et al. 1994). As evidenced by the research reported in this volume, tremendous amounts of knowledge can be acquired from studies that focus on vegetation responses within individual disturbance zones, such as the debris-avalanche deposit. As the responses to the eruption continue to develop, however, it becomes increasingly important to understand the larger context for specific study sites: What responses are common among disturbance zones? And what responses are distinctive to certain disturbance mechanisms and sites? Can the lessons from a local area be generalized throughout the disturbed area or even throughout a zone dominated by one disturbance type? These questions can be addressed in at least two ways:

- Studies at different sites can be compared for similar or divergent processes and states.
- Spatial-analysis tools can be used to evaluate response patterns across the disturbed area.

The first approach can be achieved through a comparative analysis of the disturbance-zone-specific studies reported in this volume and elsewhere. In this chapter, vegetation-response patterns present across disturbance zones are evaluated for, among other things, consistency with the ground-based observations and analyses available from other studies.

It is important in studying the first 20 years of vegetation response across the disturbed landscape at Mount St. Helens that the analysis be stratified, both spatially and temporally. Previous research indicated that early vegetation responses were largely dependent on the variable effects of disturbance mechanisms (Adams et al. 1987; Lawrence and Ripple 2000) as well as the substrates resulting from the volcanic events (del Moral and Clampitt 1985). Areas that had substantial biotic legacies (buried seeds, sprouting roots, or downed woody debris), for example, had much faster early vegetation development than areas dominated by primary successional processes, although posteruption management practices might be at least equally important (Figure 8.1). Within these broad categories, additional distinctions might be made based, for example, on the nature of the volcanic deposits (e.g., pumice deposits versus mudflow remnants). In addition, the area devastated by the 1980 eruption has experienced three distinctive posteruption management regimes (Franklin et al. 1988): (1) Mount St. Helens National Volcanic Monument (Monument), where natural processes of ecological recovery were allowed to dominate after its establishment in 1982 (although seeding with nonnative plants and salvage logging occurred in limited areas before that time); (2) Gifford Pinchot National Forest (GPNF) outside the Monument, which experienced salvage logging that was substantially completed by 1984 and then planted with commercial conifer species, mainly Douglas-fir [*Pseudotsuga menziesii* (Mirbel) Franco] seedlings; and (3) private forestlands, where portions were seeded with nonnative grasses and legumes, salvage logging was completed by 1982, and commercial conifer species were planted, also mainly Douglas-fir seedlings, although limited areas were left unplanted. Finally, spatial stratification by disturbance type and management regime enables important comparisons between analyses across disturbance zones and many of the analyses that provide more detail regarding individual disturbance zones.

Temporal stratification enables the analysis of changes in factors driving vegetation response over time. Early responses were likely most affected by factors relating to growth of survivors and success of colonizers, while later responses might have been affected more by factors relating to growth rates, both of individual plants and of established colonies through reproduction. Further, the timing of any such shifts in the relative influence of important factors could have depended on disturbance mechanisms or management practices.

The purpose of this study was to examine patterns of vegetation responses relative to selected ecological driving factors within each disturbance zone resulting from the 1980 eruption

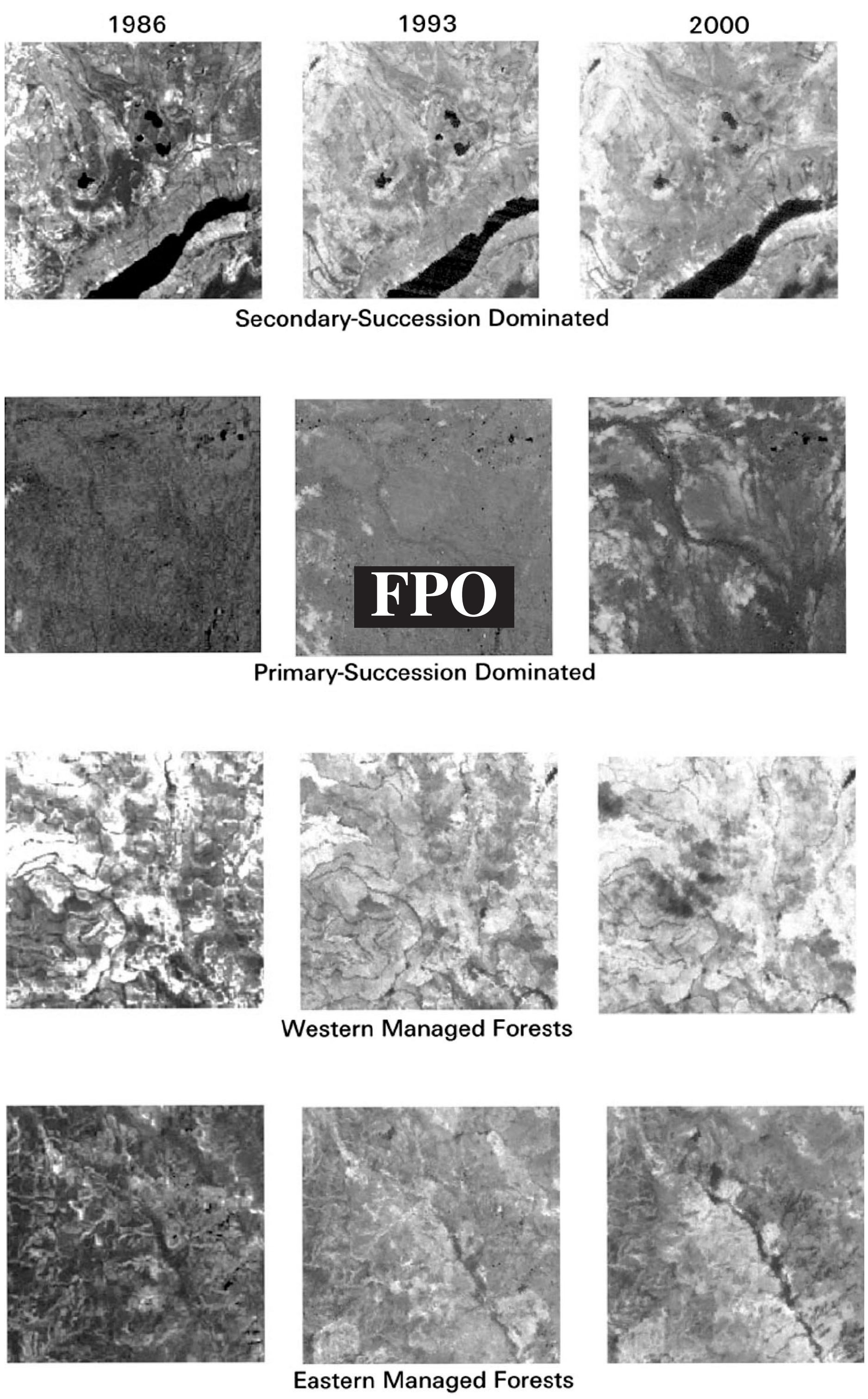

FIGURE 8.1. Patterns of recovery are visually strikingly different among different disturbance zones and different management regimes. These 12 images show normalized difference vegetation index (NDVI) for four locations at the end of each of the study periods. The secondary-succession-dominated location is primarily within the blowdown zone whereas the primary-succession-dominated location is primarily within the pyroclastic-flow deposits.

of Mount St. Helens and the subsequent management zones and to compare the responses across zones. The first question examined, therefore, was why certain locations within disturbance and management zones were developing differently than were other locations within the same disturbance and management zones, while the second question addressed whether differences existed among zones. This analysis both provides a view of the importance of certain factors within the entirety of each zone, which can be viewed in conjunction with ground-based studies within each zone, and enables rigorous comparisons across zones because the same data and methods are applied to all zones.

The impacts of these factors were analyzed over three time periods for six broadly defined disturbance types within the portion of the study area allowed to respond in a largely unmanaged manner as well as within areas planted with trees by the U.S. Forest Service and private industry. The study used a surrogate for vegetation response (change in a spectral index related to vegetation amount) rather than direct ecological measures, such as changes in absolute biomass, vegetation cover, or plant-community composition. That surrogate measurement was made at a spatial detail or resolution of approximately 25 m. Vegetation patterns can vary depending on how vegetation is measured, what vegetation characteristics are measured, and what resolution or scale is used. A patchy vegetation pattern at ground-plot scales, for example, might not be patchy at coarser resolutions, whereas a pattern that might show little variability across spatial extents measured on the ground might exhibit substantial variability when the entire zone is measured. The conclusions and inferences drawn from this study, therefore, as with all other observational studies, are limited to the nature of these measurements. A review of multiple studies at different scales and involving other vegetation measures provides a more complete picture of the developing vegetation patterns and their underlying processes.

8.2 Methods

The study area (Figure 8.2) included most of the area denoted by Lipman and Mullineaux (1981) as devastated by the 1980 eruption of Mount St. Helens. Excluded were talus deposits, lava domes, and new crater walls because they have not shown any detectable vegetation in the imagery acquired for the study. The central portion of the study area was part of the Monument where ecological response occurred with a minimum of human intervention (Franklin et al. 1988). Managed forests were present to the east and west.

The study area was divided into eight geographical strata, consisting of six disturbance zones within the Monument and two additional management strata outside the Monument (Table 8.1). The strata were not necessarily contiguous; areas of pyroclastic-flow deposits, for example, were scattered within the study area (see Figure 8.2). The six disturbance zones within the Monument were based on broad disturbance types mapped by the U.S. Geological Survey (USGS) (Lipman and Mullineaux 1981), including four zones dominated by primary successional processes (the debris-avalanche, mudflow, and pyroclastic-flow deposits and the tree-removal zone) and two zones that were dominated by secondary successional processes (blowdown zone and scorch zone) (Lawrence and Ripple 2000). It is important to note that these distinctions refer to the broad-scale dominance of certain types of processes and that, for example, isolated survivors within the mudflow and tree-removal zones resulted in some responses within those zones being of a secondary successional nature. The two strata of lands with intensive forest management included the eastern portion managed by GPNF and the western portion managed predominantly by private industry, each of which included a variety of disturbance types.

The study was stratified into three time periods, each encompassing seven growing seasons (the initial eruption occurred

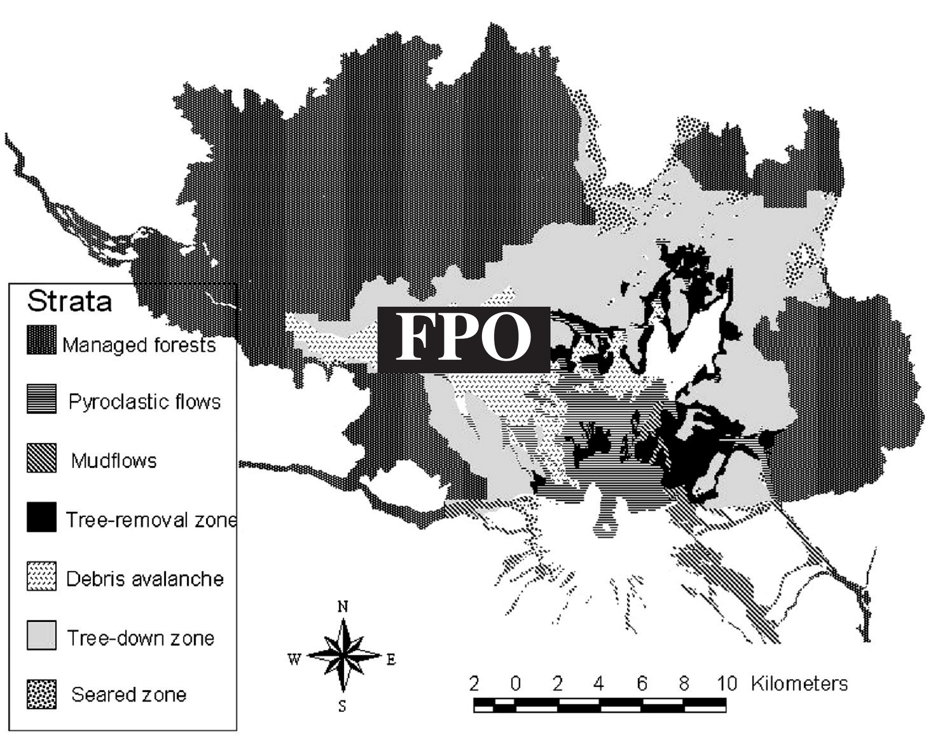

FIGURE 8.2. Map of the study area showing spatial strata based on major disturbance types and management regimes.

TABLE 8.1. Area of each stratum of the landscape studied.

Stratum or zone	Area (km^2)
Debris-avalanche deposits	36
Gifford Pinchot National Forest (NF) (outside national monument)	80
Mudflow deposits	17
Private industry land	247
Pyroclastic-flow deposits	30
Scorch zone	15
Blowdown zone	120
Tree-removal zone	32

Areas of strata other than the Gifford Pinchot National Forest and private industry lands include only those areas within the Mount St. Helens National Volcanic Monument.

before the 1980 growing season) and each beginning when the previous period ended: 1980–1986 (period 1); 1986–1993 (period 2); and 1993–2000 (period 3). Although these time periods were arbitrary, they coincided with available satellite imagery and enabled comparisons in intervals of equal length throughout the 20 years following the eruption.

Previous research suggested that three broad categories of factors affecting vegetation response should be examined (Lawrence and Ripple 2000):

- Direct effects of the eruption
- Posteruption physical forces
- Other habitat conditions

Although most factors could not be measured directly (as is often the case in observation-based ecological studies), it was worthwhile to examine variables related to these factors because, if a certain factor was important for vegetation development, then we would expect to see a correlation between a related variable and our measure of vegetation change. If temperature differences related to elevation were important, for example, we would expect to see a correlation between vegetation change and elevation even though we were unable to collect temperature readings for all locations consistently throughout the study period. Direct effects of the eruption examined included four factors:

1. More specific disturbance types were assigned to each geographical stratum originally containing multiple types, as mapped by the USGS, because the disturbance types affected the initial conditions for vegetation development (see Figure 8.1) in terms of both available substrates and potential for surviving vegetation and propagules. Seven zones within the debris-avalanche deposits were identified, for example; the tree-removal, blowdown, and scorch zones did not contain multiple disturbance types.
2. Direct exposure to the directed blast was assessed because topographic shielding from the blast could also affect initial conditions (Figure 8.3).
3. Distance from the crater was measured. That distance could be related to the intensity of the impacts and, among other things, the presence of surviving vegetation and propagules.
4. Initial air-fall tephra thickness from eruptions through July 22, 1980 was determined (Waitt et al. 1981) because it could affect the ability of survivors to establish and the ability of colonizers to reach organic soils.

Posteruption physical forces were also examined in terms of (1) slope gradient (Figure 8.4), with the assumption that steeper slopes experienced more erosion of tephra deposited in 1980, and (2) distance from surviving forests (Figure 8.5), which was potentially related to windborne and animal-borne seed dispersal (including in planted forests, where nonplanted vegetation, such as shrubs, forbs, and grasses, might have dispersed from surviving forests). Other habitat conditions examined included elevation and aspect (see Figure 8.3), which can affect growing conditions, such as temperature and incident solar radiation (Allen and Peet 1990). In addition, for period 2 and period 3, the effect of previous period vegetation on subsequent vegetation change was evaluated separately because the presence of established vegetation could result in higher growth rates and more-proximate seed sources.

Analysis was conducted with Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery from August 26, 1986; August 29, 1993; and July 7, 2000. Although the 2000 image was from an earlier portion of the growing season than the other images and this difference might have affected the results, it was the closest date for which a clear image was available. Images were georeferenced to a Universal Transverse Mercator grid, resampled to a 25-m pixel size, and coregistered to less than 12.5-m root mean squared error. All image values were converted to exoatmospheric reflectance based on current calibration data, which accounted for differences in dynamic ranges of the TM and ETM+ sensors, sun angle and distance differences, and some atmospheric scattering (Clark 1986; Chavez 1996; NASA 2001).

For each image, the normalized difference vegetation index (NDVI) was calculated as a surrogate vegetation response because ground calibration data were not available to estimate vegetation parameters with the imagery. NDVI is the most widely used index of vegetation amount from remotely sensed imagery and is calculated as

$$\text{(near-infrared reflectance} - \text{red reflectance)/} \\ \text{(near-infrared reflectance} + \text{red reflectance)}$$

(Rouse et al. 1973). NDVI values theoretically range from -1 to 1; but in practice, values near 0 (where near-infrared and red reflectance are roughly equal) represent little or no vegetation, whereas increasing positive values (where near-infrared reflectance increases relative to red reflectance) represent increasing vegetation amounts. NDVI has been found to be highly correlated with a wide variety of vegetation parameters, including leaf-area index, aboveground biomass, vegetation cover, and the fraction of photosynthetically active radiation (fPAR) absorbed by vegetation (Running et al. 1986; Anderson et al. 1993; Yoder and Waring 1994). NDVI is particularly

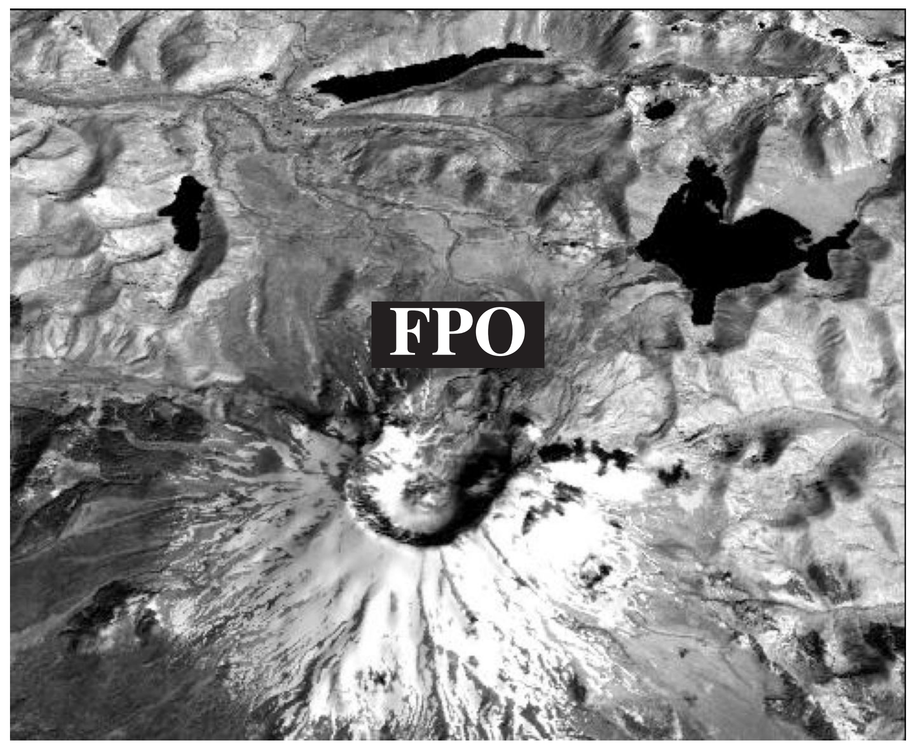

FIGURE 8.3. Three-dimensional rendering of a 2000 Landsat ETM+ panchromatic image illustrates several potential factors affecting vegetation responses. A careful examination shows that some slopes on the far side of ridges from the crater might have more vegetation, possibly as a result of topographic shielding from the directed blast. The analysis, however, generally did not show this to be statistically important. Possible effects of elevation and topographic aspect might also be seen.

useful, therefore, as a surrogate for vegetation amount when it is logistically impractical to collect ground reference data to calibrate remote-sensing data [for example, when spatial extents are large (e.g., Eastman and Fulk 1993) or when legal or safety restraints restrict sampling]. Some disadvantages to using NDVI as a surrogate are that it does not relate to any specific vegetation measure (such as biomass), its relationship to specific vegetation measures is not perfect, it can be

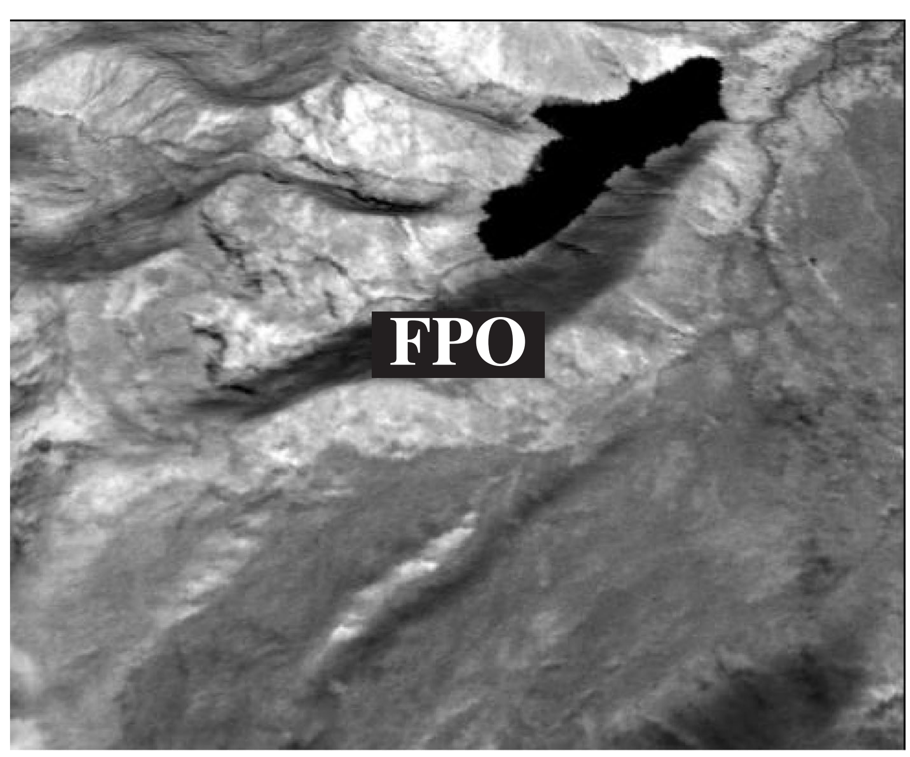

FIGURE 8.4. Three-dimensional rendering of a 2000 Landsat ETM+ panchromatic image shows effects possibly related to slope gradient. The steeper slopes show a different response than flatter locations.

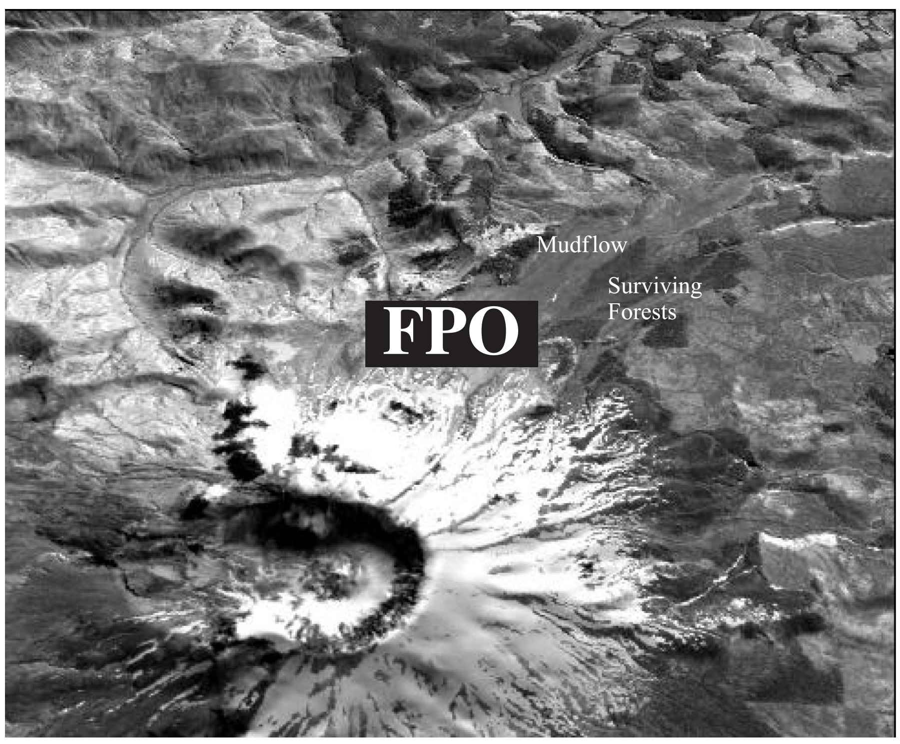

FIGURE 8.5. Three-dimensional rendering of a 2000 Landsat ETM+ panchromatic image shows areas of surviving forests next to disturbed zones, such as mudflow deposits. If seed dispersal from surviving forests was important in the varying responses across the mudflows, then we would expect a strong statistical relationship between distance to surviving forests and changes in NDVI. This statistical relationship was present during all periods but was especially strong during period 1.

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sensitive to soil variations, and it loses sensitivity at high leaf-canopy densities. NDVI was found to perform better at Mount St. Helens than did other common vegetation indices, such as soil-adjusted indices and tasseled-cap greenness (Lawrence and Ripple 1998). NDVI was used, therefore, as a measure of relative vegetation response, although for this study the data were not available to statistically correlate it to any specific measure of vegetation amount.

Relative vegetation response for each period was calculated as NDVI at the end of the period minus NDVI at the beginning of the period (with the assumption of no vegetation immediately after the May 18, 1980 eruption detectable with 25-m-resolution satellite imagery) (Figures 8.6, 8.7, 8.8). This approach permitted an analysis of only vegetation growth during each period. Our previous study focused on vegetation trajectories during the first 15 years following the eruption without temporal stratification (Lawrence and Ripple 2000).

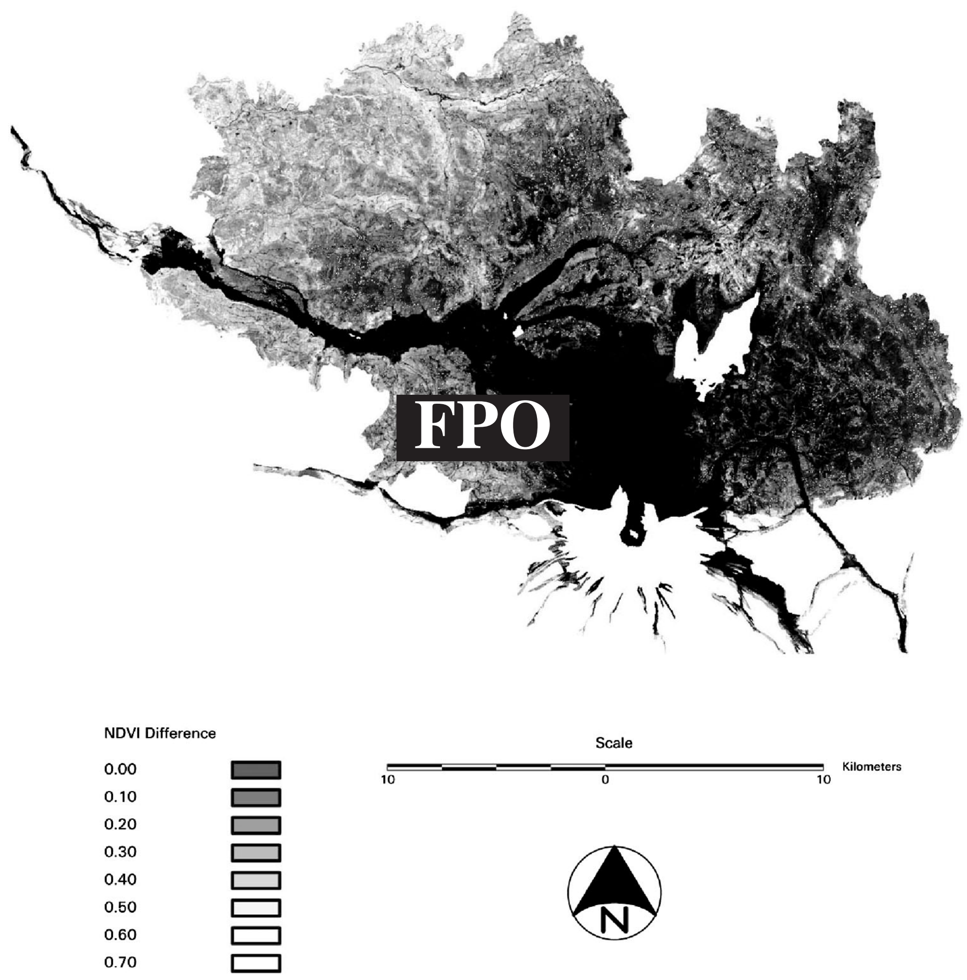
Statistical analyses were conducted with regression-tree analysis (RTA) (Breiman et al. 1984; Lawrence and Ripple 2000). Although multiple linear regression was examined, RTA consistently explained a larger portion of the variability in the data. Further, the spatially correlated nature of the data violated the assumption of independent observations for multiple linear regression. For each of the spatial strata, data from all pixels within the stratum were extracted for statistical analysis. The analysis was, therefore, a complete description of the relationships among the variables within each stratum because a complete census was analyzed rather than a sample. Analyses initially were conducted with all explanatory variables except previous-period NDVI to isolate the effects of previous vegetation amount from other factors, and then the effect of previous-period NDVI was added. For consistency of analysis, all regression trees were pruned to the 10 most important terminal nodes (response values), except when there were ties for the 10th node, in which event all tied nodes were evaluated. With eight strata and three periods, 24 regression trees were analyzed, plus an additional 16 to add the effects of previous-period vegetation for period 2 and period 3.

8.3 Results

The results of the RTA were examined for trends over time and for differences among strata. Importance of factors was determined primarily as a function of statistical deviance explained (i.e., the sum of the squared differences from the mean of the response variable) because this method provided a relative measure of the strength of the relationship between each explanatory variable and change in NDVI. Important factors considered were

- The total amount of deviance explained by the analysis;
- The amount of total deviance explained by each variable (the percent of total deviance);
- The relative amount of deviance explained by each variable (the relative deviance); and, most important,
- Changes in the relative importance of explanatory variables over time.

FIGURE 8.6. Differences in NDVI from 1980 to 1986. The study area was assumed to have no vegetation detectable by the Landsat imagery immediately after the May 18, 1980, eruption.



Many factors might affect vegetation responses, and no doubt many of these potential influences were not and could not be quantified for this study. Rather than attempt to explain all factors influencing vegetation responses, the variables that were included in this study reflected patterns and processes found to be potentially important in previous ground-based and remote-sensing studies (Lawrence and Ripple 2000).

RTA results are in the form of dichotomous trees that are often complex and reveal multiple interactions among predictor variables. An analysis of the resulting trees, however, revealed that the effect of important variables was as expected. Generally, as measured by predicted NDVI, when statistically important in the analysis, slower vegetation development was predicted by direct exposure to the directed blast, closer distances to the crater, thicker initial airfall-tephra layers, less-steep slope gradients, longer distances from surviving forests, and higher elevations.

8.3.1 Primary-Succession-Dominated Strata

During period 1 on the debris-avalanche deposits, the strongest factor related to vegetation response examined was distance to surviving forests, which accounted for more than half of relative deviance (Table 8.2). Avalanche units and slope each accounted for about 14% of relative deviance; aspect, distance from the crater, and tephra thickness were less important. On the mudflow deposits, distance to surviving forests was even more important, accounting for 78% of relative deviance. Tephra thickness, aspect, slope, and elevation were minor contributors. The pyroclastic-flow deposits exhibited a different pattern, with elevation and distance to the crater having the strongest relationship, collectively accounting for 65% of relative deviance. Distance to surviving forests and slope gradient had moderate relationships. Responses for the tree-removal zone were largely related to distance from the crater (79% of relative deviance), with moderate correlation to elevation.

During period 2 on the debris-avalanche deposits, distance to surviving forests explained somewhat less deviance; elevation was added as an explanatory variable, with the second largest impact; and tephra thickness, slope, and aspect ceased to be included in the model. The same pattern, but more pronounced, occurred on the mudflow deposits, where, compared to period 1, the importance of distance to surviving forests decreased by 68% and the importance of elevation increased by

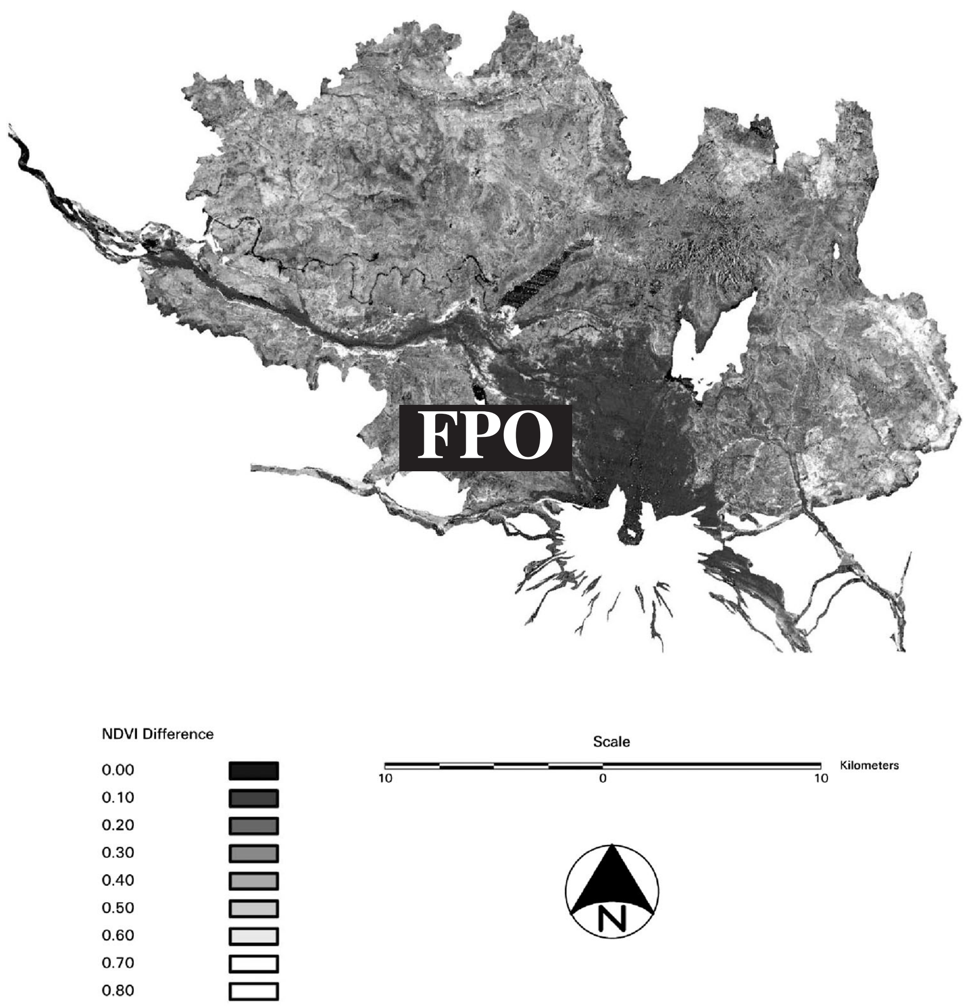


FIGURE 8.7. Differences in NDVI from 1986 to 1993.

70%. On the pyroclastic-flow deposits, elevation became the dominant factor, and some distinctions became evident among the various pyroclastic flows. An exception to this pattern was seen in the tree-removal zone, where elevation increased as a percent of relative deviance but was close to stable in terms of total deviance. There, distance to the crater was greatly reduced in importance relative to other factors.

During period 3, elevation became the dominant factor affecting vegetation change for the debris-avalanche and pyroclastic-flow deposits and especially for the tree-removal zone. On the mudflow deposits, distance from the crater increased greatly in importance whereas elevation decreased in importance. This trend might be misleading because, on the mudflow deposits more than any other stratum, elevation and distance from the crater tended to be correlated.

Including NDVI from previous periods had varying effects, depending on the stratum. In general, this measure of previous-period vegetation improved explanation of deviance by 5% $\pm$ 2%. The exceptions were for the mudflow deposits, where improvement was 9% in period 2 and 11% in period 3, and for the pyroclastic-flow deposits, where improvement was only 2% in period 3.

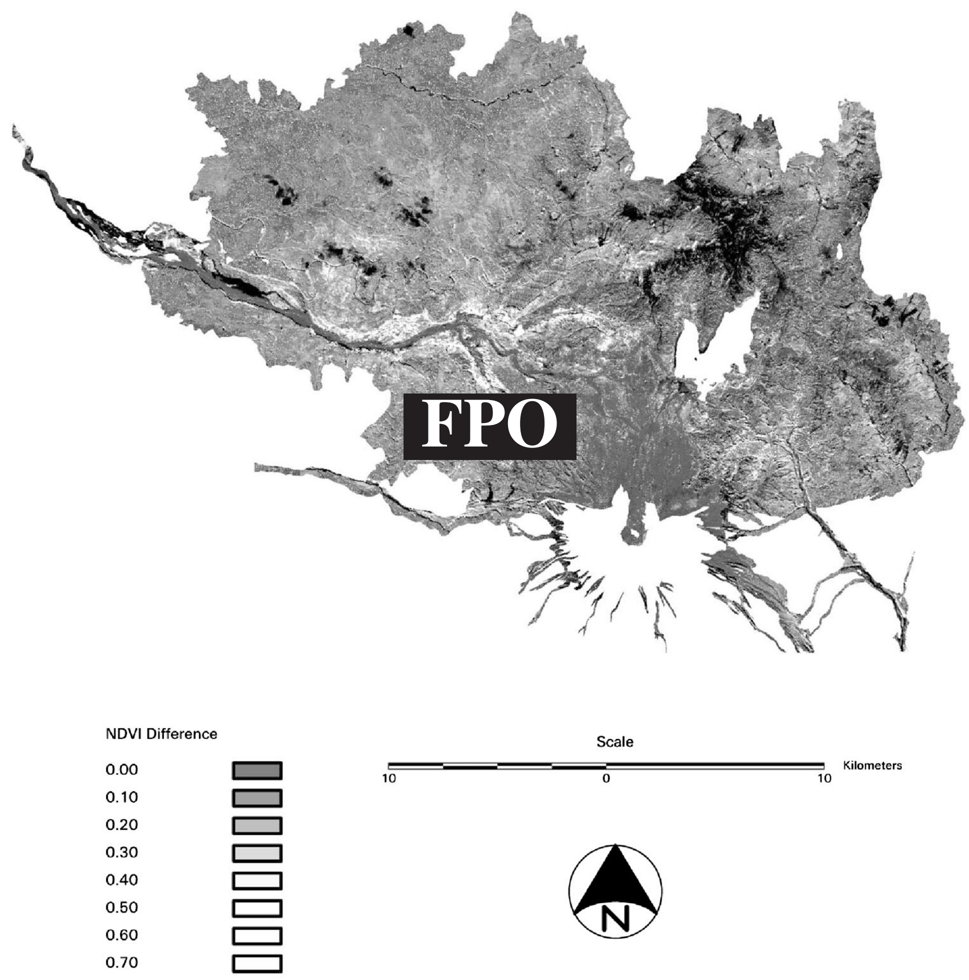
8.3.2 Secondary-Succession-Dominated Strata

For period 1 in the blowdown zone, most deviance was explained by slope gradient and tephra thickness, which together accounted for 70% of relative deviance (Table 8.3). Distance from the crater had a moderate relationship to vegetation change, and other factors were relatively minor. In the scorch zone, distance to surviving forests and aspect were most important, slope had a moderate relationship, and other factors were minor. The scorch zone in period 1 was the only instance in which direct exposure to the directed blast was included, accounting for 7% of relative deviance.

In period 2 for both the blowdown and scorch zones, the least amount of total deviance was explained for any of the analyses of unmanaged strata: 10% for the blowdown zone and 15% for the scorch zone. Of the deviance explained, the most important factors were aspect for the blowdown zone (61%) and distance from the crater and elevation for the scorch zone, collectively accounting for 70%.

During period 3 for both secondary-succession-dominated zones, elevation was the dominant factor. Also for both zones, aspect was a moderately important factor. Distance from the

FIGURE 8.8. Differences in NDVI from 1993 to 2000.



crater was a moderately important factor for the scorch zone and a minor factor for the blowdown zone.

Inclusion of previous-period NDVI had a substantial positive effect on total deviance explained in secondary-succession-dominated strata during period 2, when total variability explained was otherwise low. Improvement was 6% in the blowdown zone and 23% in the scorch zone. For period 3, however, improvement was less than 3% in both zones.

8.3.3 Managed-Forest Strata

Vegetation response for the eastern managed forests was most related to distance to surviving forests during period 1 (Table 8.4) Distance from the crater and variation among disturbance zones were moderately important, whereas elevation and slope were minor factors. Responses for the western managed forests were strongly related to distance from the crater and disturbance type, with lesser impacts of tephra thickness, distance from surviving forests, and elevation.

For the eastern managed forests, disturbance zones, elevation, and slope increased in importance during period 2, whereas distance from the crater remained fairly constant in relative effect and distance from surviving forests decreased substantially in importance. For the western managed forests, elevation became the dominant factor, while distance from surviving forest had moderate impacts.

During period 3, elevation was the dominant factor for all the managed forests. Also, for all the managed forests, distance from the crater increased substantially in importance. For the eastern managed forests, disturbance zones continued to have moderate influence, while aspect also became moderately influential.

Adding previous-period NDVI to the analysis had a moderate impact on analysis of the eastern managed forests, similar to most other strata. Increases in total deviance explained were 8% for period 2 and 6% for period 3. The impact on the western managed-forest analyses was more dramatic, however, with increases in total deviance explained of 20% in period 2 and 11% in period 3.

8.4 Discussion

The most important factors for early (period 1) vegetation response were factors likely correlated with vegetation survival and reestablishment, consistent with some previous studies

TABLE 8.2. Importance in the regression-tree analysis of each explanatory variable for each period for the primary-succession-dominated strata.

	Period 1 (1980–1986)		Period 2 (1986–1993)		Period 3 (1993–2000)	
	Total deviance (%)	Relative deviance	Total deviance (%)	Relative deviance	Total deviance (%)	Relative deviance
Debris-avalanche deposits						
Disturbance	10.5	14.8	4.1	12.9	0.9	4.0
Exposure	—	—	—	—	—	—
Tephra depth	1.2	3.0	—	—	—	—
Crater distance	1.6	4.0	5.3	16.6	3.6	16.0
Forest distance	22.1	55.4	14.9	46.5	6.3	28.1
Elevation	—	—	7.6	23.8	11.6	52.1
Slope	5.5	13.9	—	—	—	—
Aspect	3.6	9.1	—	—	—	—
Total	39.8	100.0	32.1	100.0	22.3	100.0
Mudflow deposits						
Disturbance	—	—	0.6	1.9	—	—
Exposure	—	—	—	—	—	—
Tephra depth	2.6	6.0	0.9	2.6	—	—
Crater distance	—	—	1.3	3.8	10.6	42.1
Forest distance	34.1	77.6	3.2	9.2	6.6	25.9
Elevation	2.3	5.3	25.9	75.2	3.8	15.0
Slope	2.4	5.4	—	—	—	—
Aspect	2.5	5.7	2.5	7.3	4.3	16.8
Total	44.0	100.0	34.5	100.0	25.2	100.0
Pyroclastic-flow deposits						
Disturbance	—	—	5.0	12.9	3.7	15.4
Exposure	—	—	—	—	—	—
Tephra depth	3.3	7.0	0.6	1.6	—	—
Crater distance	12.6	26.3	2.4	6.3	2.7	11.4
Forest distance	6.0	12.4	1.9	4.9	2.8	11.6
Elevation	18.5	38.6	25.9	67.1	13.9	58.3
Slope	5.5	11.5	—	—	—	—
Aspect	2.0	4.2	2.7	7.1	0.8	3.2
Total	47.9	100.0	38.6	100.0	23.8	100.0
Tree-removal zone						
Disturbance	—	—	—	—	—	—
Exposure	—	—	—	—	—	—
Tephra depth	0.7	1.1	—	—	—	—
Crater distance	48.6	78.9	2.4	12.0	2.7	6.5
Forest distance	1.4	2.2	4.5	22.3	2.9	6.8
Elevation	6.9	11.1	7.5	37.5	33.9	80.2
Slope	3.1	5.0	4.3	21.6	—	—
Aspect	1.0	1.6	1.3	6.6	2.7	6.5
Total	61.6	100.0	20.1	100.0	42.3	100.0

Percent of total deviance is relative to total deviance in the response variable. Relative deviance explained is proportional to deviance explained by the first 10 terminal nodes of the regression-tree analysis.

(Halpern and Harmon 1983; Wood and del Moral 1987; Lawrence and Ripple 2000; but see Dale 1989). In primary-succession-dominated zones, where vegetation response was dependent almost exclusively on colonizers, the statistically most important factor was distance to surviving forests in most cases. This finding was consistent with some studies of early reestablishment that found that isolation appeared to be the primary limiting factor on primary successional sites. Although one study that examined this question did not find a statistically significant correlation between seedling density and distance from seed sources (Dale 1989), that study did show a general decline in density with distance up to 1.09 km. The lack of significance in the earlier study was attributable to the high variability in the seed and seedling locations and chance events, factors that were found to be important in several other primary-succession sites at Mount St. Helens (del Moral and Bliss 1993; del Moral et al., Chapter 7, this volume). High variability can interfere with the detection of statistically significant differences in studies based on sampling. The current study, however, is based on a complete census of the observational units (image pixels). The observed pattern was true for the debris-avalanche and mudflow deposits whereas distance to

TABLE 8.3. Importance in the regression-tree analysis of each explanatory variable for each period for the secondary-succession-dominated strata.

	Period 1 (1980–1986)		Period 2 (1986–1993)		Period 3 (1993–2000)	
	Total deviance (%)	Relative deviance	Total deviance (%)	Relative deviance	Total deviance (%)	Relative deviance
Blowdown zone						
Disturbance	—	—	—	—	—	—
Exposure	—	—	—	—	—	—
Tephra depth	10.9	32.1	—	—	—	—
Crater distance	4.3	12.5	1.7	17.3	0.7	1.9
Forest distance	2.2	6.6	0.3	3.4	—	—
Elevation	1.0	2.8	1.8	18.5	29.7	85.4
Slope	12.9	37.8	—	—	—	—
Aspect	2.8	8.2	6.0	61.0	4.4	12.7
Total	34.1	100.0	9.8	100.0	34.8	100.0
Scorch zone						
Disturbance	—	—	—	—	—	—
Exposure	1.4	6.6	—	—	—	—
Tephra depth	—	—	—	—	—	—
Crater distance	1.1	5.5	5.2	35.6	6.5	13.1
Forest distance	7.0	34.3	1.2	8.4	—	—
Elevation	1.4	7.0	5.0	33.9	32.0	64.2
Slope	2.3	11.4	0.9	5.8	—	—
Aspect	7.2	35.0	2.4	16.4	11.3	22.7
Total	20.5	100.0	14.6	100.0	49.8	100.0

Percent of total deviance is relative to total deviance in the response variable. Relative deviance explained is proportional to deviance explained by the first ten terminal nodes of the regression-tree analysis.

TABLE 8.4. Importance in the regression-tree analysis of each explanatory variable for each period for the actively managed strata.

	Period 1 (1980–1986)		Period 2 (1986–1993)		Period 3 (1993–2000)	
	Total deviance (%)	Relative deviance	Total deviance (%)	Relative deviance	Total deviance (%)	Relative deviance
Eastern managed forests						
Disturbance	7.8	17.9	9.8	33.6	1.4	13.3
Exposure	—	—	—	—	—	—
Tephra depth	—	—	—	—	—	—
Crater distance	5.8	13.3	3.6	12.5	3.0	29.2
Forest distance	23.5	53.8	2.9	9.9	0.3	3.1
Elevation	3.2	7.4	9.0	30.9	4.1	40.6
Slope	2.6	6.0	3.8	13.2	—	—
Aspect	—	—	—	—	1.4	13.6
Total	43.8	100.0	29.1	100.0	10.2	100.0
Western managed forests						
Disturbance	14.2	31.7	—	—	0.6	3.2
Exposure	—	—	—	—	0.6	3.3
Tephra depth	6.0	13.3	1.1	6.3	—	—
Crater distance	18.9	42.3	0.6	3.5	2.5	13.3
Forest distance	3.7	8.4	2.6	14.3	1.6	8.4
Elevation	1.9	4.3	13.7	75.8	13.8	71.8
Slope	—	—	—	—	—	—
Aspect	—	—	—	—	—	—
Total	44.8	100.0	18.1	100.0	19.2	100.0

Percent of total deviance is relative to total deviance in the response variable. Relative deviance explained is proportional to deviance explained by the first ten terminal nodes of the regression-tree analysis.

surviving forests was moderately important for the pyroclastic-flow deposits. At least one other study covering period 1 also found that seed dispersal was not an important factor on the pyroclastic-flow deposits (Wood and Morris 1990). The exception to this pattern was the tree-removal zone, which on average tended to be more distant from surviving forests (as were many, but not all, of the pyroclastic-flow deposits). For the tree-removal zone and the pyroclastic-flow deposits, the most important factor was distance from the crater, which might have been correlated with the intensity of the eruption's impacts.

In secondary-succession-dominated zones, where previous studies have shown biotic legacies potentially were more important than colonizers, at least initially (Franklin et al. 1985; Lawrence and Ripple 2000), a notably different set of factors was statistically most important in the early period. In the blowdown zone, which dominated secondary successional zones in area (Table 8.1; Franklin et al. 1988), the primary factors were tephra thickness and slope. This result was partially consistent with previous studies that found that factors favoring recovery of buried survivors should be paramount in this zone and that tephra depth was the most important site characteristic for this zone during period 1 (Halpern et al. 1990). Halpern et al. (1990) did not find slope gradient significant; however, this finding might have been the result of lack of statistical power ($n = 35$ for Halpern et al. 1990). Tephra thickness was the primary factor determining depth of burial, whereas steeper slopes resulted in greater erosion of tephra layers (Collins and Dunne 1986), thereby enhancing chances of establishment by buried survivors. In the scorch zone, distance from surviving forests was important (Lawrence and Ripple 2000), perhaps influenced by a combination of lessening of the force of the directed blast and the impedance of seed dispersal by upright, dead trees and shrubs.

In both primary- and secondary-succession-dominated zones, the most notable trend during period 2 and period 3 was a reduction in importance of the factors likely correlated with vegetation establishment and an increase in importance of factors more likely related to vegetation growth, including reproduction. Most important was the steady increase in importance of elevation as a factor. Increases in elevation are associated with decreased plant growth because of associated decreases in temperature and evapotranspiration and increases in snow depth and persistence (Allen and Peet 1990). In all primary-succession-dominated zones, elevation became at least one of the most important factors during period 2 and the most important factor by period 3, except for the mudflow deposits, where distance from the crater (which was highly correlated to elevation for that stratum) was most important. This finding was consistent with previous studies that found reproducing colonies of species beginning to develop in period 2 (del Moral and Wood 1993a). Slope, which was important during period 1, possibly because steeper slopes created relatively safe microsites through erosion, was not important during period 2 except in the tree-removal zone. Previous research found that, by 1993, persistent erosion in gullies resulted in reduced vegetation in some sites on the Pumice Plain (Tsuyuzaki and Titus 1996), which is consistent with this study. For the secondary-succession-dominated strata, very little deviance was explained during period 2, but elevation and, to a lesser extent, aspect were the dominant factors by period 3.

The importance of elevation and aspect was in marked contrast to our earlier study across disturbance zones, which found these factors to be relatively unimportant (Lawrence and Ripple 2000). That study, however, examined only response variables that incorporated, at least to some extent, early-period vegetation responses. When responses for each of the three periods were isolated, it was evident that an important shift over time had occurred throughout the study area. Factors probably related to vegetation reestablishment, whether through colonizers or survivors, were critical initially, but those processes might have largely run their courses or have been overwhelmed later by growth of reestablished vegetation. Recent vegetation responses appear to have been much more influenced by factors affecting growth of the early established vegetation.

Patterns observed in the managed forests were similar to some patterns in the unmanaged strata but also exhibited important differences. For the western managed forests, which were quickly salvaged and replanted (Franklin et al. 1988), the most important factors for early responses (period 1) were distance from the crater, disturbance zone types, and tephra thickness. These were all factors that likely affected the planting soil conditions and the ability of the planting crews to place roots in the relatively rich soils that existed before the 1980 eruption. In the eastern managed forests, which were not planted as quickly, early responses were most related to distance to surviving forests, with disturbance type and distance from the crater as moderate factors. The longer period to complete planting in the eastern managed forests might have resulted in a greater influence of colonizing and surviving vegetation relative to planted trees during the first 7 years in this area, thus explaining the importance of distance to surviving forests during this period.

As with the unmanaged strata, during period 2 and period 3, elevation became increasingly important for the managed forests and was the most important factor by the end of the study period. Compared to other strata, however, the impact of previous-period vegetation had a greater effect on the managed forests. This relationship was likely related to the growth patterns of the planted conifers. Because well-established trees often exhibit higher growth rates than poorly established trees and because tephra suppressed competing vegetation, areas where planted trees were thriving in one period might be expected to have higher growth rates in the next period.

The relation of NDVI to explanatory variables was consistent with the shifting of vegetation responses from a period dominated by establishment mechanisms to dominance of annual growth of established vegetation, including nucleation as previously noted (Franklin and MacMahon 2000). The spatial resolution of the satellite imagery used (25 m), as well as its spectral resolution, however, precluded a closer link between observed patterns and the processes of vegetation response. The Landsat imagery did not permit, for example, distinction of changes in plant-community composition because the spectral resolution did not enable the accurate identification of plant communities. Moreover, the spatial resolution was often larger than patch sizes and thus did not allow the analysis of vegetation patch patterns. The analysis *is* valuable, however, when evaluated in conjunction with ground-based studies conducted within each of the strata. Such multiscale analyses enable the evaluation of whether observed fine-scale patterns and processes are taking place throughout a stratum and across other types of disturbances and management regimes.

Author Queries

[CE1] Author: The labels that are shown on the hard copy of Figure 8.5 are not visible on the image in the file available to the copyeditor.