STOCHASTIC SPATIAL MODELS

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SPATIAL ANALYSES OF WILDLAND FIRE FUELS

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A B S T R A C T : Quadrat analysis is used in earth sciences research to study the spatial heterogeneity and patterns of natural phenomena. Since wildland fire fuelbed nonuniformity is a function of spatial variability in physical properties of fuels, quadrat analysis of two fire fuel properties was employed to assess the relation between variation and sampling distance. A range of spatial resolution was established for sampling Wyoming big sagebrush *(Artemisia tridentata* spp. *wyomingensis)* and lodgepole pine *(Pinus contorta)* fuel profiles. Quadrats provided homogeneous strata and precise measures of central tendency on both fuelbeds examined. Field inventories in which sagebrush is viewed as a fire fuel could use sample spacings up to 60 m and small sample sizes. The optimum range of resolution for the lodgepole pine fuel type was down to 20-30 m. An attempt was made to supplement the quadrat analysis with a spatial statistical description of the same fuelbed arrays. This spatial analysis, known as the isarithmic mapping technique, generated continuous surfaces of fuel quantity and depth suitable for fire management needs, but with certain sampling intensity qualifications. With sampling and interpolation methods held constant, errors produced using the isarithmic method were inversely proportional to sample size. Four or 9 sample points were too few for use in the isarithmic mapping of the fuel types studied and a minimum of 16 points was required. There was agreement between findings of quadrat and isarithmic analyses for the larger sampling intensities (16 and 36 points) in terms of selecting a more representative and precise field sample.

K E Y W O R D S : fire management; quadrat analysis; isarithmic mapping; geographic information systems.

INTRODUCTION

Wildland fire behavior prediction in a nonuniform modeling environment is an important step towards more efficient levels of fire management planning and decision-support. Such a modeling scheme should simulate wildfire behavior as realistically and accurately as possible. Nonuniform environmental conditions complicate the prediction of fire behavior potentials because microsite variations affect fire behavior changes, and spatial aggregation over heterogeneous environments is prone to erroneous and unrealistic estimations. Disaggregation of averaged input parameters should provide more refined spatial data for fire modeling.

Simulation of wildland fire behavior requires an integration of vegetative fuel and other environmental determinants. This basic relationship has been developed into a mathematical model that predicts fire spread and intensity in wildland fuels (Albini 1976, Rothermel 1972). The model assumes that the fire behavior determinants are uniform over some unspecified interval. Spatial and temporal uniformities, however, are more often the exception than the rule in nature, so the assumptions of the model are violated in heterogeneous environments. When uniformity and other assumptions are violated, model predictions differ considerably from fire behavior observations, resulting in frequent complaints from fire management personnel about the inadequacy of the fire spread model.

Fire responds to spatial variation of wildland fuels by exhibiting a range of spread rates and intensities that is difficult to predict realistically. By partitioning the fuel environment into less variable units of space, fire behavior might be determined more precisely since conditions would be closer to the fire spread model's requirements. Thus, the fire spread model could be utilized without violating the uniformity assumptions (Fujioka 1985). Subsequently, establishing an "optimal" resolution for the inherent variability of the fuel environment would be a critical element in proper fire modeling. Within the above analytical scheme, a quantitative description of fuel continuity--which is actually a component of uniformity--would also be possible as a function of the pattern of the fuel distribution being sampled. For example, if the fuel distribution has no pattern, then all levels of spatial resolution will give similar levels of continuity. Existence of areal pattern in the underlying distribution would suggest a relationship between distance and fuel continuity. As a consequence, the consistency of the pattern should be examined at different scales.

Another topic of concern to fire and geographic information systems (GIS) scientists is errors and their propagation in natural resources databases (pers. comm. with Dr. Joseph K. Berry, 1989). Undoubtedly, studies are needed to assess the reliability of GIS databases in fire management, since a great amount of decision-making could rely on such fire databases (e.g., strategic placement of fire suppression resources). Therefore, information content, procedures, and methods (e.g., isarithmic mapping) of these databases must be thoroughly examined. Within fire databases, elements that critically determine fire behavior and effects would be logical to analyze for precision and validity (e.g., wildland fuel attributes).

The above concerns informed the focus in this study. The following subchapters summarize the experimental and analytical schemes designed to examine the use of two spatial analysis techniques (i.e., quadrat and isarithmic), in an attempt to assess and map the variability of natural fuelbeds. This paper briefly introduces new "spatial analysis" concepts into the field of wildland fire science; it is not intended as a detailed report of the subject. More comprehensive descriptions per se are available in Kalabokidis and Omi (1992), and Kalabokidis and Omi (in preparation).

METHODOLOGY

In order to isolate and analyze the variation as it relates to spatial resolution, one needs to examine separately the basic elements that compose the wildland fire environment: vegetative fuels, terrain, and weather conditions. This study addresses the variability of fuels alone. Accordingly, only fuel quantity (or loading) and depth were examined, since these physical fuel properties show a high degree of spatial variation and have greater impact on fire behavior modeling than other fuel parameters (Brown 1981, Frandsen and Andrews 1979). Thus, the study attempted to establish an optimum range of resolution or sample spacing for sampling and mapping two structurally distinct fuel profiles: a Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis*) shrubfield, and a natural forest stand of lodgepole pine (*Pinus contorta*).

A regular 12x12 grid of 10-m on a side square cells was superimposed on both study areas, and fuel characteristics were sampled within each of the 144 cells included in the grid matrix. Loading of leaves and branch particles by size (1-hour, 10-hour, and 100-hour timelag), and depths for the sagebrush plants were inventoried in the shrubfield site. This inventory utilized a random 10-m long belt transect (Bunting *et al.* 1987) and biomass regression equations (Frandsen 1983, 1991 pers. comm.) within each cell. Loading and depth of downed woody fuels for the forest site were sampled at one randomly located 10-m transect per cell, using the planar intersect technique (Brown 1974). Sample variance and spatial autocorrelation of all the fuel parameters inventoried are illustrated in Figure 1. One-hour, 10-hour, 100-hour, and 1000-hour moisture timelag classes correspond to dead fuel particle diameter classes of less than 0.6 cm, 0.6-2.5 cm, 2.5-7.6 cm, and greater than 7.6 cm, respectively (Deeming *et al.* 1977). Spatial autocorrelation was estimated with Geary's contiguity ratio c (Taylor 1977). The closer this statistic is to zero, the smaller the difference among adjacent areas, hence the higher the autocorrelation; a value of one indicates independent values that show no spatial autocorrelation.

QUADRAT ANALYSIS AND RESULTS

Quadrats are commonly used in geographical research techniques designed to search for point patterns in maps. The method, known as *quadrat analysis*, employs a grid of quadrats superimposed on the study area to examine homogeneity of ordinal spatial data (Upton and Fingleton 1985). Various quadrat sizes have been suggested in plant ecology and geography studies, but the type of data (e.g., ordinal vs. ratio scales) may influence the selection of optimal size. In fact, my analysis of spatial patterns deals with ratio data that lends itself to another approach--including analysis of variance (ANOVA)--to the size problem. Also, the scale of pattern in wildland fuels needs to be examined. Thus, the issue of determining a single quadrat size is resolved by examining scale effects on fuel variation, leading to an approach employing quadrats of more than one size.

Another issue associated with a grid of quadrats is the presence of autocorrelation that implies covariation between adjacent quadrats. This situation will lead to the lack of independence in observations, violating a critical assumption of parametric inferential statistics (Sokal and Rohlf 1981). As a consequence, the use of ANOVA to test the homogeneity of fuel data between quadrats would be intrinsically invalid. My data, showing a high degree of independence (spatial autocorrelations between 0.82 and 0.97), were analyzed with the one-way ANOVA model and mean square comparisons among quadrats (Ripley 1981). These quadrats were generated with areal stratification of the original sampling grid into four schemes representing 60-m, 40-m, 30-m, and 20-m on a side quadrats, respectively. In the statistical analysis, the source of variation was sampling distance with quadrat size representing the treatments.

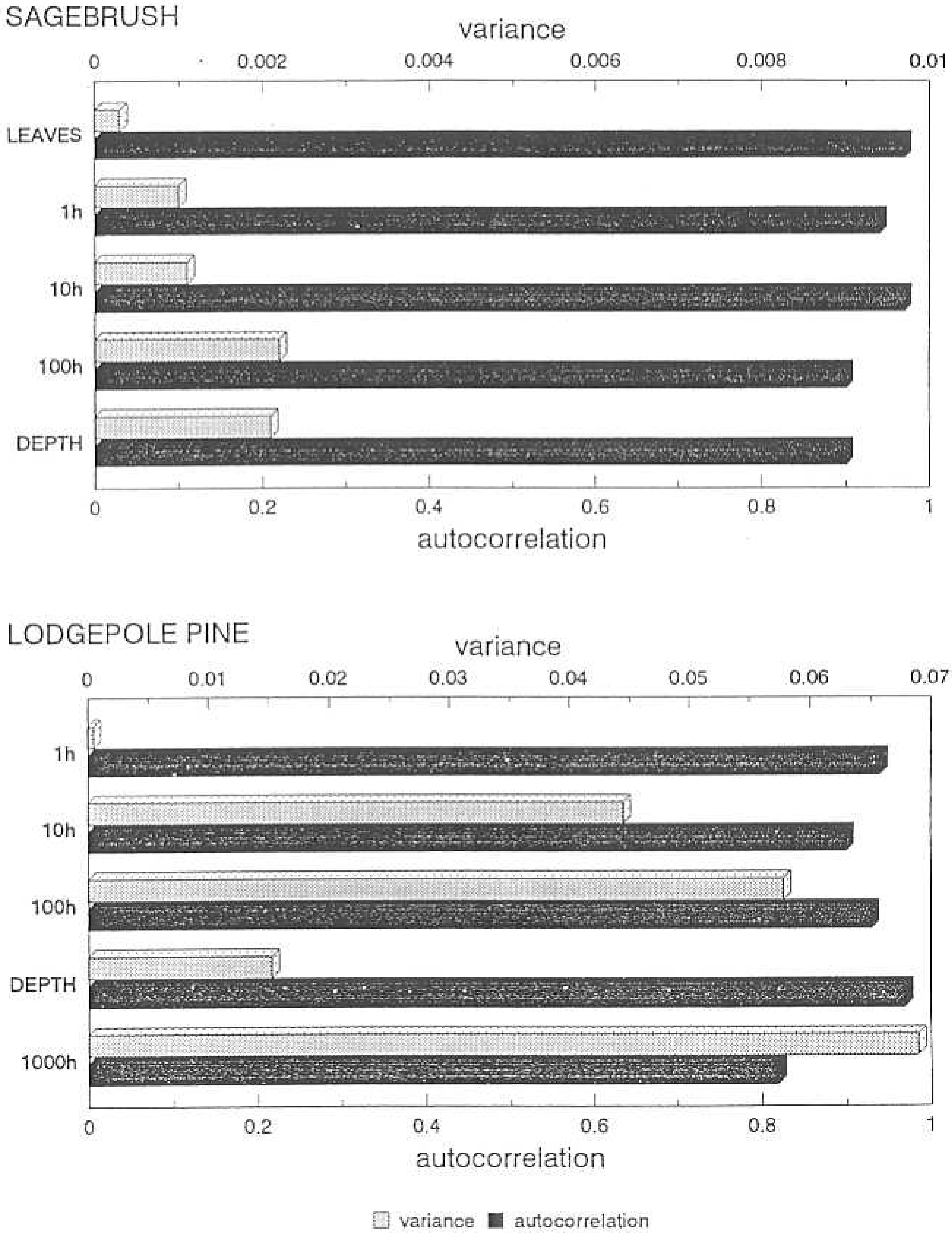

FIGURE 1. *Sample variance and spatial autocorrelation of shrub leaves, 1-, 10-, 100-, and 1000-hour loadings, and depths for sagebrush and lodgepole pine fuels (resolution of the 1000-hour variance bar is 100 times lower than the rest).*

One-way ANOVA mean squares of all sagebrush measurements showed no significant differences at the 5% level among quadrats for all four quadrat sizes (Kalabokidis and Omi 1992). This suggested that the means of the sagebrush fuel loading and depth measurements were produced from homogeneous quadrats, and size had no statistically discernible effect on variability. As a result, less variable measures of central tendency should be expected even at large sample spacings (e.g., up to 60 m).

The analysis of variance of the fuel parameters in the lodgepole pine stand gave statistically significant results at quadrat sizes of 40 and 60 m, suggesting nonuniformity at this scale. Twenty- and 30-m quadrats did not present any discernible differences, indicating more uniform strata (Kalabokidis and Omi 1992). Fuel loadings at all sizes showed directly proportional variability with quadrat size, and peaks at 60-m quadrats; smaller size quadrats clearly exhibited less heterogeneity (Figure 2). Depth results in the lodgepole pine fuels showed a scale of pattern similar to the sagebrush data.

ISARITHMIC ANALYSIS AND RESULTS

Isarithmic is one of the more common techniques used in cartography for mapping natural phenomena; this spatial analysis technique infers the character of a continuously variable distribution by the use of isolines based on data values sampled within the study area (Robinson *et al.* 1984). Wildland fuel profiles tend to be discontinuous, but they are transformed conceptually into continuous data layers by applying the density concept. For example, fuel weights can be related to the space that they occupy and made continuous--since all areas will have an average density value. The isarithmic method could then be employed to create continuous statistical surfaces of fuel parameters. Further, method-produced errors and the statistical validity of these spatially continuous fuel profiles could be assessed.

To utilize the isarithmic technique, one follows a number of necessary steps (Morrison 1971). First, a set of data is sampled or given that describes the phenomenon under study. Second, an interpolation model is assumed and established that will estimate values intermediate to those collected in the first step. Third, the procedure is carefully carried out and the isarithmic maps or surfaces are produced. Thus, precision of isarithmic surfaces--including those proposed for wildland fuels--is a function of data sampling procedures, spatial interpolation methods, as well as spatial variability of the phenomena represented.

Based on results of previous research (Ayeni 1982, Maling 1989, Morrison 1971), data sampling utilized an unaligned stratified random scheme. Consequently, my data grid cells were randomly selected from equal sized quadrats that were generated with areal stratification of each fuel parameter's original sampling grid into 60-m, 40-m, 30-m, and 20-m on a side square quadrats. These four quadrat sizes resulted in four sampling intensities with each quadrat representing a sampling point; thus, 60-m quadrat size was equal to a sample size of 4, 40-m was equal to 9, 30-m was equal to 16, and 20-m was equal to 36. SURFER software's kriging interpolation algorithm was used to generate the continuous isarithmic surfaces from the stratified fuel samples.

For each fuel parameter in Figure 1, an "original" continuous surface was generated by using the actual sampled point values. These original data surfaces were directly

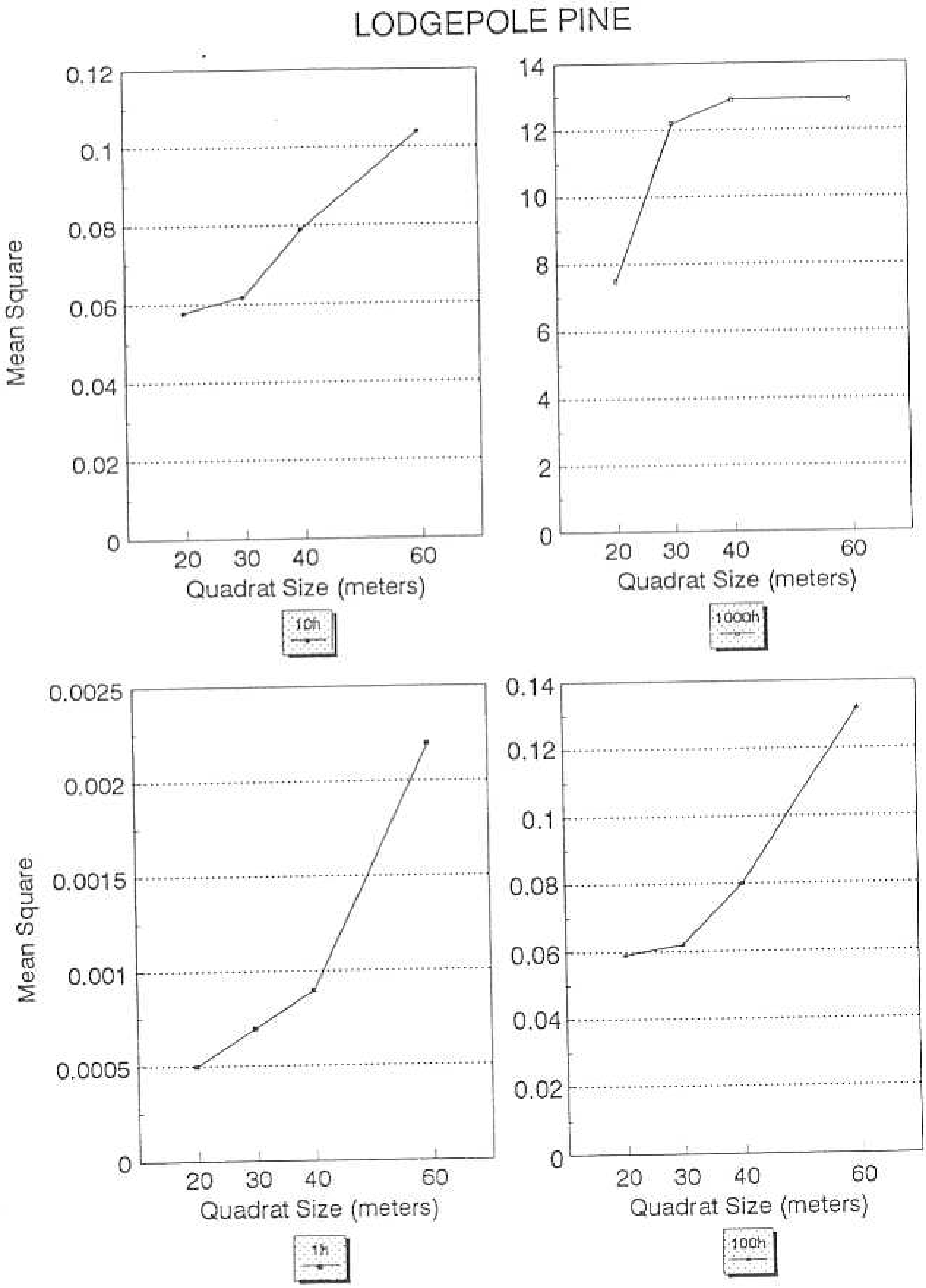

FIGURE 2. Mean squares versus quadrat sizes for lodgepole pine 1-, 10-, 100-, and 1000-hour loadings, showing increases of variance with increasing quadrat size (Kalabokidis and Omi 1992).

compared with their corresponding interpolated ones from the four sample sizes employed in the study. Precision was determined by using a residual error term. First, the absolute values of the difference between original and interpolated data at each point were estimated, and their means were then computed. This mean absolute error gave a quantitative measure of the interpolated surface's agreement with the original data.

Mean absolute errors of sagebrush loadings and depths showed a consistent increasing trend as sample size decreased. Thus, precision of the interpolated loadings and depths was directly proportional to sampling intensity. Error of all interpolated lodgepole pine loadings was also increased with decreasing sampling intensity, indicating reductions in precision. However, results of fuelbed depth gave inconsistent error values, implying random estimates (Kalabokidis and Omi, in preparation). In fact, this random trend supports the contention of depth being an elusive fuel variate not only to measure but to predict as well (Brown *et al.* 1982). Accordingly, lodgepole pine fuel depths were dropped from the next step of analysis.

Next, the previously mentioned mean absolute errors of all fuel surfaces were plotted against sample size (Figure 3). A curvilinear inverse gradient was fitted to the residual errors in the form of:

$$MAE = a\, n^b \qquad [1]$$

where MAE is the mean absolute error of the interpolated fuel surfaces; a is the intercept coefficient that may represent the nature of the fuel surface; n is the sample size used to interpolate each surface; and b is the exponent coefficient that determines the curvature of the regression. R-squares of the fitted lines for the error terms were equal or greater than 0.90 (Figure 3), except that of lodgepole pine 1-hour fuel load. Even though sample size was small, Equation 1 still delineates a trend between precision of the isarithmically produced continuous fuel parameter surfaces and sampling intensity. It is clear that more data will be required before ad hoc regression equations can be developed in various fuel types.

Statistical validity was empirically determined by running a set of t-tests between inventoried and interpolated fuel parameters, with null hypotheses of no difference between their means. In the sagebrush, the means for the larger sample sizes (i.e., 16 and 36) were not statistically different, whereas in the lodgepole pine, only the largest sample size (i.e., 36) showed insignificant differences (Kalabokidis and Omi, in preparation). These results implied that at the smaller sample sizes the interpolated surfaces would provide a limited level of precision. Fuel depth interpolated surfaces of the lodgepole pine stand, however, for all sample sizes revealed statistically discernible differences at the 5% level of significance, indicating imprecise mean estimates.

CONCLUSIONS

For the first part of this study, an exploratory analysis was designed to portray scales and patterns of variability in a sagebrush field and a forest stand of lodgepole pine. The results indicated that a spatial pattern of variation did exist for both fuel profiles. Sample variation exhibited low to moderate levels in both fuel types, primarily because of the highly stratified sampling (i.e., grid cells or quadrats). Variability demonstrated an increase with increasing sampling distance only for the lodgepole pine fuel array. A similar trend for the sagebrush fuel array was not detected; it showed more uniform descriptors at all the

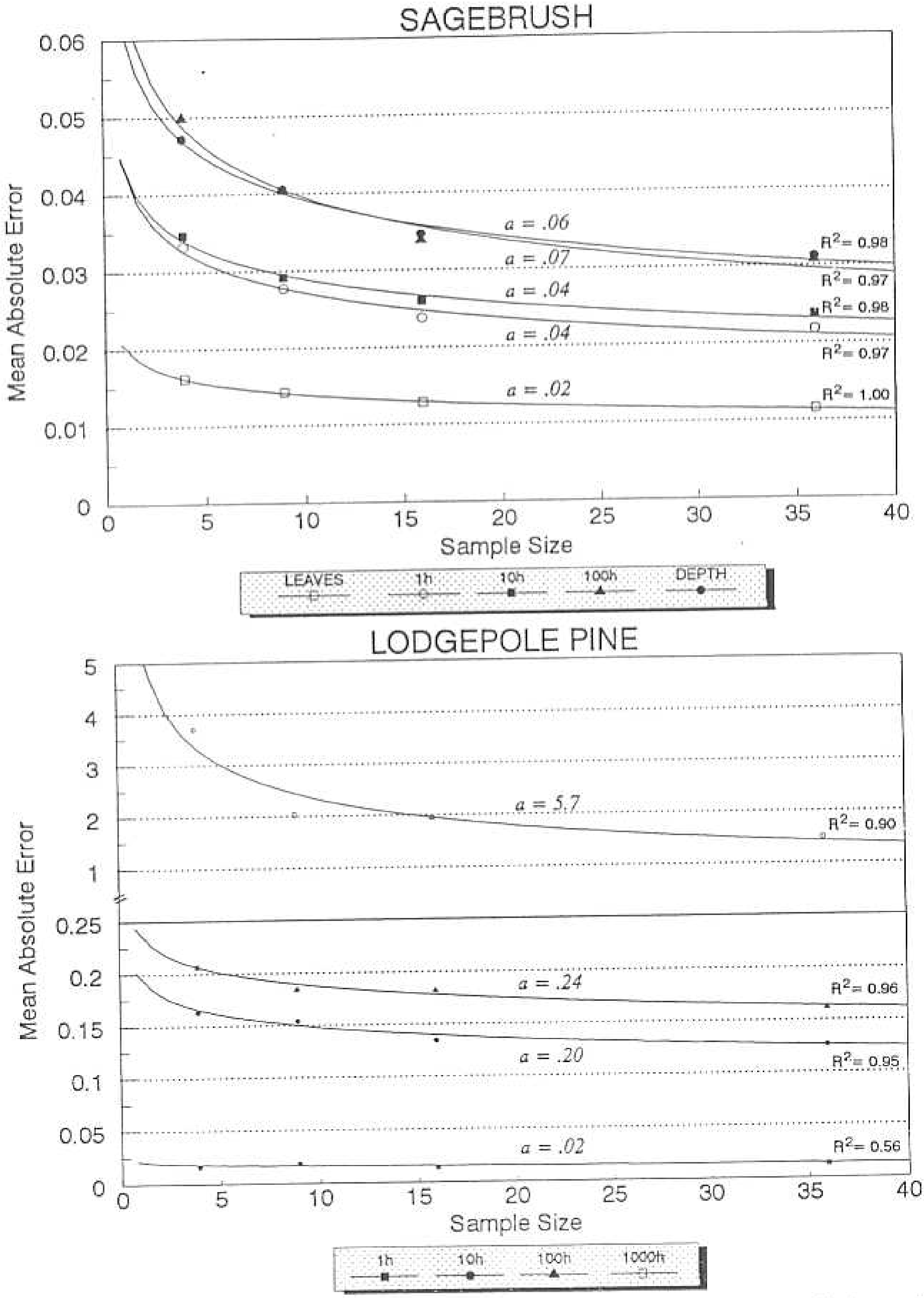

FIGURE 3. Mean absolute errors plotted against sample sizes, including coefficients of determination (R^2) and intercept coefficients (a); exponent coefficients (b) for the fitted curves were fairly consistent with a mean of -0.20 (and S.E.=0.03).

resolution scales tested. The sagebrush findings imply that biomass field inventories which view the shrub as a fire fuel will not have nonuniformity complications even at the largest spatial aggregation level of this study. Spatial disaggregation of the forest stand fuel profile must go down to 20-30 m before variability will decrease sufficiently to lead to more precise estimators of central tendencies. This might be attributed to higher levels of variation encountered in forest fuelbeds, and the changes in the horizontal pattern of forest fuel distributions.

These findings could also relate to field sampling intensities. Each block of cells represents a sampling point; thus, 60-m quadrat size is equal to a sample size of 4, 40-m is equal to 9, 30-m is equal to 16, and 20-m is equal to 36. The fact that spatial resolution as low as 60 m is adequate in sagebrush sampling would suggest that a sample of four be taken. Even this small sample could still achieve relative standard errors within recommended limits of $\pm 20\%$ for fuel appraisal, because of the low variance. For inventorying downed woody fuel in lodgepole pine stands, fire managers would have to use much higher sample sizes to accomplish adequate precision for most fuel problems.

A technique, known in cartography as isarithmic analysis, was examined for mapping the study fuel arrays. Using an unaligned stratified random design and kriging interpolation, a mathematical relationship was identified between sample size and method-produced error for loadings and depths of sagebrush and lodgepole pine fuelbeds. I found that the mean absolute error was proportional to (sample size)$^{-0.20}$ times an intercept coefficient that directly reflected variance of each fuel parameter interpolated. As a result, the magnitude of error decreased, at a decreasing rate, with increasing sample size. Moreover, fuel parameters that exhibited high variability also had higher magnitudes of error due to larger intercept values (Figures 1 and 3). Empirically, statistical comparisons showed that at the smaller sampling intensities the isarithmic analysis would provide very low levels of precision.

Results of the isarithmic analysis indicate quite conclusively that significant method-produced errors potentially exist for interpolated data layers of wildland fuels. Other information layers of wildland fire databases are likely to contain more or less similar errors that may contribute to the overall uncertainty of fire management decisions. Within the analytical scheme presented, the magnitude of error for continuous data layers derived from point samples can be appraised before the layers are made. Thus, necessary minimal sampling intensity is predetermined for the desired precision of layer generation. Overall, this technique may aid in proper and quantitatively-supported fire management responses by providing precise and valid information on conditions that control fire behavior and effects.

While I focused primarily on spatial resolutions and variability, an attempt was made to provide insights into the more general issue of fire fuel nonuniformities (i.e., an appropriate parameterization with practical limits for nonuniformity). Fuel uniformity--or the lack of it--determines how and if a fire ignites and burns, in conjunction with topographic and weather conditions. The significance of fuel nonuniformity has been expressed in previous studies, but it has not been defined in a rigorous fashion to be useful in fire modeling. Undertaking this research, I tried to deal with nonuniformity and variability of fuels in a parallel and quantitative manner. However, the need for a number of critical variables, beyond the scope of the original study, prohibited a proper parameterization of nonuniformity (e.g., subject to fuel properties and spacing within a range of relevant weather events and terrain attributes). Nevertheless, I do submit that wildland fire researchers explore nontraditional techniques and theories used in geosciences and elsewhere to answer their questions. For example, *chaos* theory may be proved suitable for examining whether the degree of nonuniformity is constant at different scales (i.e., a uniform nonuniformity) for similar or specific fuel types.

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