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A Variogram Model Comparison for Predicting Forest Changes

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Abstract

Changes in forest lands can be assessed by comparison between real images taken on different dates. However, the main forest features (e.g., basal area, stand height and aerial biomass volume) are better estimated by indirect methods related to the forest canopy. Variogram models have been used to measure forest stand structure; however, they have a known dependence on image parameters such as pixel size, contrast and sensor type. In addition, variogram methods allow us to select among different mathematical fitting functions that have different characteristics for estimating forest stands. Consequently, the above factors should be considered and corrected for when analysing forest changes from different images.

The study focuses on the problem of choosing a mathematical function to fit the experimental semivariograms of high-spatial-resolution images of forest stands and the relationships between the semivariogram parameters and forest-stand features of a cluster of pine trees (*Pinus pinaster Ait.)* in a Mediterranean region (Madrid, Central Spain). The work compares the characteristics of spherical and exponential functions. In particular, the following issues were studied: (i) which model best fits the experimental semivariogram; (ii) how semivariogram models perform according to image spatial resolution; and (iii) the relationships between different models fitted to a particular experimental semivariogram. All of the analyses were carried out using five series of real images, including 2 aerial photographs from 1990, 2 orthophotographs from 2000 and an IKONOS image from 2003. The analysis considered up to 4 semivariogram features, namely range, sill, gradient and slope. The obtained results show that there is no optimum unique model and that the best mathematical function for fitting depends on the pixel size and on the forest variable that to be predicted. In particular, spherical models performed better for large pixels and exponential models performed better for small ones. According to the results, equalisation and normalisation image procedures improved forest prediction in comparison over analyses of raw images. As a general rule, exponential models obtained better forest-diameter predictions than did spherical models, while spherical models obtained better forest-stand height estimations. As a consequence, predicting forest changes using semivariogram models would require the use of normalised images and two different fitting functions for two different pixel sizes.

Keywords: Semivariogram; Forest inventory; Spherical model; Exponential model

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1. Introduction

Raw information about forests is frequently provided by a variety of sources, including field-sampling plots, photograms and (recently) remote sensing. The changes in forest surfaces over time can be assessed by merely quantifying the difference between maps. However, determination of the changes in dasometric features requires more complex analyses related to the forest canopy structure. The common variables by which forest canopy structure is described include crown size, density, crown closure, total height, basal area and biomass [1, 2, 3, 4]. The problem arises when the aim of identifying forest changes requires analysis of different images characterised by different pixel sizes and different photographic features (e.g., light, exposure and focus distance). For analysis of a particular date, a forest stand inventory should be made using semivariogram techniques that address forest texture by extracting the repetitive pattern of the canopy [4].

The semivariogram has been used as a primary geostatistical tool in many vegetation studies [5, 6]. It is generally used by assessing the relationships between semivariogram basic features and the tree elements within a forest image. In particular, the range of a semivariogram has been shown to be directly related to the size of objects (e.g., tree crowns) in a scene [7, 8] and also to the height of the tree stand [9]. On the other hand, the sill has been found to be related to density [10, 11], vertical stratification, horizontal distribution [12] and percent canopy cover [1, 5, 8].

To analyse forest canopy changes, important issues are how semivariogram features depend on the image scale, the appropriate spatial resolution for characterising the variation in natural processes and the calculation of the relationship between spatial scene properties and forest variables [12, 13].

The present work focuses on the problem of choosing a mathematical function [14] to fit the experimental semivariograms of high-spatial-resolution images of forest stands. It presents an in-depth analysis of the characteristics of, and the relationships between, the selected models and their features. In particular, we ask the following questions: (i) Which model best fits the experimental semivariogram? (ii) How does the semivariogram model behave depending on the image spatial resolution? (iii) What are the relationships between the different models fitted to a particular experimental semivariogram?

2. Methodology

2.1. Data and study zone

Four datasets were used for ortho-rectification purposes: (i) aerial photographs, (ii) digital orthophotographs, (iii) an IKONOS satellite image and (iv) digital planimetric and altitude maps (1:5000). Aerial photographs were black and white ortho-rectified positives taken in 1990-91 during a 1:6500 flight (hereinafter, airphotos 1990) used in the Second Spanish Forest Inventory (NFI). The digital orthophotographs were taken in 2000 when fieldworks of the Third NFI were been made. The orthophotographs were in colour (RGB bands), so a Principal Component Analysis (PCA) was performed to keep only one band for which the texture was then analysed (hereinafter, orthophotos 2000). The IKONOS image was taken on May 18th, 2003, and only the panchromatic band of the IKONOS image was used (hereinafter, IKONOS 2003).

The study refers to the patches of *Pinus pinaster* Aiton from the Sierra de Guadarrama mountain range in the Madrid region. This pine species is a medium-sized tree with a straight trunk, a large crown and a regular shape. Analysed subimages correspond to the 72 sample plots that are located within the mentioned patches.

2.2. Semivariogram models

The semivariogram is a plot of the expected semivariance (γ) between the radiance levels (DN_i) recorded at different locations (x_i) and separated by the lag (h) distance [15]. In this context, pixels are treated as spatially random regionalised variables where detected radiation is a function of spatial location ($DN_i = f(x_i)$) [16]. The semivariance formula is *(1)*

$$\gamma(h)=1/2\ E[\ f(x_i) - f(x_i+h)\ ]^2 \qquad (1)$$

The shape of the semivariogram is usually characterised by its sill and range. In addition, four other semivariogram features were considered: (i) the nugget effect (the semivariance value at distance 0), (ii) the sill slope, (iii) the gradient (the ratio between range and sill) and (iv) the slope (the ratio between sill and range).

Experimental omnidirectional semivariograms were calculated over 100x100 m subimages of airphotos 1990, orthophotos 2000 and IKONOS 2003. Every subimage was located around one of the 72 NFI sample plots.

Eight semivariogram theoretical models were fitted: the spherical model, the spherical model with a nugget effect, the spherical model plus a linear sill, the spherical model plus a linear sill with a nugget effect and four similar exponential models. The theoretical models were fitted to the experimental semivariograms by the least squares method [17], and the goodness of fitting was evaluated by the Akaike information criterion (AIC) [14].

2.3. Modulated images

Cressie [18] also pointed out the importance of accomplishing certain calibration processes on an image before the semivariogram is calculated. In this sense, the airphotos 1990 and the orthophotos 2000 were normalised and are denoted as modulated airphotos 1990 and modulated orthophotos 2000.

2.4. Analysis of the pixel-size effect

To study the influence of the image pixel size on the results of the texture analysis [10, 12, 13], the spatial resolution of the images was degraded from the original (0.5 m) to 1, 2, 3, 4 and 5 m. For the IKONOS 2003 image, the spatial resolution was degraded from the original (1 m) to 2, 3, 4, 8 and 10 m. As a result, we calculated experimental semivariograms for the following 5 series of images: (i) 72 subimages of the airphotos 1990 and orthophotos 2000 (both modulated and not) and (ii) 18 subimages of the IKONOS 2003. Considering all of the spatial resolutions applied, this resulted in a total of 1836 experimental semivariograms.

2.5. Relationships between models

Finally, we investigated the relationships between the different models when fitted to a particular experimental semivariogram. For this analysis, we calculated the Pearson-product correlation coefficient between corresponding exponential and spherical semivariogram parameters at different spatial resolutions.

3. Results

3.1. Which theoretical model best fits the experimental semivariogram

The exponential model with a linear sill and a nugget effect was the one that produced the lowest error; it was followed by the exponential plus linear model. The spherical plus linear model with a nugget effect and the spherical plus linear models also fitted to the experimental semivariogram.

3.2. Model goodness-of-fit for different pixel sizes

For images of the same forest plot but with different pixel sizes, the exponential and the spherical semivariogram models were built and AIC were compared by applying a paired mean Student's t-test for seeking significant differences.

As a result, AICs are significantly lower for the exponential models at higher spatial resolutions (0.5 and 1 m). Conversely, at coarse resolutions, spherical models are preferable. Concerning the modulation of images, AIC differences are greater in modulated images than in non-modulated images. In the case of IKONOS 2003, the spherical model is significantly better than the exponential model.

3.3. Effects of spatial resolution on the semivariogram parameters

For four semivariogram parameters (range, sill, slope, and gradient) Pearson-product correlation coefficients were calculated at different sizes of pixel degradation. As a result, correlations between ranges across two- or three-step degradations were high. Otherwise, modulated and non-modulated images presented similar performance when degraded. The increment of pixel sizes produced a highly significant increase in the range size (in both exponential and spherical models).

When analysing the correlation between sills for different pixel sizes, the best correlation coefficients were found for one-step degradation and for the finest spatial resolutions. The sills obtained from the spherical models generally showed improved results over the exponential model. In addition, pixel-size degradation produces a decrement in the sill that was greater in the exponential than in the spherical model.

3.4. Relationships between exponential and spherical semivariogram parameters

After obtaining the Pearson-product correlation coefficients between the main exponential and spherical semivariogram parameters at different spatial resolutions resulted that the best correlations where found for ranges and slopes. Concerning pixel size, original resolutions tended to produce the best results no matter which semivariogram parameter were considered, while coarser resolutions tended to behave erratically and produce non-significant results. Considering the entire set of spatial resolutions, range is the semivariogram parameter that displayed the most stable behaviour with degradation and was also the parameter that accounted for the greatest number of significant correlation coefficients. The results for modulated photographs were generally better than results for the non-modulated photographs.

4. Discussion

4.1. Theoretical models

The results indicate that exponential models fit better than do spherical models, especially for small pixel sizes. However, when an experimental semivariogram has a flat sill, exponential models are less effective. This is likely due to the proprieties of exponential functions, which make it difficult to rapidly approach a bounded sill. On the contrary, spherical models adapt better to constant sills, although they usually overfit the variances in the first lags.

The obtained results focus attention on exponential models as better than spherical ones for small pixel sizes. When the pixel size is large, spherical models are better than exponential models because the sill is lower. As a consequence, when we need compare forest features with related ranges, exponential models are preferable. Otherwise, forest features that are related to the sill [19] (such as stand height) should be analysed with spherical models.

4.2. The effects of spatial resolution on the semivariogram parameters

Jupp et al. [20] emphasises that the spatial structure of a remotely sensed image is a function of the relationship between the size of the objects within the scene and the resolution of the image pixels. As the spatial resolution of an image is degraded, its spatial structure is therefore altered [21]. In particular, the shape of the semivariogram becomes simpler as the height of the sill decreases and the range increases [22, 23].

Our results showed significant Pearson-product correlation coefficients for almost every model and degradation, proving that the range increases with the image degradation. Furthermore, it seems that spherical ranges are the most sensitive to degradation because their Pearson's correlation coefficients are frequently worse than the coefficients for exponential ranges.

4.3. Relationships between exponential and spherical semivariogram parameters

Range and slope both present a good correlation between exponential and spherical models; however, the correlation coefficient of the sill between the models is weak and unstable. The obtained results show that the capacities of the range and the semivariogram slope are invariant to the mathematical models chosen. Therefore, the performance of the sill should be analysed indirectly, possibly as a product of the range and semivariogram slope.

5. Conclusion

In our study, the best outputs were obtained by applying exponential models to modulated 2000 photograms of high pixel resolution. Goodness-of-fit improved when a nugget effect and sill slope were added to the semivariogram models, although not in all cases. Spherical models performed better at low resolutions, whereas exponential models were better at high resolutions; however, this result was not so clear as the result for as spherical models at low resolutions.

The study established some relationships among semivariograms models that will be useful for working with photograms captured on different dates and with different sensors. This set of linear relationships can be applied to coordinate different forest images to forecast forest stand changes over time.

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