ESTIMATION OF STAND DENSITY USING AERIAL IMAGES: A FORESTRY APPLICATION OF THE BOOLEAN SPATIAL MODEL

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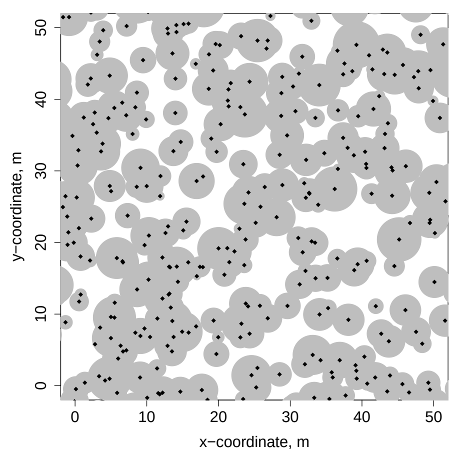
The *Boolean model*, also called *Poisson germ-grain model* is specified as follows. Assume that locations X_i, called *germs*, are generated by the stationary spatial Poisson process with intensity λ. Furthermore, assume that a mark is associated with each location, the marks being i.i.d. random compact sets Z_i, called *primary grains*. The processes generating the grains and germs are independent. The resulting union of the primary grains is a random closet set, which is called the *Boolean model* (Stoyan et al, 1995). A realization of the model with circular primary grains in $\mathbb{R}^2$ is shown in the graph below. The *porosity* of a germ-grain model specifies the proportion of the area not covered by the model or, in other words, the probability that an arbitrarily placed point misses the union of primary grains. In the case of Boolean model, the porosity is $q = e^{-\lambda E(||Z||)}$, where $||Z||$ is the area of primary grain Z.



Aerial data are increasingly used in forest inventories. Especially, aircraft-mounted laser scanners (ALS) are used to collect three-dimensional data on forest canopies (e.g. Maltamo et al. 2014). To estimate forest characteristics of interest (e.g. stand density or standing volume per ha) one of the most evident algorithms to use such data for forest inventory is to detect individual tree crowns from the ALS data. As a result, the the ALS image provides the (projected) crown area for those individual trees that were detected on the image, and an additional measurement of the canopy closure, i.e., the proportion of the image area that is coverted by tree crowns. Unfortunatetly, small trees may grow below dominant trees and remain undetected. Therefore, the detectability of a tree on the ALS image is a function of its size.

In this presentation, we apply the Boolean model in the analysis of aerial forest data. We assume that an aerial image of a forest sample plot is a realization of the Boolean model with germs indicating the centers of circular crown discs (grains). Furthermore, we assume that tree i is detectable on an image if the germ i does not hit the union of crowns that are larger than the crown i. These assumptions enable writing the detectability as a function of tree crown size. The resulting expression together with the empirical size distribution of detected tree crowns further enables estimation of the probability distribution of Z and $E(||Z||)$, the mean of crown areas on the image. Finally, setting the observed canopy closure on the image (cc) equal to $1 - q$ yields an estimator for stand density as (Mehtätalo 2006)

$$\widehat{\lambda} = -\frac{\ln(1 - cc)}{\widehat{E(||Z||)}} .$$

We evaluated the above-specified procedure and estimator of stand density empirically with a dataset of 40 sample plots from Kiihtelysvaara, Eastern Finland (Vauhkonen and Mehtätalo, forthcoming). The results showed good performance on most (33) sample plots. The 7 plots with poorest performance provided significant overestimation of stand density. A further analysis on the field-measured tree locations indicated that these plots showed a significant departure from the homogeneous Poisson pattern towards the regular pattern. Interestingly, all these plots also had the canopy closure above 85%, which might serve as a useful practical indicator for potentially problematic sample plots. Further analysis is needed for recognizing the spatial pattern of tree locations using aerial images and developing the approach for more advanced point patterns.

Keywords: Boolean model, spatial point patterns, Forest inventory, Airborne laser scanning.

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