論文の内容の要旨

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論文題目　Assessing Density and Indexing Spatial Patterns of Trees – Plots, Distances and Angles in Forest Regeneration Surveys –
（　樹木の本数密度評価と空間配置の指標－森林更新木調査におけるプロット、距離、角度－　）

Importance to assess information regarding density and exhibited spatial patterns of juvenile trees in forests has been emphasized in the thesis. Maintaining composition of forests in order to increase a yield of a timber and increase the income by maintaining a quality of the growing stock is being even more important to support development of impoverished countries. Successful achievement of the sustainable use is also greatly dependent on the quality of collected information regarding renewable resources being the target of the management. Successful forest regeneration is the one of most important preliminary conditions in achieving sustainability of forest management. Appraisal of a success of forest regeneration as well as designs of forest regeneration surveys and interpretation of a collected data, whether imposing natural regeneration, artificial or supplemental planting practices, is the one of most responsible tasks of forest management. An indispensable effort, and a good start in achieving tasks given by principles of the sustainable forest management, is to ensure a success of forest regeneration. Forestry policies in most of the countries, devoted to principles of the sustainable management, are also prescribing the obligatory conduction of forest regeneration surveys. Necessity to evaluating a success of forest regeneration is emphasized for all managed forests. That is of particular importance if a target of management is to maximize benefits and services being provided by forests along to a sustainable utilization of timber.

Field surveys are still the main source of information regarding a success of forest regeneration and in the case where remote sensing is still unable to detect juvenile trees. Assessing only the relative density of juvenile trees, what use to be a practice in most of the forest regeneration surveys, can not be sufficient. Indexing spatial patterns of juvenile trees is also being an elementary measure of a success of forest regeneration. Juvenile trees in forests are likely to exhibiting various spatial patterns. Naturally regenerated juvenile trees are likely to exhibit clustering while artificial or supplemental planting practices can result to regular spatial patterns. Foresters seek for a simple index of the degree of clustering or regularity, being practical to apply in forest regeneration surveys. Total count or mapping positions of juvenile trees is not practically justified in order to indexing their spatial patterns. The use of fixed-area plot sampling in indexing spatial patterns of trees is questionable since the indices are influenced by a size of plots.

Statistical methodology to assessing density and indexing spatial patterns of individual trees in forests is elaborated in the thesis and practical aspects are considered to a great state. The main stress is placed to statistical methods being recognized in the past as rapid approaches in field surveys. Simple measurements of angles between the lines of sight from sampling points to their nearest two neighboring trees, being known as the Mean of Angles method, was proposed by Assunção (1994) for the use in testing whether trees in forests exhibiting a random spatial pattern. Also being simple to obtain in field, a measurement of distances from sampling points to a given number of the nearest individual trees (*c*-tree sampling) was proposed in the past to be used in indexing spatial patterns.

To assess relative density of juvenile trees, the conventional practice in forest regeneration surveys is the use of fixed-area plot sampling. These are also used in stratifying forest area by the abundance of juvenile trees; for example, forest stand area being abundant in juvenile trees to that being not regenerated. Besides conventionally used fixed-area plot sampling, *c*-tree sampling can be used in assessing relative density of trees and it has a potential use in stratifying forest area. On the other hand, *c*-tree sampling is known as a biased approach in assessing information regarding individual tree parameters; not equal probability of selecting individual trees in clusters. It is also known that *c*-tree sampling can yield biased density estimates, with the bias dependent on exhibited spatial pattern and the estimator used.

The main given hypothesis of the thesis is that indexing spatial pattern distributions of juvenile trees in forests can serve in choosing an appropriate density estimator for the *c*-tree sampling approach and thus increase reliability of density estimates. The main objective of the thesis is to propose methodology, being both practical and sufficiently reliable, for the use in forest regeneration surveys and in order to assessing relative density and indexing spatial patterns of juvenile trees. Specific objectives of the thesis include analysis of potential of the arithmetic mean of angles to serve as practical measure of the degree of regularity or clustering. Furthermore, the performance of the best-performed spatial pattern index being proposed by Liu (2001) for the *c*-tree sampling approach was compared to the index based on the measured angles. Besides objectives relating to indexing spatial patterns of trees, emphasize is given to studying statistical performance of density estimators for *c*-tree sampling. It was considered use of density estimators being robust and reliable enough to enable they use in forest regeneration surveys. Fixed-area plot sampling was also compared to *c*-tree sampling by the practical meant of variance, the precision in estimating the density and stratifying the population of naturally regenerated saplings.

Statistical performance of *c*-tree sampling and the Mean of Angles method was investigated, and hypothesis tested, by conducting simulation studies in point populations having known spatial pattern and density. In general each individual tree in forest can be represented by a point in a plane area. This allows mapping individual tree positions or to mimic real forests by simulating point spatial patterns. In addition to simulating point populations being designated as theoretically most significant, a new methodology being denoted as the "Gap-process" is being introduced in the thesis. This method to simulate clustered point populations may be recognized as a modified Gibbs field process which uses the so-called spatial birth-and-death processes. In ecological terms, the Gap-process can be seen as a disturbance; artificial (for example harvest) or natural (for example damage caused by strong winds, forest fires etc.). The practical applicability of the methodology was tested by mapping naturally regenerated *Chamaecyparis* saplings sized from 1.5 to 5 m in height and conducting simulation studies at the mapped population. In all simulated point populations, random sampling procedure was conducted. In the mapped population of saplings, along to applying random sampling, systematical sampling was also applied since it can have a practical advantage. That is particularly important in stratifying forest area and in the cases when remote sensing can not detect juvenile trees. The practical meant of variance and the precision in estimating the density of the population of naturally regenerated saplings by fixed-area plot sampling and *c*-tree sampling was conducted applying the bootstrap statistical technique.

It is concluded that it is not necessary to map positions of juvenile trees in forests and in order to acquire reliable indices of their spatial patterns. A mean of angles can serve as a simple spatial pattern index and its use is recommended to indexing the degree of regularity or clustering of juvenile trees. That is also a practical approach to apply in forest regeneration surveys since the method is simple and robust enough. Moreover, the measurements of angles do not need to be performed with a high precision. On the other hand, applications requiring much reliable indices should consider precise measurement of the angles and relatively large sample along to analyzing its frequency distribution. Higher precision in studying spatial patterns can be also achieved by introducing measurement of distances along to measuring the angles. Moreover, distances between sampling points and trees are dependent upon the relative density of trees and it can be worthwhile to obtaining such measurements. Indices based on measured distances are also applicable to distinguishing between clustered, random and regular populations. In particular, their use can be more practical in testing whether trees in forests are distributed at random, where measuring angles would require a slightly larger sample. However, the use of the distances between sampling points and trees in indexing spatial patterns of trees may not give a reliable insight into the degree of regularity or clustering. Furthermore, an extensive statistical expertise is necessary in order to look beyond these indices, what is clearly not appropriate in supporting practitioners in the field.

The use *c*-tree sampling in assessing a relative density of juvenile trees is feasible but that requires indexing spatial patterns of trees. It is also necessary to choose an appropriate density estimator. Choosing different density estimators in regard to exhibited spatial pattern distributions enable setting the *c* to some small value; such as applying a sampling procedure based on measuring distances from sampling points to their second or third nearest tree. Furthermore, these estimators of density need to be robust enough to find a practical use in forest regeneration surveys. It is proposed to use the GM estimator (Trifković 2005) in assessing density of trees exhibiting uniformly regular spatial patterns; uniformly regular spatial pattern refer to forest stands where the majority of angles between the lines of sight from random sampling points to their nearest two neighboring trees is larger than 90 degrees and the relative density do not differ significantly. The Pollard estimator (Pollard 1971) is not as robust as estimators accounting for variable circular plot areas but it is appropriate in the case when the trees are distributed uniformly at random.

The (c-1) estimator (Eberhardt 1967) is robust enough to be used in a wide spectrum of clustered spatial distributions. However, it is important to emphasize the finding that the (c-1) estimator is an applicable estimator of density for the cases when frequency distributions of variable circular plot areas (squared plot radiuses) fit the generalized Pareto frequency distribution or the normal frequency distribution. In forest stands having randomly distributed trees, applying *c*=5 sampling or any higher *c* value is the most likely to yield frequency distributions of variable circular plot areas fitting the normal frequency distribution; that explains its applicability in the case when the trees are distributed at random. Juvenile trees being naturally regenerated are likely to exhibiting clustered spatial patterns and with clusters being irregular in size and shape. In such populations, applying *c*=2 sampling was the most likely to yield variable circular plot areas being not significantly different from the generalized Pareto frequency distribution. Furthermore, measured population of naturally regenerated saplings exhibited moderately clustered spatial pattern; spatial pattern being caused by a competition driven change toward randomness and forward to regularity. In such a case, applying the *c*=3 sampling procedure was the most appropriate. In general, a bias does not increase with the increase in the number of measurements (sample size) and thus increasing the sample size would increase a confidence. Increase in the *c* value may also increase a reliability of density estimates in populations exhibiting randomness or regularity but a caution is necessary in populations exhibiting clustering. It should be emphasized that increasing the *c* value in some clustered populations can yield variable circular plots being not significantly different from the exponential frequency distribution. That can still produce relatively high bias, and overestimate the true density, unless deriving a more appropriate density estimator.

The use of *c*-tree sampling is particularly remarkable in forest regeneration surveys to stratifying forest area where remote sensing can not contribute to a great extent. Especially practical designs are those based on the measurement of distances to second nearest juvenile trees from systematically distributed sampling points. These also can give a greater confidence in stratifying forest area than compared to a conventional practice of applying small sized fixed-area plots.

Methodology based on measuring the angles and the distances to the second nearest trees is recommended for the use in forest regeneration surveys. However, that should not exclude the use of fixed-area plot sampling. In particular that is emphasized when the precision of density estimates is much required. Combined use of plots, distances and angles can even more contribute in assessing a potential of juvenile trees to mature into an ecologically sound and an economically worthwhile forest.