Spatial Interpolation and Simulation of Post-burn Duff Thickness after Prescribed Fire

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Abstract

Prescribed fire is used as a site treatment after timber harvesting. These fires result in spatial patterns with some portions consuming all of the forest floor material (duff) and others consuming little. Prior to the burn, spatial sampling of duff thickness and duff water content can be used to generate geostatistical spatial simulations of these characteristics. Results from field studies indicated that spatial patterns of duff characteristics occurred, and they were then modeled by kriging, simulation and a trend-surface modeling techniques. The higher elevations of the study unit burned more severely than the lower portion. This is believed to be due to the heat generated by the fire drying out the upper portions of the units, thus consuming more duff material and thinner pre-burn duff thickness due to ground-based harvesting techniques. Attempts to predict duff consumption and subsequent post-burn duff thickness were successful using a trend-surface model developed for this site and a general duff consumption model. Knowledge of spatial patterns of duff remaining may help land managers adjust prescriptions and alter ignition patterns to reduce areas where total consumption of duff might occur.

Keywords:

Geostatistics
Forest floor
Duff water content
Spatial patterns
Northern Rocky Mountains.

Introduction

Prescribed burning is the controlled use of fire to achieve specific forest management objectives (Walstad et al. 1990). These fires do not burn uniformly across a broad landscape or even at smaller scales on a hillslope. Thus, micro-scale spatial patterns may exist for duff consumption and, more importantly, post-burn duff depths remaining after the fire. Geostatistical methods provide a way to characterize and predict these spatial patterns. Greater understanding of the spatial patterns or spatial variability of duff consumption by fires may help land managers plan burning prescriptions and alter ignition patterns to reduce the areas where total consumption of the duff might occur.

Timber harvesting and site-preparation practices can create a wide variety of conditions throughout harvest units. During ground-based operations, skid trails and landings are the most disturbed areas; and during cable operations, log drag areas and landings are the most disturbed. The remaining portions of the harvest unit are generally covered with slash left after the logging operation. Prescribed fire often is used to remove logging slash; dispose of flammable residues to reduce the risk of subsequent wildfire; remove vegetation that interferes with efficient reforestation; reduce the risk of insect hazards; release nutrients; and initiate the establishment of shrubs and grasses for wildlife (Reinhardt et al. 1991, Walstad and Seidel 1990).

The forest floor can contain several kinds of organic material including a litter layer, the recognizable plant debris that has not decomposed; the fermentation layer, partially decomposed litter often bound with fungus; decomposed woody debris; and the humus layer, extensively decomposed unrecognizable organic material. Duff is an inclusive term that refers to the fermentation and humus layers. It is often desirable to remove fine woody fuels and some of the duff (or organic forest floor) while leaving some duff to protect the mineral soil from erosion and to maintain nutrients.

Duff thickness and duff water content strongly influence duff consumption during fires. Fires can merely remove litter to totally consume the duff and alter mineral soil structure (McNabb and Swanson 1990, Wells et al. 1979). When the duff is thin or when its water content is low, fires consume

much of the duff and may alter mineral soil properties (Reinhardt et al. 1991, Sandberg 1980). Following a burn, runoff and sediment yields generally increase with increasing duff consumption (Wells et al. 1979, Soto et al. 1994). If the duff layer is consumed and mineral soil exposed, soil infiltration and water storage capacity are reduced significantly. Such impacts may last weeks or years, depending on the fire's severity and intensity, soil type, remedial measures, and vegetation establishment (Baker 1990).

First-order, fire-effects computer models can predict the immediate results of a fire, including duff and woody fuel consumption, fire-caused tree mortality, and smoke production (Brown et al. 1991, Reinhardt et al. 1997). In related work, Brown et al. (1985) developed a duff reduction (consumption) equation for the Northern Rocky Mountains based on averaged pre-burn duff thickness and lower duff water content:

$$DR = 26.1 - 0.225*DM + 0.0417*DEPTH, \qquad (1)$$

where *DR* is reduction in duff thickness (mm), *DM* is the lower gravimetric duff water content (%), and *DEPTH* is pre-burn duff thickness (mm).

This relationship is based on field data sets analysed by multiple regression assuming sample independence. Another approach to predicting duff consumption is to use geostatistical spatial methods that treat samples as being spatially dependent (Robichaud 1996) and compare observed spatially-distributed duff consumption values and post-burn duff thickness with predicted estimates. This paper describes geostatistical methods to identify spatial patterns in duff characteristics and evaluates the predictability of spatial patterns using the Brown et al. (1985) duff reduction equation (equation 1) and a site-specific, duff reduction model.

Methods

The study site, Slate Point, was on the West Fork Ranger District of the Bitterroot National Forest in western Montana, USA (lat. 45° 44′ N, long. 114° 14′ W). This site was characterized by a Douglas-fir (*Pseudotsuga menziesii*)/lodgepole pine (*Pinus contorta*) forest. Slope angles within the study area ranged from 30 to 70 % with a northern aspect. Elevations ranged from 1620 to 1780 m. A prescribed burn was conducted in June 1994 as part of the prescribed burn program of the West Fork Ranger District.

Prior to the burn, steel pins were installed to measure pre-burn duff depth and duff reduction at 20 locations within the 7-ha unit using a systematic grid (30 m by 30 m) adjusted for a road bisecting the unit. The heads of 200-mm long steel pins were installed flush with the duff surface at each sampling plot (eight pins per plot). They were located on the corners and side-midpoints of an imaginary square sampling box (1-m sides). The eight measurements were averaged for each sample plot. Three additional sampling plots were located

within the site grid to obtain shorter distances between plots for shorter lag distances to aid in the spatial analysis. Fuel loadings were measured by methods of Brown (1974).

Immediately prior to burning, 15 samples of the duff were collected adjacent to the sample plots to measure duff water content. Samples were placed in plastic bags, held in a cooler and weighed the same day. Duff samples were oven-dried at 60°C for 48 hours and re-weighed to measure water content. Post-burn measurements were taken after several days, allowing the ash to disperse and settle. Duff consumption at each plot was estimated using differences between the pre- and post-burn measurement surveys.

Data Analysis

Geostatistics offers a way to describe the spatial continuity inherent to natural phenomena, such as duff thickness, and provides adaptations of classical regression techniques to take advantage of this continuity (Isaaks and Srivastava 1989, Rossi et al. 1992). First, variograms are developed from the existing data; then interpolation or simulation methods are used to develop estimates at unsampled locations. The output then can be used to compare predicted vs. actual spatial characteristics of duff consumption and post-burn duff depths.

The variogram function provides a method to characterize spatial dependence of an attribute as a function of lag, or separation distances (Journel 1983, Isaaks and Srivastava 1989). Calculating the estimated variogram for lag *h* consists of identifying all data pairs separated by distance *h* (or within a defined range of *h* values), computing and squaring the difference in value for each data pair, and summing the squared differences for all n_h pairs, then dividing by 2 n_h. This entire process is repeated for another lag *h*:

$$\gamma(h) = \frac{1}{2n_h} \sum_{i=1}^{n_h} (x_i - x_{i+h})^2, \qquad (2)$$

where $\gamma(h)$ is the semivariance, n_h is the number of data pairs where each pair is separated by "lag" distance *h*, x_i is one of the data values in the pair located at spatial position *i*, and x_{i+h} is the other data value in the pair at location *i+h*. In practice, when the data are irregularly spaced, the data pairs must be grouped into lag cells (one cell might be all pairs with *h* = 0–10 m and another with *h* = 10–20 m, etc.). Then, the average of equation (2) is calculated cell by cell, and the mean *h* within each cell is used as the *h* for the variogram value in that cell.

Generally, as the lag *h* increases, so does the variogram value (see example in Figure 2). The variogram value usually stops increasing beyond a certain lag and becomes somewhat stable about a limiting value known as the sill value, which corresponds to the variance of the sample population. The *h* that defines the beginning of the sill is known as h_r, the range

of influence. Beyond that distance, sample values are no longer related to each other. The variogram value at which the model appears to intercept the ordinate is known as the nugget value, which represents the apparent discontinuity at $h = 0$ (Journel 1983). The nuggets represent all unaccounted spatial variability at distances smaller than the smallest sampling distance. Nuggets are important because the difference between a model's sill and the nugget represents the proportion of the total variance that can be modeled as spatial dependence from the available sampling grid (Englund and Sparks 1991). Variograms were calculated for duff properties and their properties summarized in Table 1.

Spatial characterization of an attribute involves the generation of maps by estimating values of the attribute at numerous unsampled locations. Such filling-in processes are usually achieved by interpolation or simulation. Spatial interpolation methods tend to smooth the spatial pattern of the attribute (causing the set of estimates to have a smaller variance than the actual data set), but generally provide good local estimates. Spatial simulations, on the other hand, provide more realistic fluctuations, with the set of simulated values having a variance that approximates that of the actual data.

The common geostatistical interpolation method, ordinary kriging, has been well described in the literature (see David 1977, Journel and Huijbregts 1978, Isaaks and Srivastava 1989). The procedure involves calculating a weighted average from neighborhood data, where the weights represent least-squares regression coefficients obtained by incorporating spatial covariance between the neighborhood locations and the estimate locations, and between pairs of the data values. Ordinary kriging provides unbiased and minimum-error estimates, and can be used to estimate values at point locations or to estimate the average values of blocks (areas). Because kriging is an interpolator, it produces a smoothed representation of the spatial data.

Another interpolation method, trend-surface analysis, describes a regional best-fit trend through the spatial data set based on a multiple-regression, least-squares method. It is a function of a set of spatial observations defined such that the squared deviations from the trend are minimized (Davis 1986, pp. 405–430). Typically, a trend-surface model is used to estimate values at unsampled locations based on two geographics coordinates—east and north. For this study, a trend-surface model was developed based on the two "coordinates" of pre-burn duff thickness and pre-burn duff water contents. This model (a second-order equation with two coefficients for duff thickness, two coefficients for duff water content, and one coefficient for their combination) provides estimation of duff reduction which was compared to results obtained with equation (1).

Several types of spatial simulations also are available for mapping a spatial attribute. Our spatial simulations of duff properties were based on sequential Gaussian simulation methods described by Deutsch and Journel (1992). Simulation provides natural-looking fluctuations in spatial patterns, while still honoring known data locations and preserving the desired variance and spatial covariance.

Results

The Slate Point prescribed burn area had a mosaic pattern, indicating variable duff consumption. The upper portion of the unit initially burned very slowly and with low intensity. But as the lower portion ignited, the resulting heat caused the duff to dry out and the upper portions of the unit to reburn. Duff thickness averaged 47 mm prior to the burn and 19 mm following the burn (Table 1) and pre-burn duff thickness

Table 1. Univariate statistics and variogram models of observed pre-burn duff thickness, duff consumption, post-burn duff thickness and pre-burn duff water content. $N = 20$ for all variables unless otherwise noted. Variogram model describes spatial dependence as a function of lag or separation distance. The first number is the nugget, the second number is the difference between the sill and nugget value, Gaus is a Gaussian model and Sph is a Spherical model. These models are used to describe the shape of the variogram curve. The third number (subscript) is the range of influence.

Attribute	Mean (mm)	SD (mm)	Min (mm)	Max (mm)	Variogram model
Pre-burn duff thickness	46.6	20.8	19	88	$30+380\text{Gaus}_{65}$
Duff consumption	27.3	22.9	0	86	$50+448\text{Sph}_{65}$
Post-burn duff thickness	18.8	9.8	2	37	$30+61\text{Sph}_{70}$
Pre-burn duff water content[1]	(%) 72.1	(%) 48.2	(%) 23.9	(%) 204.6	$138+600\text{Sph}_{50}$

[1]Fifteen samples of duff water content were taken.
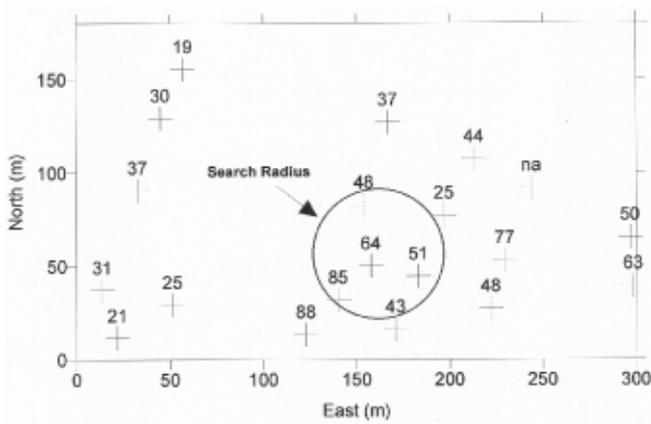
Figure 1. Plan view of the Slate Point timber harvest unit indicating pre-burn duff thickness (mm) at each sampling location. Search radius describes the area included in the kriging and simulation estimation techniques.

appeared thinner near the western portion of the site (Figure 1). Fine fuel loading was 28 t ha^{-1} and large fuel loading was 75 t ha^{-1} prior to the burn which consumed 74 and 60 %, respectively. There was no correlation between fuel loadings and any duff characteristic (Robichaud 1996).

Variograms were computed and modeled; for example, the pre-burn duff thickness variogram indicates the total variance (the sill value), was 410 mm^2. The range of influence was 65 m with micro-scale variability (the nugget) of 30 mm^2 (Figure 2). The best-fit smooth curve was the Gaussian model. Kriged estimates of pre-burn duff thickness, duff water content, duff consumption, and post-burned duff thickness were obtained using the variograms listed in Table 1. Three-by-three block kriging was used with a grid spacing of 10 m and a neighborhood search radius of 70 m (Figure 1).
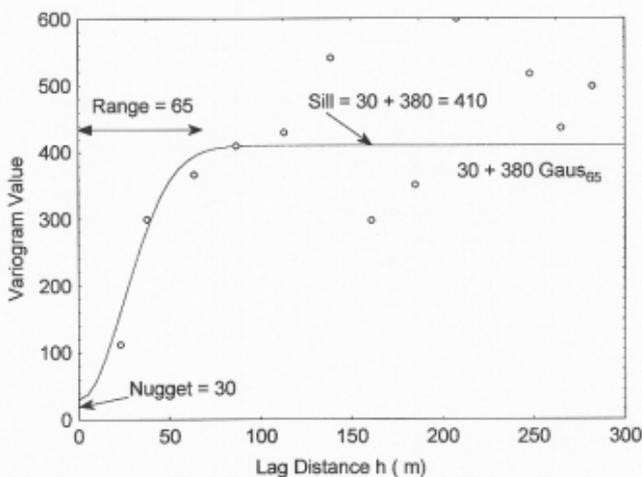
Figure 2. Variogram for pre-burn duff thickness with each component identified.

Figure 3a shows a pre-burn duff thickness kriged plot (grey-scale map) with duff thickness ranging from 20 to 85 mm. The grey-scale map (Figure 3a) indicates that the location of deeper material (lightest grey-scale) was at the coordinates (120, 20 m) corresponding to an area partially covered with vegetative ground cover. The upper portions (represented by the western portion of the grey-scale map) indicated thinner duff material (darkest grey-scale). This portion of the unit was tractor yarded, which caused more disturbance to the duff material. Thus, before the burn, duff thickness in the upper portion of the unit was thinner than the lower. Figure 3b indicates the error estimate (kriging standard deviation) for each grid cell that was kriged. The darker cells are generally near the sampling locations with an average error of 4 mm. As the distance away from the sample locations increases, error increases to 15–17 mm. Thus, kriging provides a measure of uncertainty in the resulting estimates.

A set of spatial simulation grids were generated for each of the duff characteristics and averaged. Sequential Gaussian simulation results of pre-burn duff thickness are shown in
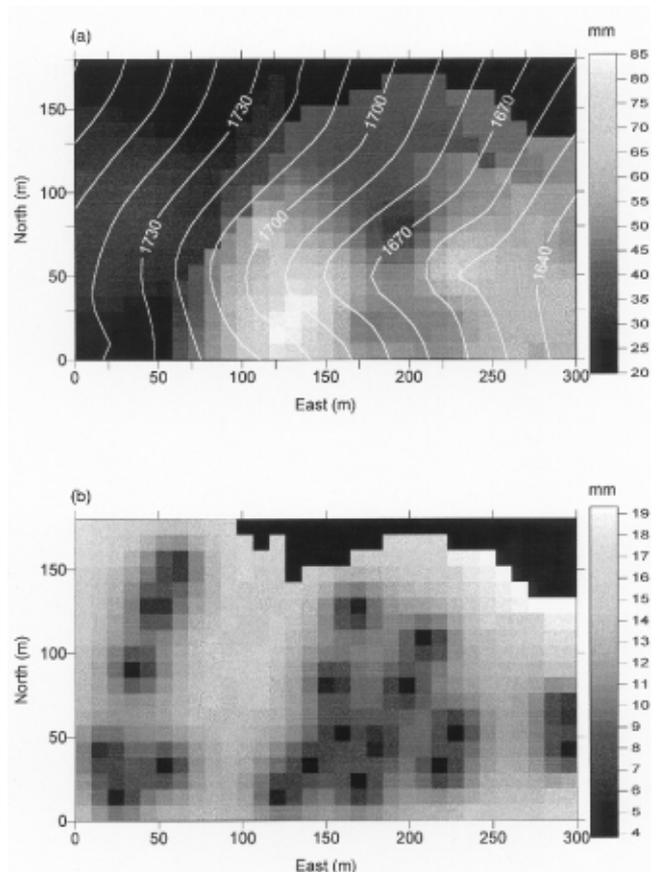
Figure 3. (a) Grey-scale map of kriged estimate for pre-burn duff thickness. White contour lines are elevation (m) to aid in site orientation. (b) Kriged standard deviation (error) estimate for each grid cell. The black areas in the north-east corner were outside the boundary of the study.
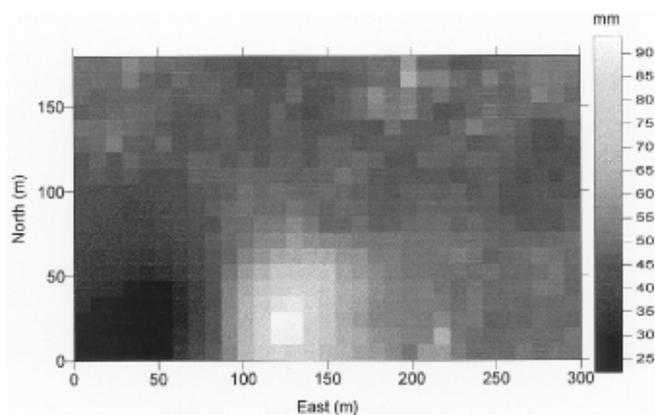
Figure 4. Grey-scale map of simulation results for pre-burn duff thickness.
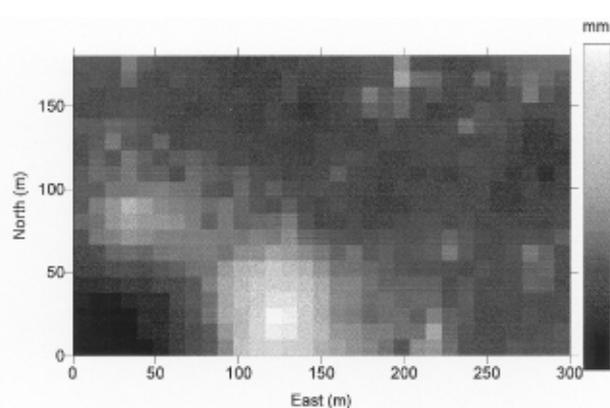
Figure 6. Grey-scale map of simulation results using equation (1) for post-burn duff thickness
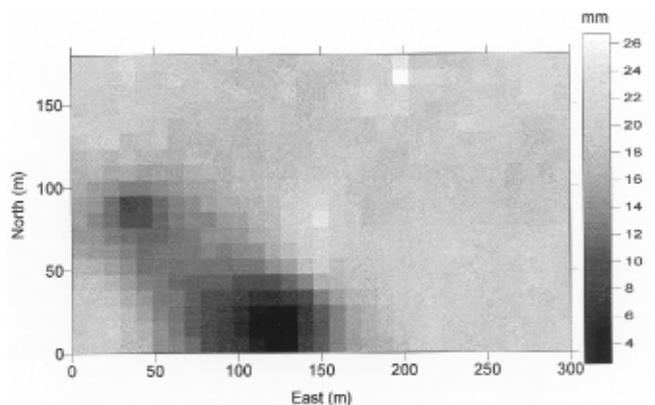
Figure 5. Grey-scale map of simulation results for post-burn duff thickness.

Figure 4. The thickest duff (90–95 mm) corresponds to the same locations as the thickest duff shown on the kriged map (Figure 3a). The locations of the thinnest duff were along the western portion of the unit but only show up in the southwestern portion of the simulation, not along the western portion as shown with the kriged estimates (Figure 3a).

The averaged post-burn duff thickness simulation plot (Figure 5) shows that the burn consumed more of the duff on the upper portion of the unit (125, 30 m to 40, 90 m) than the lower portion. This could be caused by the heat generated during the fire drying out the upper portion of the unit and consuming more of the duff.

Equation (1) was applied to 100 simulations of the pre-burn duff thickness and 100 simulations of the pre-burn duff water content to generate estimates of duff reduction. The post-burn duff depths then were calculated by subtracting the duff reduction from the pre-burn duff thickness. The average predicted duff thickness (Figure 6) indicates the greatest duff thickness (50 mm) remained near (120, 30 m) and the thinnest duff thickness (8–12 mm) near (30, 20 m).

When comparing the grey-scale maps of simulated duff thickness based on observed post-burn duff depths, and simulated depths based on pre-burn conditions and equation (1) there are some spatial discrepancies. For example, the thickest post-burn duff thickness (50 mm) simulated from equation (1) was at (120, 30 m) (Figure 6) whereas the greatest measured duff thickness (26 mm) is at (200, 160 m) (Figure 5). This discrepancy was probably due to the heat that funneled up the draw and dried the duff, causing greater consumption of duff than was predicted by equation (1).

A trend-surface model (r^2=0.98) was developed using DM and DEPTH as the reference "coordinates". The model used 15 of these paired "coordinates" of pre-burn duff water content and pre-burn duff thickness. The best-fit equation is:

$$DR = 16.5 + 0.014*DM^2 - 1.91*DM + 0.0055*DM*DEPTH$$
$$+ 1.46*DEPTH - 0.0067*DEPTH^2, \qquad (3)$$

where *DR* is reduction in duff thickness (mm), *DM* is gravimetric duff water content (%), and *DEPTH* is pre-burn duff thickness (mm).

Equation (3) was used to obtain duff reduction and subsequent post-burn duff thickness estimates by subtracting from the pre-burn duff thickness measurements (Figure 7). The results compare very well with the simulations from the observed post-burn duff thickness measurements (Figure 5). The trend-surface model underestimated post-duff thickness slightly. The magnitudes and location for the lowest (4 mm) values correspond very well. A box-and-whisker plot (Figure 8) shows the distribution of values for measured and predicted post-burn duff thickness. The range of the trend-surface model was more similar to the observed post-burn duff thickness than was equation (1). The trend-surface model correlation with the measured post-burn duff thickness was 0.73, whereas equation (1) correlation with measured post-burn duff thickness was 0.47. Although better prediction occurred with equation (3), it can not be extrapo-
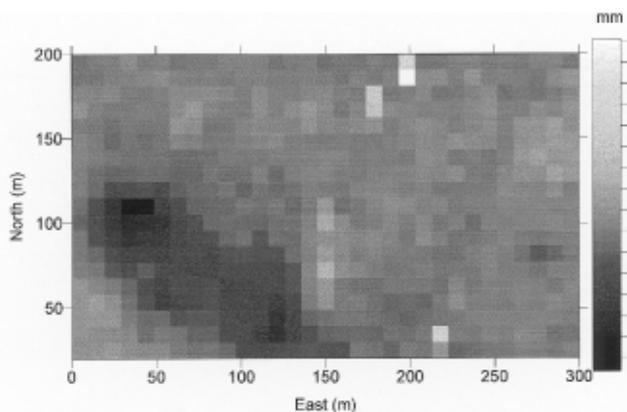
Figure 7. Grey-scale map of simulation results using equation (3) for post-burn duff thickness.
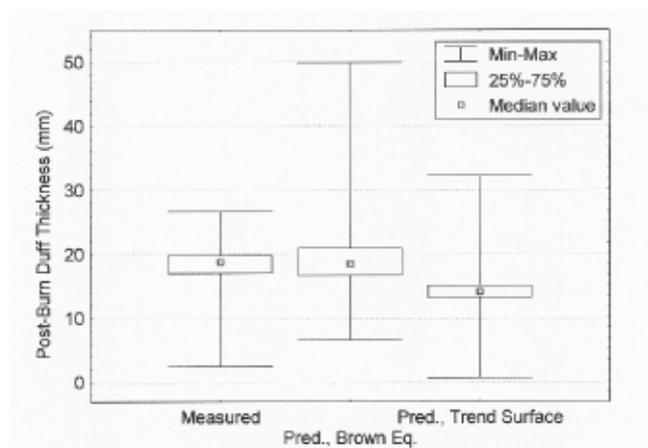
Figure 8. Box-and-whisker plot of the post-burn duff thickness observed, predicted by equation (1) and predicted by equation (3).

lated to other sites, because it was developed from these specific data. However, these results emphasize that spatial dependence occurred and that the site specific trend-surface model (Equation 3) significantly out-performed Brown's et al. (1985) model (equation 1).

Conclusion

Duff consumption and post-burn duff thickness influence soil erosion, regeneration and preparing planting sites after fire. Fire consumption was variable in this study area, based mainly on the duff water content and pre-burn duff thickness. Spatial variability in duff characteristics was modeled with variograms. These variograms allowed for site mapping through estimation at unsampled locations by using kriging and simulation techniques, and a specially adapted form of trend-surface modeling. The thinnest post-burn duff depths were located near the top of the draw where the heat from the

fire had funneled up, and at the upper elevations where thinner pre-burn duff thickness occurred. With initial estimates of the pre-burn characteristics, such as pre-burn duff thickness and pre-burn duff water content, simulation methods indicate that predictive estimates of consumption and post-burn duff thickness are possible for prescribed fires. Both the post-burn duff thickness trend-surface model (equation 3) developed for this site, and Brown's et al. (1985) (equation 1) duff consumption model show promise to spatially predict post-burn duff thickness on a hillslope.

The analysis suggests that spatial variability is an important characteristic of harvested and burned hillslopes and that geostatistical methods can be used to describe the spatial variability and topographic effects. Spatial simulation techniques generally preserve the natural variation in the data better than kriging techniques. Additional studies are underway to determine if reoccurring spatial patterns exist with prescribed fire after timber harvesting (Robichaud et al. 2000). If similar spatial patterns exist, then managers can develop prescription burn plans to take into account these various spatial patterns of duff characteristics by adjusting the timing and ignition patterns of the prescribed fire to reduce the areas where total consumption of the duff might occur, to facilitate reforestation, and to reduce soil erosion especially on steep terrain or adjacent to water courses.

Acknowledgments

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