Reconstruction of Forest Areas Using Geostatistics as an Aid in the Evaluation of Burned Areas[1]

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Summary

There are frequently no bases for economically evaluating a forest, following fire. An evaluation needs to consider: a) The original commercial value of the forest (timber, tourism, germ plasma etc.) b) The cost of restoring the forest to its original condition; and c) The opportunity cost involved in restoration. This is essentially feasible, provided that the original state of the forest area prior to the fire is known. However, one of the most frequent problems in the management of forest resources is the difficulty in defining the spatial distribution of the forest characteristics. In this study the use of geo-statistical techniques are described and the manner in which they are used to define the continuous surfaces of some characteristics of a forest: the base areas; number of species; average diameter; the number of trees per hectare, as a basis for the reconstruction of a forest area prior to a fire. The data was taken from a forest in the state of Chihuahua, México (1998). 554 points were chosen as random samples, within a 1400 hectare area. The definition of continuous surfaces was made on the basis of ordinary kriging (OK), from which it was possible to model acceptably the spatial distribution of the characteristics mentioned. In this way the original form of any area can be estimated within the study zone. If there is no previous inventory available, it is suggested that this methodology be used by taking information from the sample points around the burned area.

Introduction

The element of fire has played a part in the development process of forest resources and has long been a useful work tool for the inhabitants of the rural areas of Mexico, who employed fire to cleanse their agricultural areas (Rincón, 2002). Nevertheless, when used without due precaution it can lose control and spread to large forested areas. As a result, enormous damage is caused to forest ecosystems and other associated natural resources. This has repercussions on the economy not only of the villages working directly in production, but also affects the forestry market. Despite the importance of these effects, there are currently no strategies to reliably evaluate the loss of forest resources in the event of fire. There is a need to implement a method for evaluating the damage caused by forest fires to society; the following should be taken into consideration: a) The original commercial value of the forest (timber, tourism, germ plasma, etc.); b) The cost of restoring the forest to its original condition; and c) The cost involved in the restoration. In addition the ecological and

[1] An abbreviated version of this paper was presented at the second international symposium on fire economics, planning, and policy: a global view, 19–22 April, 2004, Córdoba, Spain.

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social impact on the region should be evaluated, as well as damage to the area water basin.

Evaluation of the economic impact of fires is relatively feasible, provided that the original state of the forest prior to the fire is known. However, one of the most frequent problems in the management of forest resources in Mexico is the difficulty in defining the spatial distribution of the characteristics of the forest. Although information in the form of forest inventories is available at the surface level statistics are managed at a mean and variance level (UCODEFO,1997), and do not reflect the potential variation in spatial distribution of the forest parameters. However it is important to point out that if the area in question is homogeneous, those statistics may be of use (Hunner et al, 2000). Nevertheless, the diversity of environmental conditions and management have led in most cases to considerable spatial variations in the conditions of forest areas (Hunner, 2000). This means that any evaluation of the economic impact of a forest fire should be considered not only in terms of the form and degree to which it is affected, but also in terms of the spatial distribution of this impact. This, in conjunction with information on the distribution of the original condition of the forest will help to provide a more precise estimation of the damage. This study describes the use of geo-statistical techniques to define the continuous surfaces of some of the original characteristics of a wooded area in a forest in the state of Chihuahua, México.

Methodology

Study Area

The study was carried out with information on a commercial forest in the ejido "El Largo and Surroundings". This area is located in a region known as Mesa del Huracán, in the eastern part of the state of Chihuahua (figure 1). The predominant tree species are: *Pinus durangensis, P. arizonica, P. engelmannii and Quercus sideroxyla.* The topography of the area is mountainous, with some valleys. Average annual temperature is between 8.5 to 12^{o} C. The lowest temperature registered is–26^{o}C, and the maximum 38^{o}C. Precipitation ranges from 690 to 1,130 mm per annum. The minimum elevation of the study was 1400 m above sea level (masl), and the maximum as defined as 2400 masl. Forest fires occur in summer in the drought season (May to June) (UCODEFO, 1997).

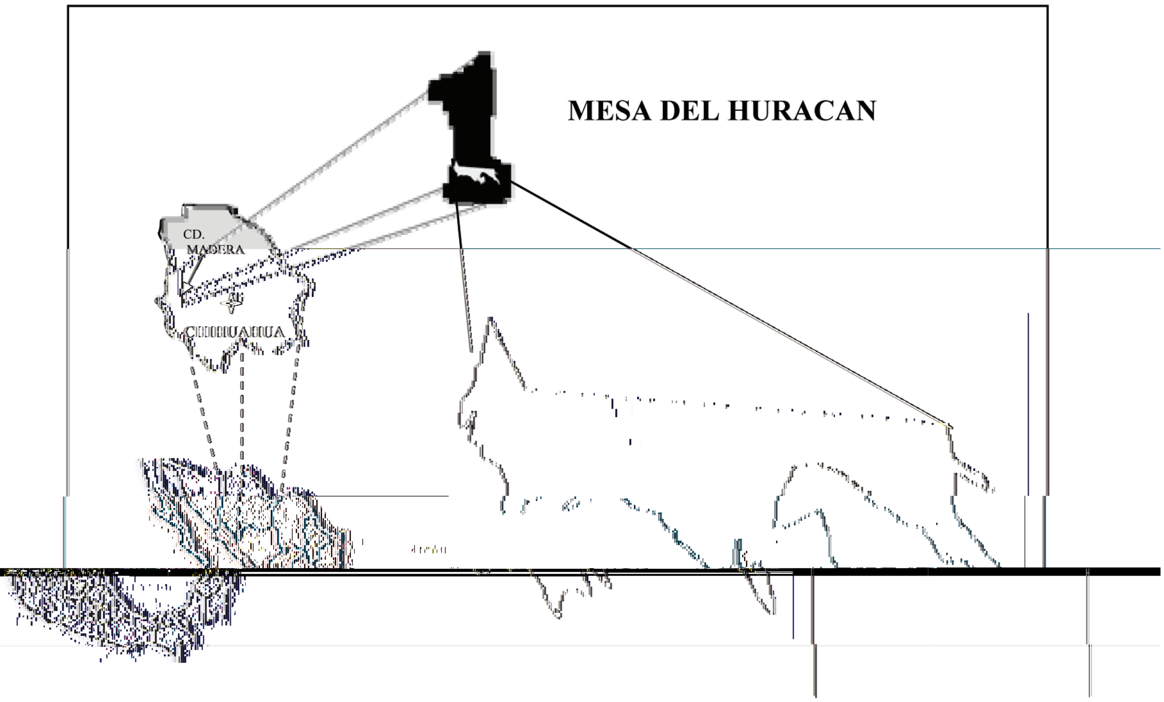


Figure 1. Approximate location of the area under study within the region of Mesa del Huracán, close to Ciudad Madera, Chihuahua.

Sampling strategy

For management purposes the woods in the ejido[4] "El Largo" are divided into sections based on their productive potential. At the same time each section is subdivided into stands (based on density, gradient and exposure) and sub-stands (based on species) (figure 2). Within this framework, the data used in this study was inventoried in 554 sample areas distributed at random in Section 3 of "El Largo" (approximately 1400 hectares). The number of sample points per sub-stand was defined by its size (UCODEFO 2) (Table 1). Although these points were chosen at random, a minimum distance was established between the stands in accordance with the following formula:

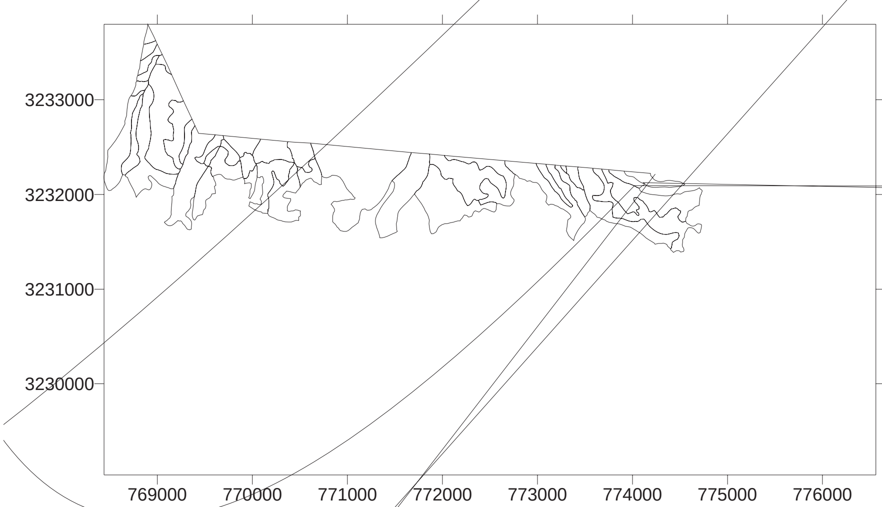
$$\text{Distance} = (\text{Area m}^2/\text{Number of points})^{1/2} \qquad [1]$$

[4] Ejido is an administrative unit of land ceded on perpetuity to peasants by the government on a communal basis. The land can be transfered from family to family but cannot be sold.

Table 1--*Number of sample points per sub-stand according to its size; Criterion employed by the UCODEFO 2 in Ciudad Madera, Chihuahua.*

Size of sub-stand (ha)	**Number of sample points**
5-10 ha	4
11-15 ha	5
16-20 ha	6
21-25 ha	7

The sample areas were circles of 1000 m^2, and the following information was obtained: (a) tree species; (b) diameter; (c) height; (d) height of crown; (e) basal area; and (f) number of trees per hectare.



surface affected (hectares or m^2). This last point may be covered either by aerial photographs, satellite images, or with the use of GPS covering the periphery of the burned area (on foot, horseback or by helicopter). It is important to identify the type of fire since it is this which will permit an estimation of the degree of potential damage.

The spatial distribution of the types of vegetation in the area should be considered, since these are associated both with the behaviour of the fire and with damage potential. This last is related to fire intensity which may spread on the basis of level of trees burned. This may be referred to in a qualitative manner considering the percentage affected in each substratum, using the following classification (Rincón, 2002):

Low - When vegetation is affected at a level of approximately 1 to 25%., bearing in mind the total structure of the vegetation, timber and foliage, in general the damage is scant and individual trees are not at risk of death

Medium - When the damage is moderate between approximately 25 and 50%, and individual trees may be at risk of death, particularly the weakest and most infirm.

High - When the damage is considerable, between approximately 50 to 80% most trees are likely to die and those which survive are seriously damaged and prone to pestilence and disease, particularly adult trees.

Damage should be assessed by vegetation substratum: 1) Adult trees or high; 2) Bushes and medium undergrowth; 3) Renewed growth or undergrowth, and 4) Herbs and pasture or undergrowth. The respective volume and distribution of products by vegetation substratum should also be established. In order to be able to infer the total affected surface so as to obtain the

Ordinary Kriging

Given that, as mentioned above, to assess the economic cost of a fire it is necessary to ascertain both the surface of the damaged area as well as dasometric characteristics, the ultimate aim of this study was to generate continuous surfaces of: (a) base area [BA]; (b) number of species [NS]; (c) average diameter [AD]; and (d) number of trees per hectare [NTH]. The definition of continuous surfaces was obtained on the basis of ordinary kriging (OK). This is a geo-statistical technique based on the theory of rationalized variables (Oliver y Webster, 1990). Ordinary **k**riging is a geo-statistical technique applied when the mean data is stationary but unknown. OK is considered as the "best unbiased linear estimator". (Olea, 1991): (a) it is linear because its estimations are linear combinations weighted from available data; (b) it is unbiased because it tends to generate a mean square of error equal to zero (E[Estimated x_0)-Real(x_0)] = 0, and ☜$\lambda_i = 0$); and (c) is better because it tends to minimise the variance of errors (E{[Estimatedx_0) – Real(x_0)]^2 = minimum). The following formulas are used to calculate the estimates with OK and the corresponding standard deviation of those estimations (Hunner, 2000; Isaaks and Srivastava, 1989):

$$\hat{Z}_{OK}(x_0) = \sum_{i=1}^{n} \lambda_i \cdot Z(x_i) \quad [1]$$

$$\sigma^2_{OK}(x_0) = C(x_0, x_0) - \sum_{i=1}^{n} \lambda_i \cdot C(x_i, x_0) + \mu \quad [2]$$

where:

$\hat{Z}_{OK}(x_0)$ = OK estimate in point x_0;

λi = weighted value of the sample point *i* at point x_i;

$Z(x_i)$ = value of the variable observed *Z* at point *xi;*

$\sigma^2_{OK}(x_0)$ = covariance of ordinary kriging at point x_0 with itself

$C(X_I,X_0)$ = covariance of the sampled area at point x_i and the place to be estimated at point x_0; y

μ = parameter of Lagrange

The required parameters of ordinary kriging were defined by means of structural analysis of the data (Phillips et al, 1992). The spatial continuity of each characteristic was defined by means of variograms, considering an isotropic point of view (Ramírez, 1980).

Results

Spatial autocorrelation

The four cases presented low spatial autocorrelation (Chou, 1991), which is reflected in the spatial continuity defined by the corresponding experimental variograms (Armstrong, 1998) (figure 3). The maximum distance in which spatial correlation was found corresponded to DP (approx. 2550 m). Whilst AB showed a maximum distance of 1000 m. NE and NAH defined a spatial correlation up to 1750 and 1850 m, respectively. Each of the experimental variograms was adjusted to a “defined positive” model (Flores, 2001). In accordance with this, the variables NAH, AB, DP and NE were exponential, exponential, spherical and exponential, respectively.

Despite the low spatial autocorrelation of the variables studied, it was possible to define the required pa**rameters by OK (Nugget [Co], Sill [Co+C] and Rango [Ao]).** By means of OK, the corresponding continuous surfaces were generated. Figure 4 shows the resulting surfaces for each of the variables in the study. It is possible to observe that the greater variability of DP is in the NE part of the studied area. In the case of species numbers, the spatial distribution is a little more homogeneous, with some peaks in the SE part. The zones with a greater base areas are situated in the NW part of the area studied. This coincides with the spatial distribution of the species number per hectare. It is important to point out that although the greater densities are found in the NW part, the greater diameters are found the NE zone. There is some logic in this, since at greater densities there is more competition between trees and therefore lesser diameters are to be expected.

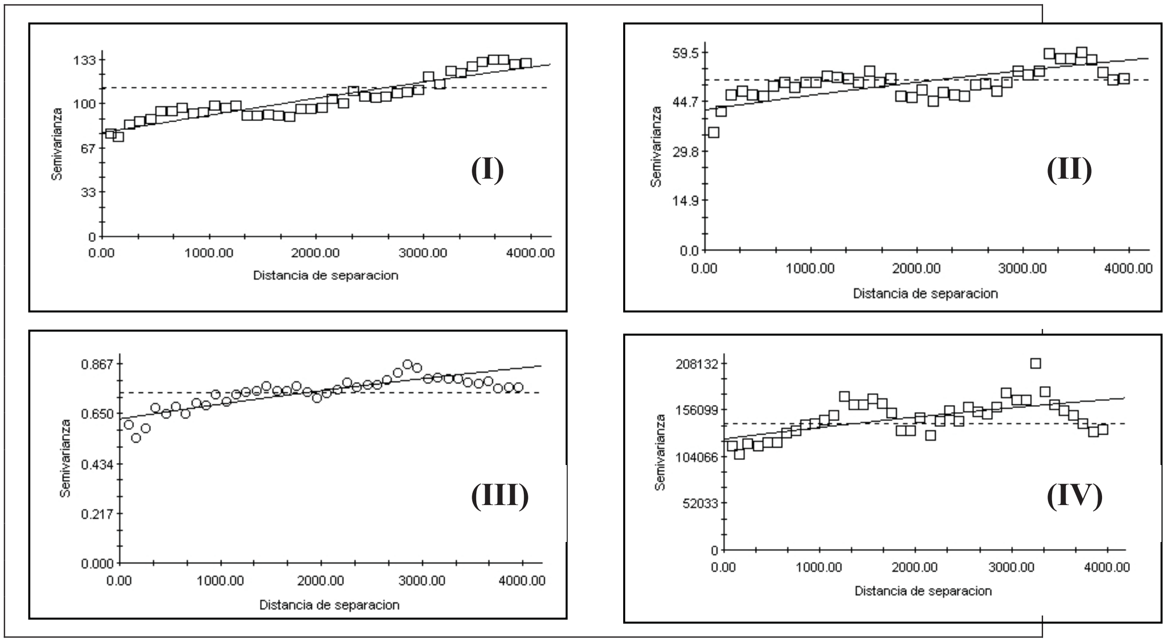


Figure 3—Spatial continuity of the variables in the study expressed in variograms: (I) average diameter [AD]; (II) total basal area [BA]; (III) number of species [NE]; and (IV) number of trees per hectare [NTH].

Once the continuous surfaces were generated, the corresponding maps were defined using geographic information. The final corresponding map can be seen in *figure 5*. The average diameter of all tree species was 36.67 cm with a maximum and a minimum of 14.05 and 72.95 cm respectively. The standard deviation was 10.58 cm. Average diameters between 30 and 40 cm were distributed along the study area. The average basal area was 10.62 m squared and a maximum and minimum of 1 and 48 m squared respectively. The standard deviation was 7.16. The majority of the basal areas in the study area were between 5 and 15 m squared. The number of tree species per hectare varied from 7 to 3,580 with a standard deviation of 376. Most of the sample areas had less than 500 trees per hectare. There was a definite pattern of distribution for density classes between 150 and 500 trees per hectare. On the other hand, the density class greater than 500 trees per hectare had a scatter distribution. The number of species per sampling site varied between 1 and 7. However, 80.3 percent of the sites had between 1 and 2 tree species. The most frequent dominant species were *Pinus durangensis, P. arizonica* and *P. engelmannii*, which were found in 45.49, 30.14, and 12.64 percent of the sampled sites respectively. All throughout the study area the spatial distribution of 1 and 2 species was very homogenous. Areas with more than 3 tree species were few.

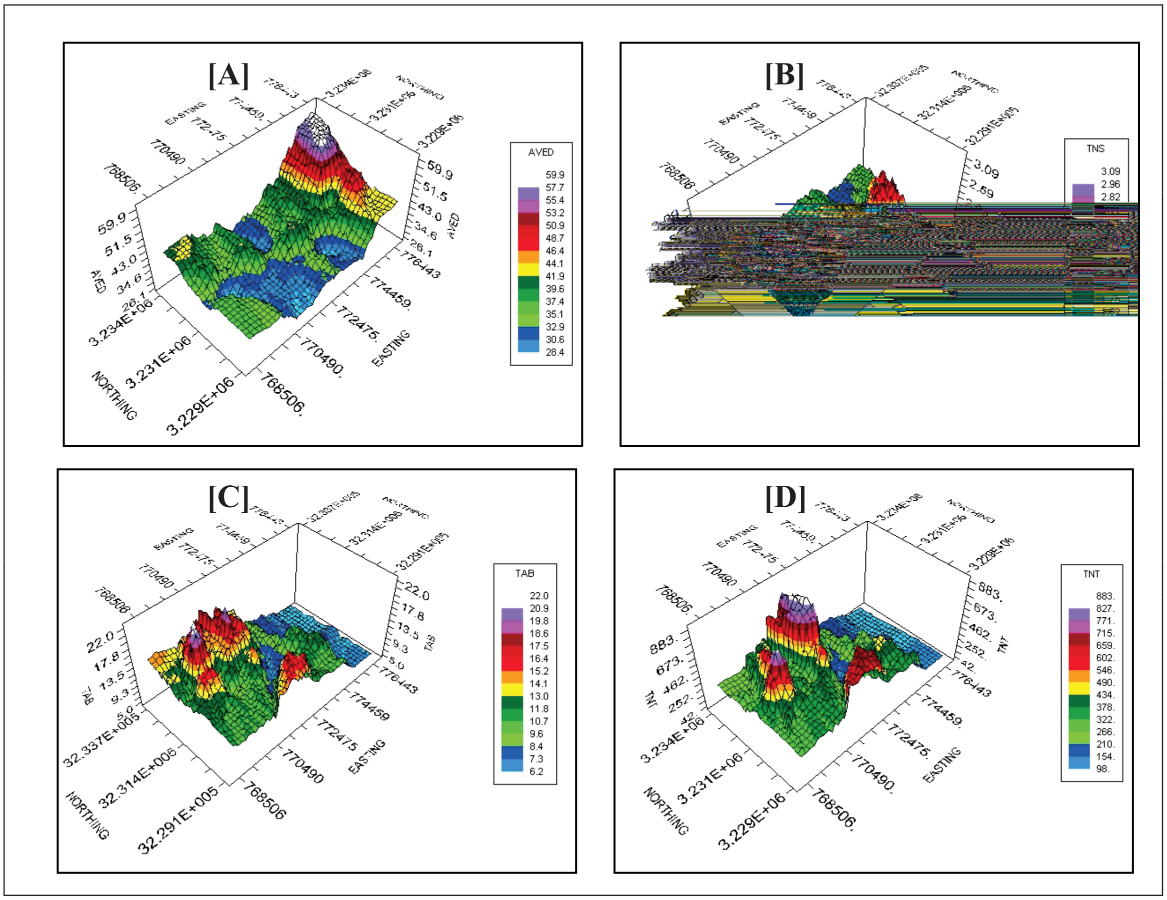


Figure 4—Continuous surfaces generated through the ordinary kriging: (A) average diameter [AD]; (B) total basal area [BA]; (C) number of species [NE]; and (D) number of trees per hectare [NTH].

Discussion and Conclusions

Spatial Continuity

The economic valuation of Forest fire damage can not be done accurately without knowledge of the condition of the Forest prior to the fire. Considering the existence of abundant forest inventory information for a specific area it is not convenient to use only general statistical information like the median and the variance to estimate the economic loss. This approach would imply, as shown in *figure* 6a, that the dasometric characteristics of the forest mass were very homogenous. In turn this would imply a spatial continuity defining large areas, as in the case of climate (Atkinson y Lloyd, 1997). Even though this may be possible in forests with pure and similar age structure stands, in Mexican forests it is difficult to find such uniform spatial continuity. This lack of spatial continuity could be the result of the different management strategies applied in a particular site. Plagues, infections, and illegal harvesting could also be factors altering the spatial continuity of the dasometric characteristics. Fire itself is a factor affecting the continuity.

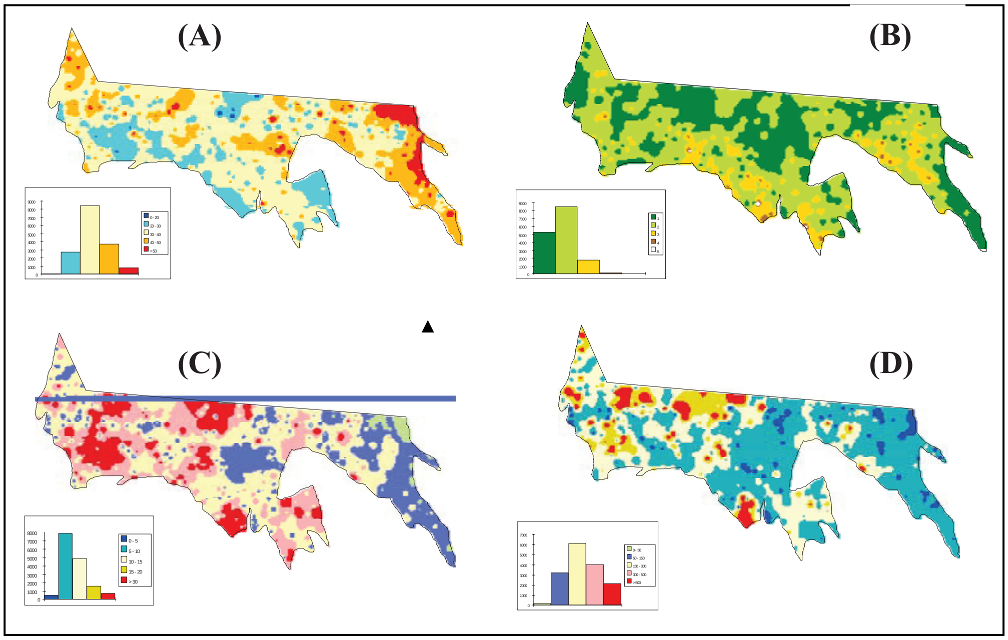


Figure 5—Final maps of the study variables spatial distribution: (A) average diameter [AD]; (B) total basal area [BA]; (C) number of species [NE]; and (D) number of trees per hectare [NTH].

Because of what explained before we need to keep in mind that just because there are spatial variations in forest characteristics, these do not follow a strict polygon defined pattern. On the contrary, this is rather a continuous variation ranging slowly, for example, from very high densities to low densities (*fig. 6b*). This spatial behavior is impossible to capture from the estimation with the mean and the variance (*figure 6a*). As illustrated here it is important to use alternatives that allow consideration of the space factor in estimating the dasometric characteristics of a forest. This will allow not only an economic valuation closer to the reality of the forest mass condition but could also allow for spatial identification of areas with lesser or grater damage. We can thus estimate not only affected areas by damage and recovery costs but establish spatially the opportunity cost of the recovery period. Finally, the integration of all this information will help in selecting priority areas (by damage and recovery costs), and even define areas not needing any investment (due to its high recovery capacity).

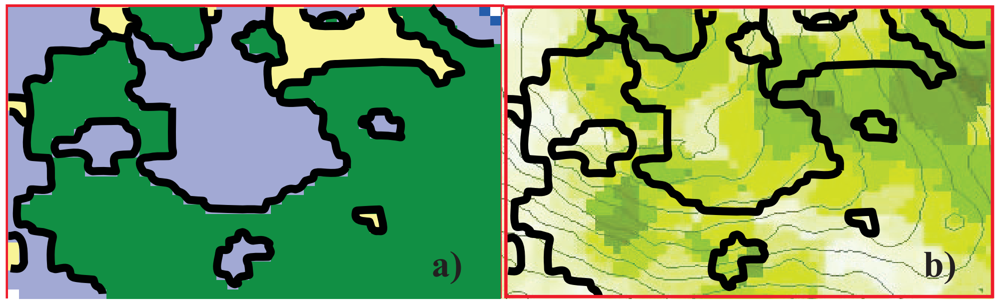


Figure 6—The variation in the dasometric characteristics of a forest could have a homogenous pattern defining large polygons (a), or a pattern of continuous spatial variation (b).

Interpolation

The use of geostatistical techniques requires that the variables studied are spatially autocorrelated. The low spatial autocorrelation found in this study suggest the use alternative methods such as co-kriging. The type and the intensity of the sampling must also be considered. Never the less, the methodology used here is relatively simple and can be used prior to a fire to define the spatial distribution of the dasometric characteristics of the forest mass. It is important to note that the methodological procedure in performing geostatistical interpolations imply a good knowledge of the spatial characteristics of the species studied. Thus, before performing the kriging iterative procedure it is important to study carefully the circumstances defining the presence of a variable. For example, as mentioned in the results section, we expected the spatial distribution of the higher density zones to be related to the areas with smaller average diameter. Other possible useful factors in the case of forestry characteristics are elevation, exposure, or slope. This type of information is relevant in the economic valuation of a fire damages.

Future work

One advantage of the geostatistical techniques (though not presented in this work) over the deterministic alternatives is that they allow you to compute the standard error of the estimates. This permits us to identify those areas in which are estimates are most reliable. The utility of this is determining the propriety of the sampling design, as well as in designing future sampling strategies. For future work is recommended to compare not only other geostatistical alternatives (for example, universal kriging, block kriging, and cokriging [Goovaerts 2000]) but also non-stochastic interpolation techniques (for example, Spline [Bishop and others 1999], polygonal mapping, and Thiessen polygons). This type of analysis will provide more precise maps, which will allow a more objective economic valuation of fire damages. This would provide support to the answers given to the following questions: a) What was the commercial value of the forest (timber, tourism, germoplasm, and others) prior to the fire? b) What would be restoration cost to the original condition? c) What is the opportunity cost of the restoration period? The answers to these inquiries require not only knowledge of the forest conditions prior to the fire but also taking into account a series of ecological (species, soil, population dynamics) economic (supply, demand, costs), and social factors (employment levels, recreation, landscape).

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