Geostatistics: A New Tool for Describing Spatially-Varied Surface Conditions from Timber Harvested and Burned Hillslopes[1]

Abstract

Geostatistics provides a method to describe the spatial continuity of many natural phenomena. Spatial models are based upon the concept of scaling, kriging and conditional simulation. These techniques were used to describe the spatially-varied surface conditions on timber harvest and burned hillslopes. Geostatistical techniques provided estimates of the ground cover (organic forest floor commonly called duff), which was used to classify burned-over hillslopes into low- and high-severity burn conditions. Rainfall simulation was conducted and the results indicated variability in two important erosion process parameters: hydraulic conductivity and interrill erodibility.

Keywords: erosion modeling, hydraulic conductivity, prescribed fire, erodibility

Introduction

Erosion from harvested and burned hillslopes varies from extensive to minor. The major determining factor is the amount of disturbance to the material, usually organic debris covering the forest floor commonly called duff, protecting the soil. Disturbance may be from tree harvesting operations, road building, or fire, all impacting the protective layer of duff. Prescribed fire is used in natural resource management to accomplish a variety of objectives such as reduce the risk of wildfires and prepare sites for regeneration. Fire effects on the duff layer are based on the severity of the fire. These fire effects are important because they determine the amount of mineral soil exposed to raindrop splash, overland flow and development of water repellent soil conditions. Observations from previous studies (Robichaud 1996) suggested there were four different surface/hydrologic conditions to monitor for infiltration and erodibility parameters. These conditions were high-severity burn areas (possibly hydrophobic), low-severity burn areas, bare soil areas (log drag areas, landings, skid trials, roads) and unburned areas. It is important to be able to characterize these various conditions to determine their effect on soil erosion and other silvicultural practices.

As part of ongoing studies of prescribed fire effects, geostatistical spatial modeling methods have been investigated that treat samples as being spatially dependent. The objective of this manuscript is to describe methods to spatially characterize timber harvested and burned hillslopes for use with erosion prediction technology. Methods are needed to assess the spatial distribution of duff consumption by fires so that management practices can enhance silvicultural practices and mitigate erosion potential.

Case Study Site

The site, Slate Point, was located on the West Fork Ranger District of the Bitterroot National Forest in western Montana, USA. This location is characterized by a Douglas-fir (*Pseudotsuga menziesii*) /lodgepole pine (*Pinus contorta*) forest. Slopes within the study area ranged from 30 to 70 percent with a northern aspect. Elevation ranged from 1620 to 1780 m. The prescribed burn was conducted in 1994 as part of the prescribed burn program of the West Fork Ranger District. Details of the experiment are discussed in Robichaud (1996).

Prior to the burn, the pre-burn duff depth was measured on 20 sample plots throughout the burn unit. A systematic grid (30 by 30 m) with three additional plots to obtain varied distances for spatial analysis was laid out in the harvested area. To estimate duff thickness and duff reduction, 200-mm steel pins (8 pins) were installed flush with the duff layer (forest floor surface) at each sampling plot. These pins were located on the corners and side-midpoints of an imaginary square sampling box (1-m sides). The eight readings were averaged for each sample plot.

Post-burn measurements were taken after several days, allowing the ash to disperse or settle before measurements were taken. Established plots were relocated and forest floor reduction was measured using the forest floor pins at each sampling plot. Differences between the two surveys (pre- and post-burn measurement) determined total duff consumed during the fire (i.e., reduction in duff thickness) and were used to classify low- and high-severity burn conditions.

Rainfall simulation plots were located randomly in each surface/hydrologic condition area several days after the burn. Simulated rainfall events were applied to 1 m^2 plots with the USDA-Forest Service oscillating nozzle rainfall simulator.

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The simulator produced a mean rainfall intensity of 94 mm hr^{-1} (S.D.= 5.5 mm hr^{-1}). Each plot received three 30-min rainfall events. These data were used to develop hydraulic conductivity and erodibility parameters (Robichaud 1996).

Geostatistical Analysis of Data

The field of geostatistics offers a way to describe the spatial continuity inherent to many natural phenomena, such as duff thickness, and to provide adaptations of classical regression techniques to take advantage of this continuity (Isaaks and Srivastava 1989; Rossi et al. 1992).

The variogram function provides a method to characterize spatial dependence of an attribute of interest as a function of lag or separation distances (Isaaks and Srivastava 1989). Calculating the estimated variogram for lag h consists of identifying all data pairs separated by distance h, 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:

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

where n_h is the number of data pairs separated by lag h, x_i is the i-th data value at location u_i, and x_{i+h} is the data value at location u_{i+h} .

Generally, as the lag h increases so does the variogram value. The curve usually stops increasing beyond a certain h and becomes somewhat stable about a limiting value known as the sill value, which corresponds to the variance of the sample population. That certain h that defines the beginning of the sill is known as h_r, the range of influence. Beyond that separation distance, samples values are no longer related. The variogram model value at which the model appears to intercept the ordinate is known as the nugget value, which represents the apparent discontinuity at h=0. The nuggets represent all unaccounted spatial variability at distances smaller than the smallest sampling distance. Calculated variograms for duff properties were generated and modeled using the Geostatistical Environmental Assessment software, GEO-EAS (Englund and Sparks 1991).

Geostatistical spatial characterization of a specified attribute involves the generation of maps by estimating values of the attribute at numerous unsampled locations. Such filling-in processes that honor the available data can be achieved by one of two methods, interpolation or simulation. Spatial interpolation methods tend to smooth the spatial pattern of the attribute (cause 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 set. Several types of spatial simulations also are available for mapping a spatial attribute. A fairly comprehensive discussion of geostatistical simulations was given by Deutsch and Journel (1992).

Ordinary kriging, the common geostatistical interpolation method, involves calculating a weighted average of neighborhood data between pairs of the data values, where the weights represent least-squares regression coefficients obtained by incorporating spatial covariance between the data locations and the estimate locations (Isaaks and Srivastava 1989). Ordinary kriging provides unbiased and minimum-error estimates, and can be used to estimate values at point locations or to estimate the average value of blocks (areas).

Results

Following the Slate Point prescribed burn, the area had a mosaic pattern indicating variable duff consumption. The upper portion burned very slowly and coolly. But as the lower portion ignited, the heat generated 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. Variograms were fitted to the data, for example pre-burn duff thickness (Figure 1). Once the variogram had been constructed, it can estimate the values at unknown locations with the model and kriging.

Figure 2a shows a post-burn duff thickness kriged estimated plot (grey-scale map) with duff thickness ranging from 4 to 35 mm. The grey-scale map (Figure 2a) indicates that the location of deeper material-a low-severity burn (lightest grey-scale) was at the coordinates (400, 680 m) corresponding to an area in the lower portion of the hillslope. The northwest portion (250, 700 m) had only 10 to 20 mm of duff remaining-a high-severity burn, due to the intense heating that occurred when the lower portions of the unit were ignited causing the upper portion to dry out and reburn. Figure 2b indicates the error estimate (kriged standard deviation) for each grid cell that was kriged. The darker cells are generally near the sampling locations with an average error of 3 mm. As the distance away from the sample locations increases, error increases to 8 to 10 mm. Thus, this estimation method provides a measure of uncertainty.

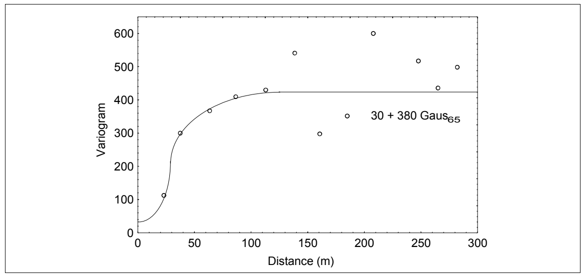

Figure 1. **Variogram for pre-burn duff thickness**.

Spatial simulations provide more realistic fluctuations that honor the original data. One hundred spatial estimates were made for unsampled locations for each of the duff characteristics and averaged together. Simulation results of post-burn duff thickness were similar to the kriged estimates but with greater variability.

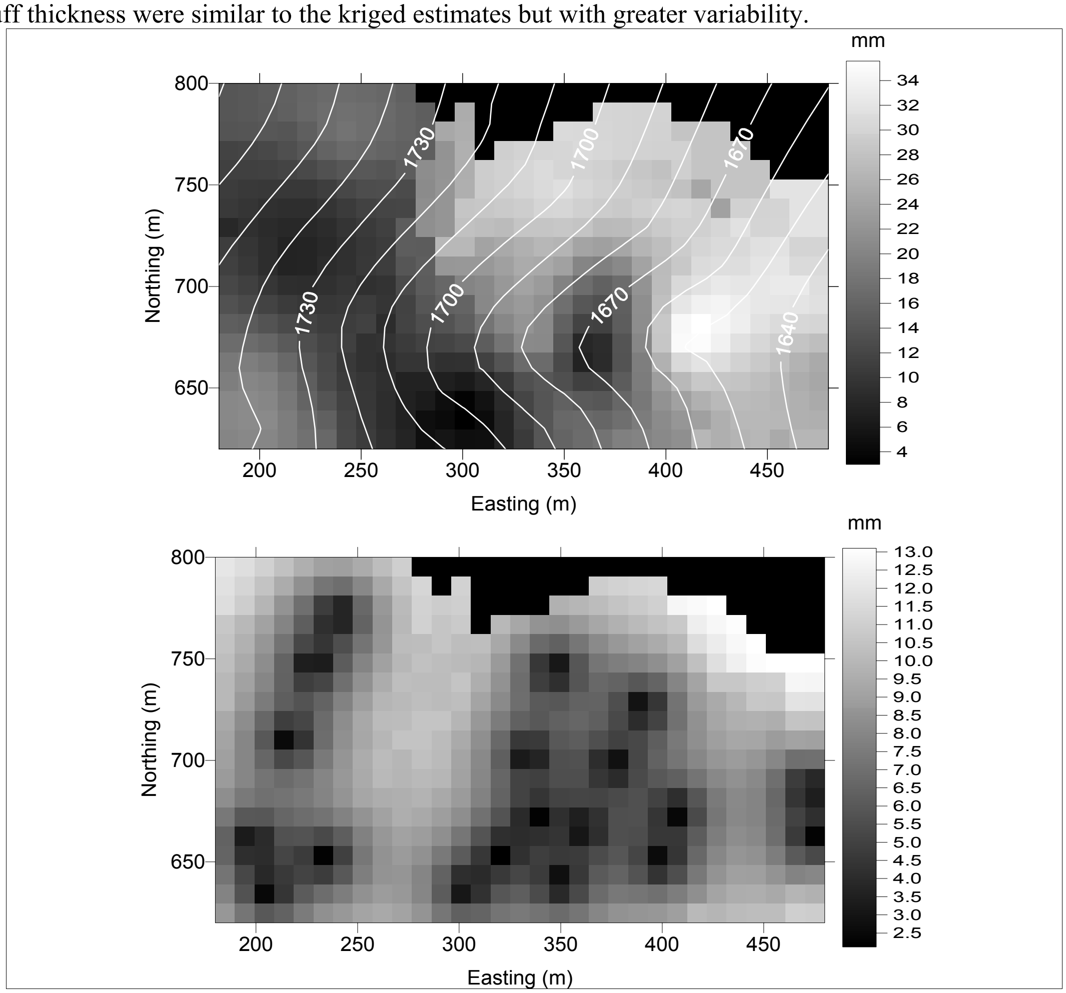

Figure 2. **a)Grey-scale map of kriged estimate for post-burn duff thickness. White contour lines are elevation (m) to aid in site orientation. b) Error estimate for each grid cell.**

The rainfall simulation results indicated variability of hydraulic conductivity and erodibility for both conditions (Figures 3). The means for hydraulic conductivity were 77 mm hr^{-1} for the low-severity burn condition and 70 mm hr^{-1} for the high-severity burn condition. Mean erodibility value for the low-severity burn condition was 75 kg s m^{-4} *1000 and for the high-severity burn condition was 1000 kg s m^{-4} *1000 with a wider range of values.

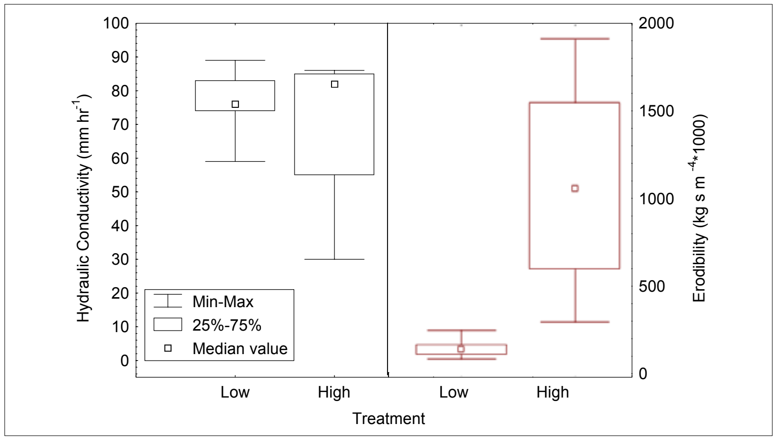

Figure 3. **Box and whisker plot of hydraulic conductivity and interrill erodibility for low- and high-severity burn conditions.**

Conclusions

Duff consumption and post-burn duff thickness is important for erosion protection, natural regeneration and preparing seed beds for planting after fire. If forest sites exhibit spatial variability, then mitigation and modeling efforts should also vary spatially to be effective and accurate. The post-fire surface conditions were variable, with the upper portions of the site consuming more of the duff resulting in high-severity burn conditions. In the remaining portion of the unit, low-severity burn conditions prevailed. Spatial variability in post-burn duff thickness was modeled with variograms. These variograms allowed for site mapping through estimation at unsampled locations by kriging.

Hydraulic conductivity varied between low- and high-severity burn conditions therefore a single value of hydraulic conductivity would not be appropriate and needs to be distributed based on post-burn duff thickness, such as low- and high-severity burn conditions. This agrees with the finding of Hawkins and Cundy (1987), that a single value for hydraulic conductivity for a particular site is not appropriate for forest conditions. Variable erodibility conditions also existed after the prescribed burn with variation for both low- and high-severity burn conditions. Again a single value would not be appropriate to model erosion. These parameters can be spatially distributed based on the low- and high-severity burn conditions from the post-burn duff thickness classification and grey-scale mapping. The analysis suggests that spatial variability is an important characteristic of these harvested and burned hillslopes and needs to be addressed to properly model erosion processes and that geostatistical techniques can be used to describe the spatial variability.

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