Reburn severity in managed and unmanaged vegetation in a large wildfire

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Debate over the influence of postwildfire management on future fire severity is occurring in the absence of empirical studies. We used satellite data, government agency records, and aerial photography to examine a forest landscape in southwest Oregon that burned in 1987 and then was subject, in part, to salvage-logging and conifer planting before it reburned during the 2002 Biscuit Fire. Areas that burned severely in 1987 tended to reburn at high severity in 2002, after controlling for the influence of several topographical and biophysical covariates. Areas unaffected by the initial fire tended to burn at the lowest severities in 2002. Areas that were salvage-logged and planted after the initial fire burned more severely than comparable unmanaged areas, suggesting that fuel conditions in conifer plantations can increase fire severity despite removal of large woody fuels.

public land management | salvage-logging | Biscuit Fire | Landsat | landscape ecology

Large wildfires are increasingly common in western North America (1). Changing climate patterns and the legacy of fire suppression within fire-prone forests suggest that this trend will continue. Postfire management is, therefore, a growing concern for public land managers. Although it has been customary to salvage-log fire-killed trees and plant seedlings after large wildfires, there is a mounting debate regarding the practice (2–4). There are several reasons one might choose this management system, including recouping economic losses through timber sales and ensuring the reestablishment of desirable tree species. Another common justification for this approach has been a perceived reduction in future fire risk associated with the removal of dead wood (2, 5–7). The threat of severe reburns is real but not well understood (4). For example, Oregon's Tillamook burns of the 1930s, 1940s, and 1950s consisted of one large fire followed by three reburns 6, 12, and 18 years later. In sum, these fires burned more than 135,000 hectares. The threat of reburns motivates public land managers to construct fuelbreaks and to salvage-log to hedge against the risks of future fire (6). Recent studies have found, however, that salvage-logging can increase surface fuels available to fires above prelogging levels by transferring unmerchantable material to the forest floor, suggesting that this postfire management practice might actually increase fire risk for a time (3, 8). Until now, no study has quantified how recent fire history and postfire management actually affects the severity of a large wildfire (4).

The 2002 Biscuit Fire was among the largest forest fires in modern United States history, encompassing >200,000 hectares primarily within the Rogue-Siskiyou National Forest (RSNF) in southwest Oregon. In the years following, the Biscuit Fire has been a catalyst for national debate regarding forest management in the aftermath of wildfires on public land. This debate is taking place in the absence of empirical research on how future wildfire severity is associated with past wildfires and how postfire forest management alters future fire severity (4). We analyzed burn severity patterns within 18,000 hectares of the Biscuit Fire that burned 15 years earlier during the 1987 Silver Fire. Both fires burned heterogeneously, creating mosaics of live and dead trees in variably sized patches. In the 3 years following the Silver Fire, >800 hectares were salvage-logged and planted with conifers. The arrangement of these disturbances presented a unique opportunity to address two important research questions. First, was severity in the Biscuit Fire associated with severity in the Silver Fire in unmanaged areas? Second, did areas that were salvage-logged and planted with conifers after the Silver Fire burn more or less severely in the Biscuit Fire than comparable unmanaged areas?

With regard to the first question, hereafter referred to as "the reburn question," a negative correlation between Biscuit and Silver Fire severity is plausible if the forests that burned severely in 1987 had less remaining fuel to support the Biscuit Fire in 2002, or if regenerating young forests did not effectively carry fire. This relationship has been observed in lodgepole pine ecosystems (9–11). An alternate hypothesis is that Biscuit Fire severity would be positively correlated with Silver Fire severity. This would occur if areas of higher Silver Fire severity had greater accumulations of fire-killed trees and vegetative growth available as fuel to the Biscuit Fire. This scenario is assumed to have influenced forest dynamics in more mesic forests of the Pacific Northwest (12). Finally, there may be no discernible association between the severity patterns of the two fires. Many independent factors influence fire severity, including weather, topography, fuel, landscape structure, and fire suppression. Any of these could overwhelm the signal from the legacy of the Silver Fire.

The second question, hereafter referred to as "the salvage-plant question," also has several plausible outcomes. The hypothesis that salvage-logging followed by planting conifers can reduce future fire severity is widely held and rests on the assumption that removing dead trees reduces fuel loads, and planting conifers and controlling competing vegetation hastens the return of fire-resistant forests (2, 5–7). An alternative hypothesis is that salvage-logging plus plantation creation exacerbates future fire severity. No studies have measured fire severity following salvage-logging, but it is known that it can increase available fine and coarse fuel loads if no fuel treatments are conducted (3, 8). In addition, several studies have documented high-severity fire within young conifer plantations, where surface fuels can be fine, homogeneous, and continuous (13–15).

Our study area is within the Siskiyou Mountains in southwest Oregon's mixed-conifer and mixed-evergreen hardwood zones

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Abbreviations: RSNF, Rogue-Siskiyou National Forest; dNBR, differenced normalized burn ratio; TM, Thematic Mapper; PAG, plant association group.

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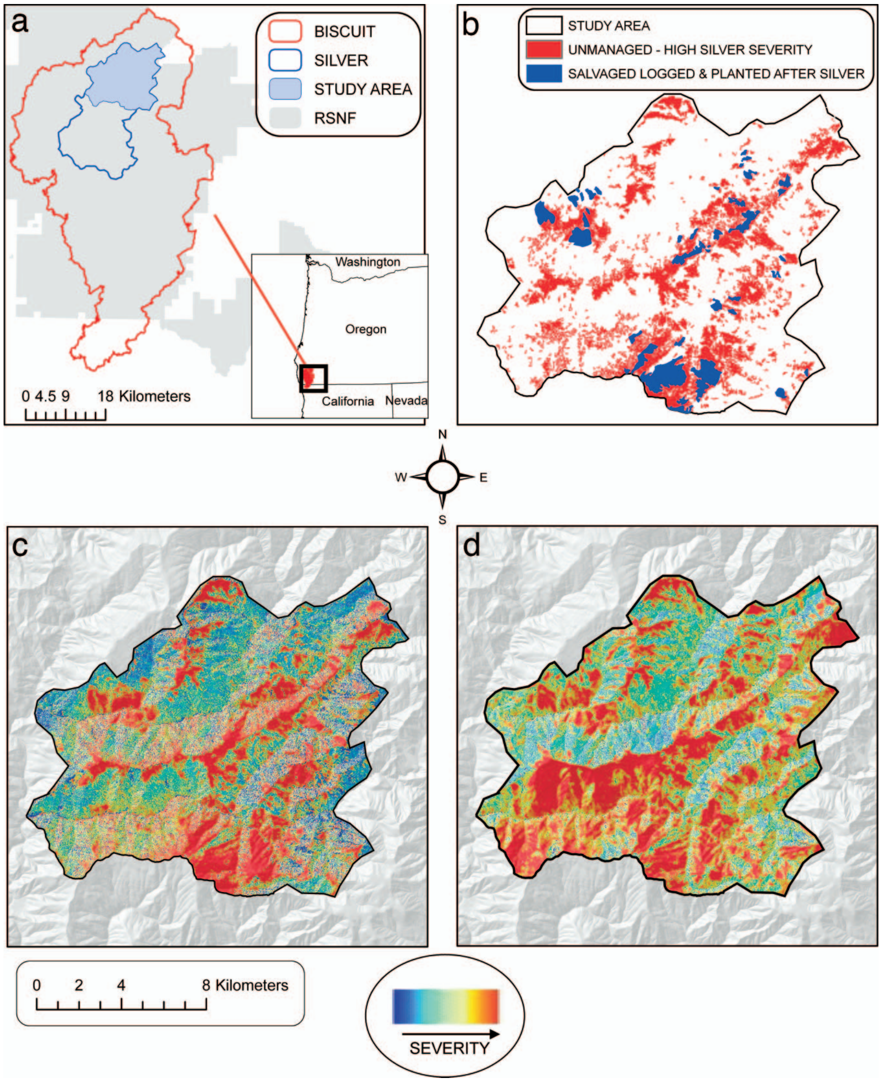

Fig. 1. The Biscuit Fire encompassed >200,000 hectares of southwest Oregon forests; 40,000 hectares had burned 15 years earlier in the 1987 Silver Fire. Both fires burned heterogeneously, leaving a mosaic of live and dead vegetation. (*a*) Study area in context of recent fires. (*b*) Disturbance history. Sampling universe for the salvage-plant question. (*c*) Burn severity of the 1987 Silver Fire. (*d*) Burn severity of the 2002 Biscuit Fire.

(Fig. 1) (16). To estimate fire severity, we calculated the differenced normalized burn ratio (dNBR) (17) (Fig. 1) from Landsat Thematic Mapper (TM) data acquired before and immediately after each fire (Table 1). dNBR is a unitless index that corresponds strongly to decreasing aboveground green biomass as well as scorched and blackened vegetation; to a lesser degree, dNBR corresponds to changes in soil moisture and color and to consumption of down fuels (17). dNBR is an effective measure of burn severity within forested landscapes (18, 19). We reconstructed post-Silver Fire management history with the help of RSNF personnel, agency documents, and aerial photography. For our analysis, logging followed by planting was considered a single management system.

Table 1. Acquisition dates of satellite imagery used to estimate fire severity

Landsat TM (path 46 row 31)	Date acquired
Pre-Silver Fire	10/13/1986
Post-Silver Fire	10/16/1987
Pre-Biscuit Fire	10/10/2001
Post-Biscuit Fire	10/6/2002

Results

To address the reburn question, we randomly sampled the nonmanaged portion of the study area. We controlled for factors known to influence fire severity by constructing the best possible geostatistical regression model of covariates (Table 2) before adding the variable of interest: Silver Fire severity. Akaike information criteria identified two "best" regression models of covariates. The first model included elevation, slope, plant association group (PAG) (20), day-of-burn, and 1986 greenness [a satellite-based metric associated with vegetation density (21, 22)]. The second model contained all of the previous variables plus a measure of topographic position (Table 2). We selected the second model because topographic position is known to have influenced severity patterns elsewhere (12, 23). Using this as our full covariate model, we then added Silver Fire severity as an independent variable and found that it was significantly and positively correlated with Biscuit Fire severity ($P < 0.0001$, df = 381; Fig. 2). An increase of 100 dNBR within the Silver Fire was associated with an increase of 84 dNBR within the Biscuit Fire

Table 2. Variables included and retained during regression model selection for the reburn and salvage-plant questions

Variables	Reburn	Salvage-plant	Definition
Disturbance history			
Silver severity	◆	†	Differenced NBR from the Silver Fire, calculated from pre- and postfire Landsat TM
Managed site		◆	Salvage-logged in 1988, 1989, or 1990, planted with conifers, then later certified as a "successful" plantation
Topography			
Elevation	†	†	In meters from a 10-m DEM
Aspect			Aspect folded around south facing slopes (folded aspect = |180 − |aspect − 180||), from 10-m DEM
Slope	†	†	In percent, from 10-m DEM
Topographic position (fine)	†	†	Difference between sample elevation and mean elevation of an annulus spanning 150–300 m from the sample
Topographic position (intermediate)			Difference between sample elevation and mean elevation of an annulus spanning 850–1,000 m from the sample
Topographic position (coarse)			Difference between sample elevation and mean elevation of an annulus spanning 1,850–2,000 m from the sample
Biophysical			
PAG	†	†	Potential vegetation in the absence of disturbance, based on climatic, biogeographical and physiographic factors; obtained from RSNF
1986 brightness			Brightness axis from tasseled cap transformation of 1986 Landsat data (15)
1986 wetness			Wetness axis from tasseled cap transformation of 1986 Landsat data (15)
1986 greenness	†	†	Greenness axis from tasseled cap transformation of 1986 Landsat TM data (15)
Soil			Soil data from Curry and Josephine counties (four soil types)
Weather and other temporal change			
Burn index			Daily fire behavior index measured using current and past weather data, heavily influenced by wind speed, Calculated by the ODF using data from the Quail Prairie, Oregon RAWS
Energy release component			Daily fuel moisture index that reflects the contribution of live and dead fuels to potential fire intensity, Calculated by the ODF using data from the Quail Prairie, Oregon RAWS
Day	†	†	The day on which the Biscuit Fire flaming front passed (a count from the first to the last day); obtained from RSNF

†, retained in full covariate regression model after AIC model selection; ◆, the variable being tested after fitting the best covariate regression model. NBR, normalized burn ratio; DEM, digital elevation model; ODF, Oregon Department of Forestry; RAWS, remote automated weather station.

after controlling for the covariates (95% confidence interval = 69–99 dNBR points). We confirmed that this relationship holds even for the low-to-moderate range of Silver Fire severity by reanalyzing the data after excluding the samples that burned at high Silver Fire severity. Overall, unburned areas or those that burned at lower severities in the Silver Fire tended to burn at lower severities in the Biscuit Fire, whereas areas that burned at higher severities in Silver Fire tended to reburn at higher severities in the Biscuit Fire.

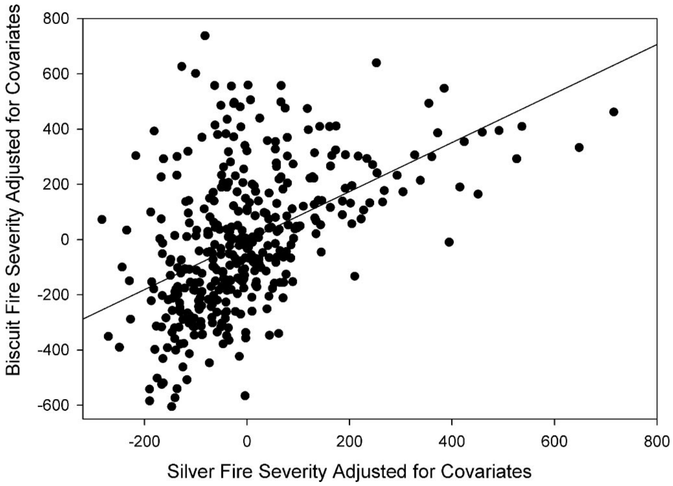

Fig. 2. Added variable plot displaying the relationship between Silver and Biscuit Fire severity as estimated through a Landsat-derived burn metric, dNBR. The effect of elevation, slope, PAG, day-of-burn, 1986 greenness, and topographic position on Biscuit Fire severity has been removed to illustrate the association between fire severities from both fires. See Table 2 for descriptions of the covariates.

To address the salvage-plant question (i.e., did logged and planted areas burn more or less severely than comparable unmanaged areas?), we restricted our second random sampling to areas that burned in the upper 20% of the Silver Fire severity range and to the logged-then-planted areas. In addition, we only sampled within those plant associations that contained managed stands. These constraints ensured that we were comparing the logged and planted sites only to similar areas that also experienced a stand-replacing disturbance. Again, there were two best covariate models. One included Silver Fire severity, elevation, slope, PAG, day-of-burn, and 1986 greenness. The other included all of these covariates plus a measure of topographic position; and again we chose the model that included topographic position (Table 2). When added to this model, the indicator for the salvage-logged and planted sites was associated with a 182.3-point increase in Biscuit Fire dNBR (Fig. 3; $P < 0.0001$, 95% confidence interval = 120.32–243.68, df = 282). Biscuit Fire severity in the logged and planted areas was 16–61% higher than comparable unmanaged areas depending on the values of the covariates. The particular ecological effects of this difference are unknown; nonetheless, the hypothesis that salvage-logging followed by planting reduces reburn severity is not supported by these data.

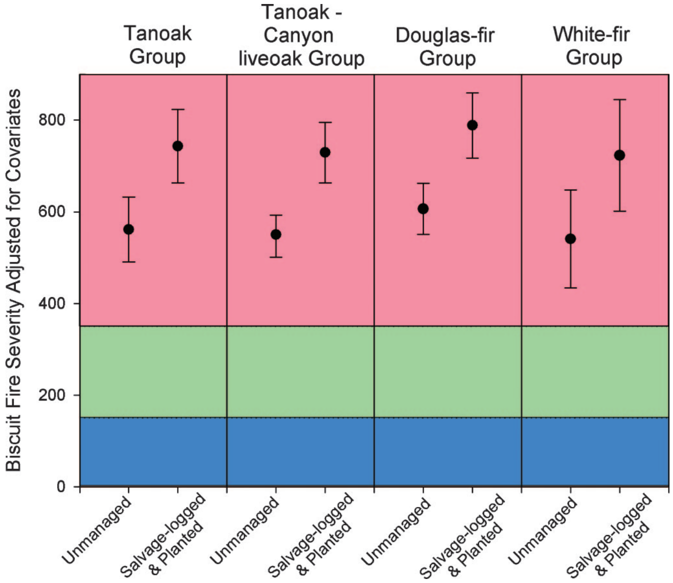

Fig. 3. Ninety-five percent confidence intervals for Biscuit Fire dNBR, a Landsat-derived burn severity metric. Estimates and confidence intervals compare regions burned at high severity in the 1987 Silver Fire that were unmanaged to areas that were salvage-logged and planted after the Silver Fire. Means were calculated at the multivariate centroid of the covariates: slope, elevation, topographic position, Silver Fire severity, day-of-burn, and 1986 greenness (see Table 2). Means were similar across the four PAGs. In this landscape, the Tanoak group is found on wetter sites in the western portion of the study area, whereas the Tanoak-Canyon live oak group is found on dryer, inland sites; the Douglas-fir group is found on relatively dry sites; and the White-fir group is found at somewhat higher elevation wetter sites (20). Colors correspond to Biscuit Fire severity calibrated through comparison with aerial photography: blue, <10% canopy scorch; green, 10–50% canopy scorch; red, >50% canopy scorch.

Discussion and Conclusion

No previous study has compared fire severity in plantations and naturally regenerated vegetation of similar ages. Our findings are consistent with studies that show that site history influences fire severity (15, 24, 25), and with studies that have found an association of high-severity fire with conifer plantations (13–15). Our limited knowledge of the fuel characteristics at the time of the Biscuit Fire prevents us from separating the effects of logging and planting. The relative influence of these management actions on burn severity would vary over time: the influence of dead fuels and harvest debris would diminish as they decayed (3) and the influence of live vegetation would increase as it developed. The patterns we observed apply to the particular conditions and history of post-Silver Fire management; they could change with shorter or longer intervals between fires.

The Biscuit Fire tended to burn at relatively high severity in young naturally regenerated stands and even more severely in young conifer plantations of comparable age and fire history. This suggests that young forests, whether naturally or artificially regenerated, may be vulnerable to positive feedback cycles of high severity fire, creating more early-successional vegetation and delaying or precluding the return of historical mature-forest composition and structure. Although patches of high-severity fire and reburns are a normal part of the mixed-severity fire regime within this forest type (12, 26), increasing occurrence of wildfire driven by climate warming in this region (1) may lead to increases in the prevalence of sclerophyllous species, which are adapted to frequent severe fires (12, 16, 20).

Our findings are inconsistent with the hypothesis that this particular postfire management system reduces the risk of high-severity fire in a reburn occurring 15 years after the original fire. The logging component of this system is often considered a fuel-reduction treatment (2, 5–7). However, the large-diameter fuels removed during harvest do not readily carry wildland fire (12, 27). Thus, logging may not reduce available fuels. In fact, harvesting fire-killed trees may increase available surface fuels by transferring unmerchantable material, such as tops, branches, and broken boles to the ground immediately after harvest (3, 8). This effect may be mitigated as logging slash decays, or through fuel reduction methods, such as broadcast-burning (15). Records of site preparation and their effectiveness in reducing fuels in the plantations are incomplete; however, at least 17 of the 44 plantations are reported as "broadcast-burned." In a separate analysis, we found that these 17 plantations also burned with higher severities than comparable unmanaged stands. The planting component of the system is intended to promote long-term regrowth of conifer trees, but it also creates dense or continuous fuels that are at elevated risk of high severity fire (14). It should be noted, however, that many of the plantations examined in this analysis had lower conifer densities and a larger component of shrubs and hardwoods than would be found in typical intensively managed plantations of the same age (11–14 years). Our analysis could not measure any details regarding differences in preburn structure and composition between the natural and artificially regenerated stands. Nonetheless, the naturally regenerated areas received no site preparation or planting; therefore, they likely contained a more diverse arrangement of young vegetation and open gaps (20, 28). Although these naturally regenerated areas also supported relatively high-severity fire, abrupt changes in fuel profiles, which can slow fire spread (12), may have reduced the average burn severity.

We currently lack general conceptual models or simulation models that can help us understand the effects of salvage-logging on fire severity over large landscapes and long time frames. As our work indicates, research needs to consider all of the components of postfire management systems, individually and together. Thus far, the few studies that have examined reburn potential in salvage-logged sites have emphasized the dead woody fuel transferred to the surface during harvest. But logging slash is only part of the fire risk story, and it may not be the most important after a few years. On public land, salvage-logging is almost always followed by conifer planting, even when the objective is ecological recovery, such as expediting the return of old-growth forests. We are currently unable to examine the short- and long-term tradeoffs associated with different postfire management systems. For example, we do not know how the apparent difference in fire hazard between plantations and natural stands that we observed at 15 years varies over time and whether this short-term risk is balanced in any way by longer term benefits in terms of stand development and reduced fire risk. However, the available evidence suggests that the combined influence from a pulse input of surface fuels resulting from salvage-logging (3, 8) followed by the establishment of uniform young plantations may increase susceptibility to severe reburns in the early stages of forest development.

Managers may have few options to reduce the risk of high-severity fire within areas that have recently burned severely. Typical fuel treatments, such as thinning, do not have much effect on fire risk in young forests (14). Reducing connectivity of surface fuels at landscape scales is likely the only way to decrease the size and severity of reburns until vertical diversification and fire resistance is achieved (29). The decision to salvage-log and plant, or not, after fire depends on a number of management considerations including risk of future high-severity fire, reducing hazards to fire fighters, timber revenue, and conservation of biodiversity. Further research, especially controlled experiments, is clearly needed to help managers understand tradeoffs. Given the difficulty of conducting experiments with large wildfires, it is important that good records of management actions are kept so that more can be learned from future wildfires.

Materials and Methods

Study Area. We limited our samples to the northern half of the Silver Fire, outside of the Kalmiopsis Wilderness Area, where an aerial photo record exists to gauge the accuracy of our characterization of fire severity and Landsat data were of sufficient atmospheric quality to map fire severity. The study area is 18,050 hectares centered at 123°89′W latitude, 42°49′N longitude. The vegetation is characterized by mixed-conifer and mixed-evergreen hardwoods (16), dominated by *Pseudotsuga menziesii*, *Lithocarpus densiflorus*, *Pinus lambertiana*, *Abies concolor*, *Chrysolepis chrysophylla*, *Ceanothus velutinus*, and *Quercus chrysolepis*. The region has steep climatic, edaphic, and topographical gradients and is renowned for floristic diversity (30). Much of the landscape has high forest productivity compared with other fire-prone ecosystems in the western United States (31). Topography is steep and complex; elevations range from 600 to >1,500 m. Soil parent materials include igneous, metasedimentary, and metamorphic types. The climate is Mediterranean, with dry, warm summers and wet, mild winters. Mean January temperature is 6°C. Mean July temperature is 16°C. Mean annual precipitation is 210 cm. Approximately 80% of the area falls within relatively dry Douglas-fir and tanoak PAGs, which historically burned at 10- to 50-year intervals at low and mixed severities (6). Most of the remaining 20% falls within moist tanoak PAGs, where the fire regime is characterized as mixed-severity with 50- to 100-year return intervals. Effective fire suppression began in 1940, and the dry PAGs are thought to have missed one or more fire cycles. The Silver Fire was ignited by lightning on August 30, 1987, and burned generally from the northeast to the southwest (32). The Biscuit Fire reburned the region of the Silver Fire beginning July 17, 2002 and continuing through August 18, 2002, burning generally from east to west (6).

Image Processing. Our procedures for image rectification and atmospheric correction and normalization were as follows. A Landsat TM scene acquired immediately after the Biscuit Fire (Table 1) was rectified to a 2003 United States Geological Survey Digital Orthoquad by using >150 tie-points, and a first-order polynomial transformation, which produced a 14.0-m root mean squared error. Three corresponding TM scenes, one acquired 1 year before the Biscuit Fire, one acquired immediately after the Silver Fire, and one acquired 1 year before the Silver Fire (Table 1), were then all coregistered to the 2002 Landsat image by using the Landsat Orthorectification tool in ERDAS Imagine version 8.7. Each rectification used a 10-m digital elevation model and >1,200 tie-points, which were located by using an automated tie-point finder (33); root mean squared errors were less than one-half pixel in all cases. Our Landsat images have a 29-m resolution and were registered in 1927 North American Datum, UTM Zone 10. The two prefire images were then converted to reflectance and atmospherically corrected by using the COST method (34). We then used an automated ordination algorithm called "multivariate alteration detection" (35, 36) that statistically located pseudoinvariant pixels, which were subsequently used in a reduced major axis regression to radiometrically normalize postfire to prefire images. We selected October imagery, despite the low sun angle in autumn, because we wanted to pair our imagery to the dates of historical aerial photos to aid an assessment of accuracy and because we wanted to capture the fire's effects without the confounding influence of spring green-up that may have occurred had we used imagery from the following summer. Moreover, the use of near-anniversary dates within a change-detection of normalized vegetation indices greatly minimizes any negative effects of late-season imagery.

Burn Severity and Initial Vegetation Condition. Our measure of fire severity was the dNBR (17). It is a measure of pre- to postfire change in the ratio band (B) of near-infrared (B4, 0.76–0.90 μm) to shortwave infrared (B7, 2.08–2.35 μm) spectral reflectance. B4 is associated with foliage on green trees and understory, whereas B7 is associated with dry and blackened soil (17). dNBR compares well to ground data (18, 19) and has outperformed other satellite-derived measures of burn severity (18). Using the processed images described above, we calculated dNBR as described in ref. 17. Normalization of pre- and postfire imagery centers the unchanged (i.e., unburned) pixels within each fire to a dNBR value of zero. A comparison of dNBR values to aerial photography suggests that dNBR values are roughly equivalent in terms of their correspondence to vegetation damage; however, the severity maps were constructed independently to maximize the accuracy for each fire. Because our images were acquired immediately after the fire, our estimate of severity does not capture any vegetation that may have experienced delayed mortality or regreening in the years subsequent to the fire.

We excluded areas with ultramafic soils from this analysis because they had an anomalous spectral response and are ecologically distinct from the rest of the landscape (<4% percent of the study area). The fire weather indices Burn Index and Energy Release Component were calculated from Quail Prairie remote weather station data (≈25 km south of the study area) by the Oregon Department of Forestry. A digital map of PAGs was provided by the RSNF and included in the model selection procedure to control for differences in biophysical characteristics (i.e., productivity and plant composition). In addition, tasseled cap wetness, greenness, and brightness indexes (22) were derived from the processed 1986 Landsat TM data and were used during model selection to control for differences in pre-Silver Fire in vegetation condition. Tasseled cap indexes are closely related to forest composition and structure in Pacific Northwest forests (21).

We used the continuous dNBR data for all statistical analysis. We also constructed categorical burn severity maps to assess the accuracy of the satellite data in relation to characterizations of tree crown damage from high-resolution aerial photos. The categorical Silver Fire severity map was also used, in part, to define the sampling universe for the salvage-plant question. Three levels of severity were classified: (*i*) Unburned/Low Severity, where <10% of the crown was scorched or consumed by the fire; (*ii*) Moderate Severity, where 10–50% of the crown was scorched or consumed; and (*iii*) High Severity, where >50% of the of the crown was scorched or consumed. Using a set of 109 randomly placed high-resolution digital aerial photo plots, we developed thresholds in dNBR values that best classified the data for each fire. An independent sample of 141 aerial photo plots was used in an accuracy assessment which resulted in an overall estimate of accuracy of 83% for unburned/low-severity pixels, 75% for moderate-severity pixels, and 85% for high-severity pixels.

Forest Management Data. We identified 44 management units (≈850 hectares; Fig. 1) that were logged in the 3 years following the Silver Fire, then planted with conifers (primarily Douglas-fir), and later certified as "successful plantations." The salvage-logging guidelines set by the Forest Service required that, within harvest units, 12–18 standing snags >60 cm diameter and >12 m tall, along with 2.8 m^3 of down wood be retained per hectare (32). Plantations were deemed successful if, 3–5 years after planting, conifers exceeded 370 stems per hectare and were considered healthy enough to survive competition with shrubs and hardwood trees. Although post-Silver Fire records from the RSNF are not complete, they indicate that some certified plantations had undergone mechanical treatment to suppress competing vegetation and that conifer stocking typically ranged from 600 to 1,100 trees per hectare. In addition to the logged and planted areas used in the analysis, we distinguished ≈250 hectares that were harvested in part or in full after the Silver Fire but were either not planted or the planted conifers were not certified "free to grow." We excluded these later areas from all our analyses because their history was too uncertain and variable to accurately characterize. All management polygons were provided by the RSNF and were edited in a geographic information system (GIS) by using a 1-m Digital Orthoquad acquired in 1994 to better fit the perimeters of harvest units. Areas logged and planted before the Silver Fire were excluded from all analyses. The bulk of the remaining 17,000 hectares in the northern Silver Fire perimeter were not harvested. However, some small unknown proportion was selectively logged but not planted; no records describing management actions are known to exist and we could not see evidence of them in careful analysis of the Digital Orthoquads. It is likely that only the largest most valuable trees were extracted from these sites via helicopter. The unrecorded, lightly salvaged sites make up no more than 10% of the study area and are included in the population of unmanaged sites.

Sampling, Variable Selection, Model Fitting, and Hypothesis Testing. All sampling and data extraction was done in a geographic information system in which all of the variables were converted to 29-m raster maps. The sample universe for the reburn question was the region within the northern Silver Fire but outside any management areas. All known management units dating back >50 years were excluded from reburn analysis. Sample locations were determined by randomly selecting locations for 381 points with the constraint that they be separated by at least 300 m to reduce spatial dependence. Sample values were calculated as the mean value of the closest nine contiguous pixels to the sample location (sample unit area, ≈0.75 hectares). When sampling for the salvage-plant question, we constrained the sample universe to the areas within the northern Silver Fire perimeter, areas within PAGs that contained management units and either burned at high severity in 1987 and received no or minimal postfire management, or areas that burned at high severity and were clearcut during 1988, 1989, or 1990, and then planted in the years following and certified by the RSNF as an established conifer plantation. All other management units were excluded. We sampled 292 random locations (225 unmanaged and 67 managed) separated from each other by at least 300 m. Any plantation that did not include at least one sample during the initial sample selection had a sample randomly located within it. Data were extracted from all of the raster maps as described above.

Statistical analysis was completed in the computing software R (37). Empirical variogram models indicated spatial autocorrelation of Biscuit dNBR data; a spherical theoretical variogram model best described the autocorrelation. This spatial dependence precluded the use of ordinary least squares regression. Instead, for model selection and hypothesis testing, we used generalized least squares regression to fit linear models of predictor variables to Biscuit dNBR data. Generalized least squares models allow residuals to have a nonstandard covariance structure (38); we used a spherical spatial correlation structure. The modeled variogram from the reburn data had a range of 2,314 m, and the nugget:sill was 0.387. The modeled variogram from the salvage-plant data had a range of 1,096 m, and the nugget:sill was 0.399. Akaike information criteria were used for model selection (39, 40). For both questions, we evaluated Akaike information criteria scores from ≈100 *a priori* candidate covariate models, including global models containing all noncorrelated predictor variables and null models that contained none. All candidate models contained plausible combinations of predictor variables based on what is known about fire behavior and from previous studies of burn severity patterns on other fires [supporting information (SI) Table 1].

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