# 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－ ）

# PHD THESIS

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# Contents

# 1. Introduction

Forests use to serve the mankind with their goods and services and probably that have started long time before first civilizations appeared on the Earth. The area of forests covering the Earth in the time of the appearance of first civilizations was greater and less fragmented than in present days. The growth of civilizations has brought a competition over the land resources and large forest areas were devastated or shifted to other land uses. Many examples of the shifted land use can be seen among expansion of urban areas or agricultural lands over the land being primarily covered by forests. Examples of devastated forest areas were reported as far as 4$^{th}$ century B.C. by Plato Critias in his famous statement "There are mountains in Attica which can now keep nothing than bees, but which were clothed, not so very long ago, with fine trees producing timber suitable for roofing the largest buildings, and roofs hewn from this timber are still in existence". Devastation of forests was increasingly present during the last few centuries which are being characterized by an overall expansion of mankind and by a rapid development in almost any field of human performance. The development has brought to us a large number of technical advances and increased productivity in overall but it also left us numerous devastated forests in inheritance. Those have led foresters to introduce principles of sustainable forest management to the practice, in order to ensure the use of renewable forest resources and services in perpetuity.

Along to preserving forests of a great environmental and educational value, the modern human society is also concern to continue utilizing benefits provided by remaining as well as by newly established forests. 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 (Matić 1973) is being even more important to support a development

and in particular that of impoverished countries. Countless number of benefits provided by forests managed in a sustainable manner can be summarized to (Smith and Scherr 2002):

- Sustainable management of genetic, biotic and ecosystem resources
- Control of soil erosion and sedimentation in water accumulations and sustainability of hydroelectric facilities
- Prevention of floods and landslides
- Permanent supply of potable water
- Reduction in the expansion of extensive and steep lands farming
- Renewable energy source
- Contribution to mitigate climate change by sequestering carbon as a natural growth process of trees
- Increased political stability
- Improved local, regional and national commercial balances
- Opening of new markets and improved positioning of agricultural and forest products in internal and external markets while certifying the products
- Reduction in migration and displacement of rural people
- Reduction of poverty among rural producers by improving their average monthly income and capital accumulation
- Increase in social investment at municipal and regional levels
- Variety of employment, scientific and educational opportunities

Among these and many other goods and services which forests provide the mankind, the main tangible product yielded from the forests is still the timber. The timber is a renewable resource but it requires a good stewardship of the forest land in order to be everlastingly yielded. Principles of the sustainable forest management are being

practiced in some forests for centuries and that was also closely related to attaining the sustained yield of the timber, the sustained income or combination of both principles (Matić 1965). The principles are also evolving through the centuries as the evolving knowledge about the sustainable use.

Improving site conditions, promoting devastated forests in order to maximize the benefits or imposing afforestation practices are very important tasks for forestry. Forestry is an applied discipline and an important economic sector dealing with forest resources. The goal of forestry should to be setting a sustainable use of renewable resources and at the same time strengthening the other benefits provided by forests. That is also the main principle of the sustainable forest management and foresters should achieve those tasks. The term forester here also encompasses ecologists, researchers, operational stuff, decision makers, profit oriented or any other person who is dealing with forest resources in order to satisfy its needs and respecting needs of future generations. Forester should have all those qualities in order to being able managing forests in a sustainable manner. To accomplish tasks of a sustainable use, one of the most important preliminary conditions is to accurately assess information on renewable forest resources. Successful achievement of the sustainable use is greatly dependent on the quality of collected information regarding renewable resources being the target of the management. It would be ideal to hold a total inventory of the stock and to collecting information about each individual tree and its growth rate. Unfortunately, that is not practically feasible and foresters are forced to applying cost effective techniques in order to acquire necessary information.

The process of collecting information regarding forest resources is widely regarded to as forest inventory or forest resources assessment. It is widely accepted opinion that the combined use of remote sensing techniques and field surveys can give the most reliable information and thus greatly improve forest management practices. Field

surveys are an important part of forest inventories. They should be designed in a cost-effective manner and the methodology should be as simple as possible to be widely accepted in the practice. It is important for the provided information to be acquired by using rapid methodology and the use of statistics is indispensable to provide confident information. Conducting field surveys is particularly important in cases when remote sensing is unable to provide reliable information regarding under-story trees or juvenile trees being difficult to detect. Such a case is in the most of forest regeneration surveys where detection of juvenile trees is highly interfered with canopy of upper-story trees or by competing vegetation. Assessed information during field surveys should be unbiased in order to draw reliable conclusions. On the other hand, we can accept biased information in the case if the amount of a bias is insignificant and in the case when the amount of bias can be predicted.

Importance to conducting field surveys is particularly emphasized in assessing state of forests. The main stress of the thesis is placed to statistical methods being recognized in the past as rapid approaches in field surveys. Along to conventional methods, the study was conducted on alternative statistical methods being widely known as distance sampling which are extensively used in assessments of density and spatial patterns of ecological populations. Prior to this research, it was believed that the use of distance sampling can benefit to foresters in assessing relative densities of trees in forests and in indexing their spatial patterns since these methods are highly valued by ecologists. Furthermore, being also alternative field surveying approaches, methods being designed to assess spatial relations of individual trees by a measurement of angles were also believed to hold a potential to benefit foresters in a field. In particular, importance of assessing density and indexing spatial patterns of juvenile trees in forests is emphasized as these are the two main indicators in evaluating a success of forest regeneration.

## 1.1. Forest regeneration

Successful forest regeneration is the one of most important preliminary conditions in achieving sustainability of forest management. That is of particular importance in the case when utilization of a timber is the one of objectives of forest management. Removal of mature trees, or so called mother trees, and an inadequate attention of foresters may result to insufficiently regenerated forest land and induce a depletion of soil. An absence of a regeneration of forest trees may also lead to an unintentional shift from the forest land to for instance a shrub or grass formation. A good start in achieving a sustainable use of forest resources is to ensure that forest regeneration is successful.

The majority of forest management systems throughout the World, which claim the sustainability of their operations, widely acknowledge that a harvest should have a primary regeneration characteristic. That applies to all forest types and regardless to their origin. Moreover, forest types are usually classified whether imposing natural regeneration, artificial or supplemental planting practices and with regard to their origin to as forest plantations, coppice forests, naturally regenerated forests or their combinations such as those formed by supplemental planting practices. Forest plantations are usually established by artificially planting seeds, young trees raised in nurseries or vegetatively propagated trees. Coppice forest types are also established artificially after a harvest by vegetatively emerged offspring's from tree stumps or roots. Forest types are termed as a naturally regenerated in the case if their origin comes from naturally dispersed seeds. Forests types are being referred as naturally regenerated also in the case when a propagation of juvenile trees from naturally dispersed seeds is artificially induced.

There are numerous of exemplary forest management systems throughout the World where forest regeneration, appraisal of its success as well as designs of forest

regeneration surveys and the interpretation of a collected data is the one of most important managerial tasks. Forest management practices in mountainous regions of Bosnia Herzegovina can serve as an example. The gap-selective cutting system practiced in mountainous mixed forests of Bosnia Herzegovina is mostly introduced because the light regime prevailing on the gaps is much favorable for a successive forest tree species than in forests managed by conventional selective cutting systems. The trees regenerated on such gaps are likely to forming trunks being more valued in the market and also the gap-selective cutting system is much favorable in achieving the low-impact utilization (Matić 1973). Forest management systems based on the harvest of forest trees which mimic natural disturbances, like this applied in mountainous mixed forests of Bosnia Herzegovina, is preferred in the case when an abundant natural regeneration can be expected. It is likely that a favorable light regime would result to an abundant natural regeneration but that may not be the rule. Abundant natural regeneration of forest trees may be absent or spatial patterns of naturally regenerated juvenile trees may be too clustered. Therefore, in all of cases, and after each such harvesting operation, the success of forest regeneration should be estimated and forest area being not sufficiently regenerated should be recorded in order to secure funds and capacities being necessary to conduct a supplemental planting.

It may not be always feasible to achieve a natural regeneration of forest trees, in each of respective World forest types, abundant enough to satisfy the needs and to ensure that juvenile trees will cover land with a tree canopy in a great extent when they reach their maturity. Such an example is the karst region of Bosnia Herzegovina where a natural regeneration of forest tree species in highly devastated land areas is not feasible (Bojadžić 2001). The karst region was affected since first civilizations in the area started practices of harvesting, causing forest fires and applying extensive grazing practices. Those, and an unfortunate history of frequent wars, highly devastated primal forests.

The karst region can serve as an example of a horrible devastation during relatively short history of the human influence compared to the long-required process of the soil formation. In such a case, conducting afforestation practices by planting tree species which use to prevail in the past can potentially increase benefits yielded from presently prevailing shrub and grass formations (Trifković and Yamamoto 2005). Such afforested area is supposed, and it is highly desirable, to be managed by imposing a natural regeneration of afforested trees when they reach they maturity. However, it may not always be the best practice to impose a natural regeneration. Plantation forestry can be preferred in forest lands where it has a potential to benefit to a higher state that that imposing a natural regeneration. The plantation forestry being practiced for centuries in Japan, and particularly the case of planting *Cryptomeria japonica* trees at Japan's mainland Honshu, can be considered as an example. Being native species in southern islands of Japan, like that of island Yakushima (Suzuki and Tsukahara 1987), the natural regeneration of *Cryptomeria japonica* is very rare occurrence at the Honshu island (Idota and Ueki 2005). *Cryptomeria japonica* was one of the most preferable planted tree species in Japan and it is still one of the main planted tree species (Suzuki et al. 2003). The good quality of the timber, its high increment rate, a diverse use and worshipping practices are being all the reasons of planting practices during the last few centuries. Such practices are highly incorporated into the Japanese tradition. The value of *Cryptomeria japonica* trees at the mainland of Japan is still esteemed by foresters and by a broader Japanese society being decisive to continue the planting practices.

Unlike in protected forest areas having assigned a strong protection regime such as the Perućica reserve (1,434 ha large in size makes the Perućica reserve largest remind virgin forest in Europe) being the core of the Sutjeska National Park in Bosnia Herzegovina (Šumarska Enciklopedija III 1987), in a largest share of World forests it is necessary to assessing a success of forest regeneration. Forestry policies, devoted to the

principles of the sustainable management, are prescribing obligatory conduction of forest regeneration surveys in most of managed forests throughout the World. Those emphasize a need to regularly conducting forest regeneration surveys. The type and the amount of information to collect should fit to specific objectives of forest management. Appropriately to a great number of forest types, a great number of management objectives exist throughout the World. However, in almost every case and when a sustainable utilization of timber is one of forest management objectives, forest regeneration surveys should be designed to assess information on spatial distribution of juvenile trees. Various parameters can be used in order to describe spatial distribution of juvenile trees. The thesis is focused on assessing a relative tree density and indexing spatial patterns of trees, being the two main parameters which can assist to foresters in drawing their final decisions regarding a success of forest regeneration.

### 1.1.1. Forest Regeneration Surveys

Collecting information regarding forest resources is indispensable to manage them in a sustainable manner, to set forestry policy measures, to support silvicultural or almost any other forestry operation. The process of collecting such information is usually referred to as forest inventory or forest resources assessment. Forest inventories are usually designed to fulfill multiple objectives and are classified by a scale and a purpose. The purpose of the inventory can be classified in regard to the use of information such as that to support forest management, forest policy or silvicultural practices. Looking at forests as complexes of mutually interconnected forest stands, forest inventory usually encompass the whole forest on the regional, national or even global scale. Provided information is crucial to support forest management or forest policy. That is particularly emphasized in forestry practices in Bosnia Herzegovina. In this impoverished country terribly affected by a recent civil war, it is of a great importance to provide everlasting services to the local communities and to support a sustained development by a constant supply of tangible goods to the industrial capacities. Such an example is the pulp and paper industry, sawmilling industry or any other economic sector being dependent on forest resources. It is of particular interest for the economy of the country to conduct regional and in particular the national forest inventory. Those can also serve to predict overall economic needs as well as the profitability of forest operations. Collecting information regarding forest regeneration usually represents a part of a much greater forest inventory design.

In order to support local sivlicultural practices and to ensure a good steward of forests, inventory can be designed to look after each respective forest stand. Such a design can be regarded to as a forest stand scale inventory. Those include assessing very site specific information and its target is to maximize the benefits that entire forest can

potentially offer. Forest stand scale inventories need to be focused on providing information regarding mutual relations between trees in specific forest stand areas as well as on providing information regarding health condition or the quality of the stock. Intensive forest management practices, and in particular owners of small forest areas, are having a crucial interest to conduct inventories at a forest stand scale in order to assess information regarding the potential of the resource they possess. Conducting inventories at the forest stand scale has a potential to improve an overall performance of a forest enterprise and managerial practices dealing with that particular forest.

The scale and the purpose highly influencing the design of inventories and the amount of information collected. Those also highly influence a required precision of the collected data. A great number of measurable parameters can be used in describing forests, assessing a state of tangible resources or monitoring changes over periods of a time. Parameters being difficult to measure or quantify are usually descriptively characterized by surveyors. For example, forest regeneration surveys in Bosnia Herzegovina were designed to assess a relative density of juvenile trees, their spatial pattern and health condition (Matić 1977). A relative density of juvenile trees was quantitative information assessed by the use of concentric circular fixed-area plots being designed proportionally to the size of trees. On the other hand, information regarding spatial pattern and health condition of juvenile trees was assessed as a qualitative appraisement of a surveyor. The collected information was usually presented in a form of tables or graphs as an average over the entire forest, forest type or forest stand area. A similar case is reported in Canada, in forests being managed by even-aged systems (Haddon 1997), where a large amount of collected data did little to infer the success or the failure of forest regeneration (Brand et al. 1991). Brand et al. (1991) have proposed to unite the data from forest regeneration surveys and forest inventories into the information system being able to store and present various collected information

regarding forest resources. Such an attempt is supposed to lead to a change of the character of forest regeneration surveys from usually being looked on as a necessary legislative requirement to the useful set of information and a supporting tool for management practices.

It is necessary to convince the people and their growing concern regarding forest management practices that we foresters are really committed to ensure and to perform the sustainable forest management. Conducting forest regeneration surveys is a step forward in ensuring sustainability of the use and it should follow after each harvesting operation. Measurement techniques need to be designed in a manner of harmony with forest resources; damage caused to the forest and its specific resources during inventories should be avoided. It is very important for surveys to be designed in a cost-effective manner. However, that should not influence the amount and the quality of collected information (Matić 1977). Collected information should be able to increase efficiency of the management whether dealing with forest stands or entire forests. Evolving knowledge with our understandings of the natural phenomena, and the amount of information being able to satisfy needs of the management, have brought and it is ever inventing new methodologies and concepts being applicable in forest inventories and forest regeneration surveys. Among the most intensively developing techniques and methodologies are in the field of remote sensing. Unfortunately, remote sensing is still not capable to give reliable information regarding the abundance and a spatial distribution of juvenile trees. In particular, juvenile trees in multistoried and mixed forests are being difficult to detect by only using remotely sensed data.

In the case when remote sensing is still unable to detect juvenile trees, field surveys are still the main source of information regarding a success of forest regeneration. In particular, collecting information about forest regeneration at the forest stand scale is essential to ensure a sustainable use of forest resources. Importance of forest

regeneration emphasizes the need to assess information regarding not only the density but also exhibited spatial pattern distributions as well as the potential of naturally or artificially regenerated juvenile trees to mature into a stable and healthy forest stand being able to fulfill our expectations (Brand et al. 1991). Those emphasize importance of a statistical approach and sampling techniques. Statistics as a scientific discipline has found a great use in almost any field of modern human society. An appropriate survey design and a correct interpretation of the data are likely to bring great advances to the forest management. That is whether targeting tangible products or investigating impacts of the management to forests in the broadest sense.

It is widely accepted statistical opinion that the only random sample would give appropriate and reliable information. However, taking samples at random may not be always the most practical approach. For example, if the individual trees are the target of interest, or their parameters such as the increment rate, it should be noted that taking a random sample of individual trees would require a total enumeration of all trees prior to their random selection. That is obviously impossible in the forestry practice. Therefore, rather than targeting individual trees, forestry practice deals with specific forest areas being either classified to forest stands or forest types. That means the forest management targets the group of trees and its crucial interest is placed to the forest area. In such a case, we are able to take a random sample of the forest area which integrates the specific measurable resource; for instance, randomly placing plots over the forest area and measuring trees, and their associated parameters, inhibiting those spots.

Placement of plots or points at random over the forest area is an easy procedure. However, even though the global positioning system or its counterparts is widely used in present practices, it may be difficult to find these spots in the field. Therefore, systematical or systematical-cluster sampling can be a more practical choice and those are widely accepted procedures in forest inventories and forest regeneration surveys. In

particular, applying systematical-cluster sampling by placing additional number of sampling points around each systematically distributed sampling point has a practical ability to increase the sample size and thus increase the statistical confidence. However, it should be emphasized that a caution is necessary when applying systematical sampling in populations of individual trees exhibiting regular spatial patterns.

Unlike random sampling, systematical sampling or systematical-cluster sampling is having a practical ability to yield the "site-specific information". An example of the site-specific information is that provided by remote sensing and the use of its most common data sources such as aerial photographs or satellite images. The digital raster data is composed by pixels, usually having the same size, where each pixel having assigned and spatially defined information. It is feasible, for instance, to divide forest into a mesh of equally sided lattice and to access information separately for each its part. Such spatial information can be presented in a form of maps and similarly to the raster digital data where the information is assigned to each of pixels. Those can give us insight into the allocation and the spatial variation of forest resources. For example, we can spatially divide sites having the abundant, moderately or no regeneration occurred. Such information can be stored and analyzed using the Geographic Information System (GIS) since it is a one of the most advanced tools to deal with a spatially assigned data.

A practical merit of systematical sampling, or systematical-cluster sampling, over the random sampling is also in its ability to conducting easier stratification of forest areas. Stratification of forest areas is a widely accepted practice in forest inventories. Along to having an ability to give us insight into a spatial variety of resources, from the statistical point of view, relatively uniform populations are characterized by a smaller variance than compared to largely diverse populations. Small variance induce that a large sample is not necessary to be obtained. Stratifying forest areas is now relatively fast and accurate to perform by the use of remotely sensed data, such as the use of air

photographs or satellite images. On the other hand, stratifying forest stand areas in accordance to for example an abundance of juvenile trees still need to consider the use of information collected on a field surveys.

Everything above suggests that field surveying designs plays an important role in assessing a success of forest regeneration. In particular, conducting a study on a methodology being proposed in past to assessing a relative density of trees and indexing their spatial patterns is believed to benefit foresters in the field.

## 1.2. Density estimators

In forestry, the term tree density represents a relative number of individual trees on a unit of forest area such as a forest stand. The hectare (1 ha = 10,000 $m^2$) is not included in the International System of Units but it is commonly used a unit of area in forestry practice with exception to only forestry practices at the United States which still use the acre (approximately 1 acre = 0.4 ha).

The relative density of juvenile trees in forests is a one of crucial indices of the forest regeneration success and it was usually quantified by the use of statistical methods such as the use of fixed-area plot sampling. The use of fixed-area plot sampling is also a conventional methodology in forest inventories as well as in forest regeneration surveys. Various fixed-area plot sampling designs have found a use in forest inventories or forest regeneration surveys. Such an example is the use of strips which is particularly useful in surveying steep forest terrains. Moreover, any geometrical fractals such as rectangles, squares or circles can be applied in forest regeneration surveys in estimating relative density of juvenile trees. Each plot is having the same size and the size is defined prior to the survey. The density is estimated simply by counting the trees felled inside plot areas and the variance is assessed by examining data sets being in a statistically discrete measurement scale. That is because plot sizes are fixed (constant) values and counted trees per plots represents a statistical variable. If applying the strips, the variance should be assessed with caution since lengths of strips can differ. The use of strips in forest plantations exhibiting regular spatial pattern can also yield biased density estimates. In such and in the most of other cases, the use of circular plots can be more appropriate. Circles are also characterized by the shorter perimeter compared to other geometrical fractals and that much reducing the decisions concerning the count of trees near the edge of the plots.

Sampling using fixed-area plots is unbiased in estimating relative density of trees. Randomly distributed fixed-area plots include an equal probability of selection for each tree of measured populations. The sample should be large enough to represent a population and a variance can be assessed by examining frequency distributions of a discretely distributed data. Usually, if relatively large plots are applied in populations of trees being uniformly distributed, the counts are likely to fit the binomial frequency distribution. Reducing the size of plots or the use of fixed-area plots in populations of randomly distributed individuals can produce a data counts fitting the Poisson frequency distribution. The counts from fixed-plot area sampling in clustered populations may also fit the negative binomial frequency distribution.

It is also possible to design fixed-area plot sampling to have a probability of selection proportional to the size of trees. Importance of such sampling designs is particularly emphasized in multistoried forests where the trees are usually classified by the DBH and the juvenile trees by their height. That is also the case in forest inventories and forest regeneration surveys of mixed-multistoried forests of Bosnia Herzegovina being managed by the gap-selective cutting system. These forests are characterized by a larger number of juvenile than mature trees (Matić 1963, Alikafić 1971). The number of seedlings per unit area is also likely to be greater than the number of saplings; in forestry practice, sapling is usually referred to the young tree larger than a seedling but still being juvenile in terms of its use. Applying the fixed-area plot design in such forests yields a higher probability to enumerate larger number of small-sized trees than those being larger in size. The effort to enumerate a great number of juvenile trees, achieving high precision of estimates by a large sample, is unnecessary in forestry practice. Therefore, the use of concentric circular fixed-area plots is particularly recognized as the most practical approach to inventory forest resources in mixed-multistoried forests in Bosnia Herzegovina. These having the same center and

the estimates, as well as variances, are assessed respectively (Matić 1977). The use of concentric circular fixed-area plots can reduce unnecessary efforts by placing a higher importance to enumerating larger-sized trees.

Fixed-plot sampling designs are often faced with difficulties regarding the size of plots or with the number of concentric circles to use. Such surveys should also consider using different designs in accordance to different forest types and management objectives respectively. Those encouraged many research in the past and yielded to various field surveying designs. Among most promising field surveying designs, being proposed in past to assess relative density of trees or relative density of various ecological populations in nature (Buckland et al. 2001), can be classified to the group of methods being known as distance sampling. The most simple among these, and being widely known to foresters, are methods based on measurements of distances between trees or between sampling points and trees. The pioneers in the development of these methods (for example: Moore 1954, Thompson 1956) were usually accounted for a probability that the trees in natural forests are distributed at random and were followed by the assumption that measured distances in random populations would fit the normal frequency distribution. The method being particularly recognized in past as practical is that based on measuring distances between sampling points and their neighboring trees. That is so called the point-to-plant method. Measurement design based from sampling points is an advantage of this sampling method, particularly when compared to methods based on distances between trees, because it allows a dispersion of points over the forest stand area whether randomly, systematically or by the use of some clustered design. Furthermore, methods based on distances between trees are faced with difficulties to randomly selecting individual trees since all individual trees need to be enumerated prior to the random selection (Pielou 1959).

The natural extension of the point-to-plant method to that based on measurement

from sampling points to second, third, etc. neighboring trees has shown an ability to reduce the variance of density estimates (Eberhardt 1967, Pollard 1971) and it has got a special attention of foresters. Measuring the only one distance from sampling points respectively was claimed to have a practical potential to reduce the cost of field surveys in forestry (Jonsson et al. 1992, Lessard et al. 1994, Lynch and Rusydi 1999, Lessard et al. 2002). This method is here referred to as *c*-tree sampling. It is widely known that *c*-tree sampling can yield biased estimates of density and particularly in forest stands where individual trees are not distributed completely at random. That is the reason for being not widely used in the forestry practice (Husch et al. 2002). An extensive effort was given in the thesis to further explain statistical properties of *c*-tree sampling and that was supposed to eventually benefit to foresters.

### 1.2.1. *C*-tree sampling

The statistical method based on measurements of distances from sampling points to the second, third, etc. ordered neighboring tree is here denoted to as *c*-tree sampling. The ordered number of neighboring trees from sampling points is constant and it is necessary to set it prior to the survey. For instance, the $c = 2$ sampling procedure requires measurement of distances from sampling points to their second nearest trees. Such a surveying design can give us insight into the relative density of trees since the short distances observed would imply a high density while that would be opposite with long distances. Such a simple relation between the distances and the tree density has resulted into various density estimators. The development of density estimators for the *c*-tree sampling method had taken the two major paths in the past. The first approach had taken into consideration the variable plot areas and the second the distances.

In the case when density estimators accounts for variable plot areas, *c*-tree sampling can be recognized as an inverse approach to circular fixed-area plot sampling. Here, the number of individual trees is fixed per plot and plot areas varied in a statistically continuous scale. Density estimators accounting for variable plot areas were most studied in the context of the forest research and *c*-tree sampling was referred to as n-tree distance sampling (Lessard et al. 1994, Lynch and Rusydi 1999, Lessard et al. 2002, Lynch and Wittwer 2003) or density-adapted sampling (Jonsson et al. 1992). The number of nearest ordered individual trees per plot remains, constant ( $c$ ), for all sampling plots in measured population. For example, the $c = 4$ sampling procedure defining the variable circular plot area by the measurement of distances from sampling points to their fourth nearest tree (Figure 1.1.).

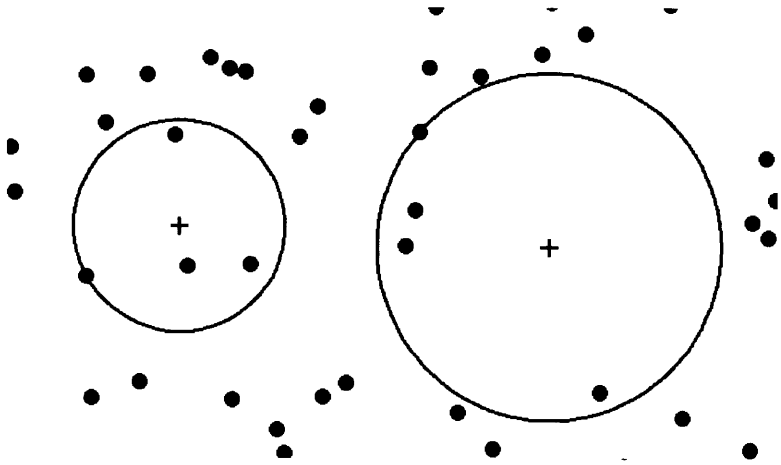


**Figure 1.1.** The *c*-tree sampling method; $c$ = 4, "+" represents centers of circular sampling plots and black dots represents individual trees in forest stands

Eberhardt (1967) was the first to propose the density estimator which accounts for variable plot areas and it assumed that sampling plots in *c*-tree sampling contains $c - 1$ trees respectively:

$$\hat{\theta}_{c-1} = \frac{c-1}{n\pi} \sum_{i=1}^{n} \frac{1}{r_i^2} \tag{1}$$

where $c$ is constant and it is determined prior to the sampling procedure; the $c$ represents an ordered number of nearest trees from sampling points which is used to define the plot radius (following the Figure 1.1., $c$ = 4). $r_i$ are radiuses of variable circular plots or the distances measured to the $c$ tree. $n$ is the number of measured distances or the number of sampling plots (following the Figure 1.1., $n$ = 2).

Increase in the constant number of trees per plot will reduce the variance of density estimates (Eberhardt 1967) and it can reduce the statistical bias which is dependent on spatial patterns exhibited by individual trees (Payandeh and Ek 1986). However, the increase in the constant number of trees per plot is likely to make field surveys difficult. Comparison studies in the past have suggested that the ($c$–1) estimator (Equation 1) can

be appropriate in forest stands having random or moderately clustered distribution of individual trees (Payandeh and Ek 1986, Lessard et al. 1994, Lessard et al. 2002). The ($c$–1) estimator was appropriate in Scandinavian forest types (Jonsson et al. 1992) as well as in North-American forest types exhibiting random or moderately clustered spatial patterns (Payandeh and Ek 1986, Lessard et al. 1994). Payandeh and Ek (1986) suggested using $c \geq 10$, while Lessard et al. (1994) have suggested that the bias when using $c = 5$ sampling is not significantly high in North-American forest types. Eberhardt (1967) has suggested that the ($c$–1) estimator is a robust density estimator applicable not only to random but also to forest stands with individual trees exhibiting clustered spatial pattern distributions where tree counts on fixed-area plots yields the negative binomial frequency distribution. In the recent study, Kleinn and Vilčko (2006) have suggested that the ($c$–1) estimator has produced only minor biases in their simulated clustered populations and a one real stand exhibiting clustered properties.

Independently from the ($c$–1) estimator of density being proposed by Eberhardt (1967), Prodan (1968) proposed the same sampling procedure, based on variable-sized circular plots, in estimating a basal area of uniformly distributed even-aged forest stands or forest plantations in Germany. In its proposal, widely known in forestry literature as 6-tree sampling, Prodan (1968) assumed that sampling plots contain $c - 0.5$ trees on the average. Being aware of the bias and considering the practical applicability, Prodan (1968) has suggested measurement of the distances to the centers of the sixth ordered tree from each sampling point and it accounted for a probability that the variable circular plot areas contains 5.5 trees in average. The Prodan's assumption can be also used to estimate the tree density (Payandeh and Ek 1986, Lynch and Rusydi 1999) and here this density estimator is referred to as the ($c$–0.5) estimator:

$$\hat{\theta}_{c-0.5} = \frac{c-0.5}{n\pi}\sum_{i=1}^{n}\frac{1}{r_i^2} \tag{2}$$

The ($c$–0.5) estimator is referred to as the generalized Prodan estimator (Payandeh and Ek 1986) or the Prodan's estimator (Lynch and Rusydi 1999). Lynch and Rusydi, (1999) have suggested that the ($c$–0.5) estimator is more appropriate for the use in forest plantations where the bias involved in the ($c$–1) estimator was higher.

Rather than accounting for variable plot areas, accounting for variable distances can bring more statistical power and reduce a variance of estimates. These estimators are known as maximum likelihood (ML) estimators (Picard et al. 2005). In the case when estimator accounts for variable distances, $c$-tree sampling is also referred to as plotless ordered distance sampling (Engeman et al. 1994). Most of ML estimators of density of randomly distributed individuals are based on findings that measured distances in random populations exhibit the normal frequency distribution (Thompson 1956). Such a ML estimator of density in random populations is the Pollard estimator (Pollard 1971):

$$\hat{\theta}_{Pollard} = \frac{nc-1}{\pi\sum_{i=1}^{n} r_i^2} \tag{3}$$

Pollard estimator is also one the most studied and is being known as a one of the best performed density estimators in random populations (Engeman et al. 1994). Pollard (1971) have suggested that his proposed density estimator resulting in a smaller sampling variance and reduced standard deviation when increasing the $c$ value but it also suggested that it is a biased estimator of density in the case if the spatial pattern of trees in forest is not uniformly random.

As introduced above, $c$-tree sampling can yield biased density estimates, with the amount of a bias being dependent on exhibited spatial patterns of individual trees or the

density estimator being applied. Frequency distribution of distances or variable plot areas, involved in *c*-tree sampling, may vary to a great extent and it largely depends on exhibited spatial patterns of individual trees in forests. Furthermore, in the case when accounting for variable plot areas, the exact number of individual trees in average per plot is not known. Therefore, it may not be possible to completely remove the bias and for all innumerable varieties of spatial patterns being possibly exhibited by individual trees in forests. On the other hand, applicability of the (c–0.5) estimator in a forest plantation exhibiting a regular spatial pattern (Lynch and Rusydi 1999) and its bias in forest stands being characterized by a random spatial pattern (Payandeh and Ek 1986) have induced Trifković (2005) to consider a probability that a variation involved in a sample of circular plot areas in regular populations is minimal and will increase in random and clustered populations. The increase in the amount of a bias, occurring in density estimates with *c*-tree sampling, thus might be proportional to the increase in variation of plot area sizes similarly to the bias occurring when averaging major and minor diameters in estimations of elliptical tree basal areas (Biging and Wensel 1988). Biging and Wensel (1988) have shown that the use of the geometric mean can minimize a bias in estimating elliptical tree basal areas. The geometric mean has also found the use in forestry when measurements follow exponential growth; for example, calculating mean values in statistical time series (Koprivica 1997). It is also known that a geometric mean of data sets is always smaler than or equal to the arithmetic mean. The geometric mean is equal to the arithmetic mean if all members of the data set are equal. Therefore, the geometric mean can be applied in averaging variable circular plot areas (Trifković 2005) and the density estimator (GM estimator) can be written as:

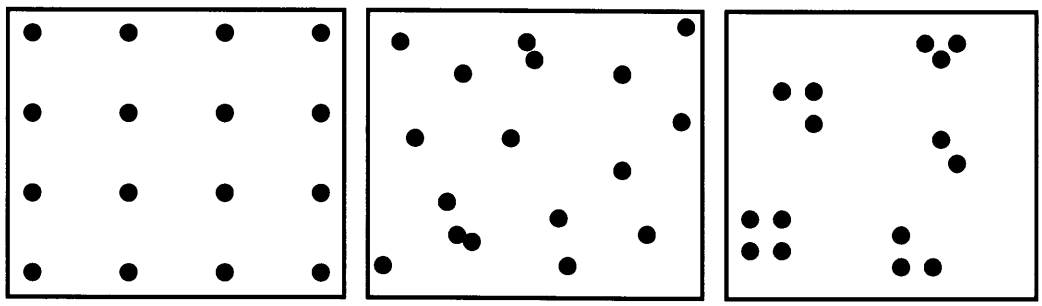
$$\hat{\theta}_{GM} = \frac{c-0.5}{\pi}\left(\prod_{i=1}^{n}\frac{1}{r_i^2}\right)^{\frac{1}{n}} \tag{4}$$

It should be emphasized that estimators, and the equations written above, would give density estimates being not expanded by a unit of forest stand area. Conducting measurement of distances (plot radiuses) in meters, multiplying estimators by 10,000 would give an estimate of a relative density per hectare. As it was mentioned above, that is also the usual procedure to present information regarding forest resources.

## 1.3. Spatial pattern indices

Indexing spatial pattern distributions of individual events in ecological populations, such are trees in forests, is essential to a wide range of ecological studies. Indexing spatial patterns of individual trees is also essential in evaluating a success of forest regeneration or in describing forest spatial structure. Moreover, acquiring information regarding spatial distribution of individual trees in forest stands is becoming more important in order to manage forests in a sustainable manner (Pommerening 2002).

Individual trees in forest stands can exhibit an almost infinite variety of spatial patterns and we generally classify them as regular, random or clustered (Figure 1.2.).



regular random clustered

**Figure 1.2.** Types of usually considered spatial distributions in ecological studies

Clustered spatial pattern is also referred to as aggregated or clumped. Clark and Evans (1954) have suggested further classifying spatial patterns of individual trees by estimating the departure (deviation) of the spatial pattern from that of the complete spatial randomness (CSR) and in the direction of regularity or clustering.

Some methods proposed in the past require excessive efforts in the field, for example mapping positions of all individual trees in forest stands (Stoyan and Stoyan 1994, Moeur 1993), but the information provided is usually a valuable indicator of ecological processes. Other methods are mostly designed to minimize field efforts

(Nishikawa 1996, Pommerening 2002). These methods are considered applicable for the use in forest inventories or in forest regeneration surveys and usually they can provide statistically confident information to support management decisions. Applying methods requiring fewer measurements during the field survey is usually preferred to inventory forest resources. The statistical power involved in the method is also important. Higher statistical power would require fewer measurements.

The fixed-area plot method, as one of the standard procedures in forest inventories, can be used to index spatial patterns but such information is influenced by the size of fixed-plot area (Pielou 1959, Moeur 1993). The use of other methods needs to be considered in order to get more reliable information regarding the spatial pattern of trees. The usual choice is to measure distances between trees or between sampling points and trees. Various methods and indices requiring measurement of distances have been proposed in the past (Nishikawa 1996, Liu 2001, Pommerening 2002). One of the firstly proposed such spatial pattern indices is the plant-to-plant method (Clark and Evans 1954). The plant to plant method requires measurement of distances from randomly chosen individual trees to their nearest neighbors. Difficulties surrounding random selection of individual trees, since all individual trees need to be enumerated prior to the selection, have induced Pielou (1959) to propose a method involving measurements of distances from random sampling points to nearest individual trees. However, the point-to-plant method (Pielou 1959) requires determining the relative density of trees in order to indexing their spatial patterns. In spite of these difficulties, both methods have found a great use in ecological studies. These basic methods were followed by many other variations, similarly to the development of the distance methods in estimating the relative density. Most of them attempted increasing reliability and a statistical power by increasing a number of distances to measure per a sampling location or involved some sort of combined use of plant-to-plant and point-to-plant methods. One of such methods

is the $T^2$ method proposed by Besag and Gleaves (1973). However, such approaches can be difficult to apply in the field and particularly in steep terrain conditions (Assunção 1994).

Recently, Liu (2001) has noticed that the Pollard estimator (Pollard 1971) in estimating the relative density (Equation 3) is greatly sensitive to a change of a spatial pattern. The $c$-tree sampling method requires the only one distance to be measured from a sampling point to the ordered constant individual tree. Therefore, it is a practical approach in the field and especially when applying small $c$ values such as the $c = 2$, $c = 3$ or even the $c = 4$ sampling procedure. Liu (2001) has utilized that to propose the $L_p$ spatial pattern index:

$$L_P = 12c^2 n\left[ n\ln\left(\sum_{i=1}^{n} r_i^2 / n\right) - \sum_{i=1}^{n} \ln(r_i^2)\right] / \left[(6cn + n + 1)(n-1)\right] \qquad (5)$$

Liu (2001) has recommended the $L_p$ spatial pattern index (Equation 5) to be used with $c \geq 2$ sampling. Setting the $c$ value to one ($c$ =1), being equivalent to the point-to-plant method studied by Pielou (1959), has not being recommended since it produced a higher bias. Moreover, applying larger $c$ values like the $c = 4$ sampling procedure has produced more reliable spatial pattern indices than in the case of applying smaller values like $c = 2$ sampling (Liu 2001). It implies that, similarly to the use of $c$-tree sampling in estimating relative density, the decision regarding the $c$ value need to be made prior to the survey. The $L_p$ spatial pattern index can be appreciated by foresters since it promising simple indices of spatial patterns and without necessity to conducting excessive field surveys. The $L_p$ value being not significantly different to 1 would suggest the spatial randomness, less than 1 would indicate the regular and greater than 1 would indicate the clustered spatial pattern.

Instead of using above introduced methods based on measurement of distances, the choice to assessing information regarding spatial patterns of trees can be the use of

methods requiring measurement of angles. There are two methods being identified as practical in indexing spatial patterns of trees. These are the Mean of Angles (Assunção 1994) and the *Winkelmaß* (Gadow et al. 1998). The *Winkelmaß* method is requiring the random selection of sample trees what, as introduced earlier, is not as practical as the random distribution of points. Once a sample tree is selected, four nearest trees from the sample tree needs to be identified. The *Winkelmaß* method can be used to index mingling and differentiation of individual trees and, along to indexing spatial patterns, it can give a further insight into the spatial forest structure (Aguirre et al. 2003). On the other hand, the Mean of Angles (Assunção 1994) method was not as much known in the context of forest research and a practical forestry. It is believed that a further study of a potential of the Mean of Angles method to serve in indexing spatial patterns of trees can benefit researchers in various fields of a science. Most of all, it is believed that a proposal of a simple spatial pattern index based on such measured angles can benefit to foresters.

### 1.3.1. Mean of Angles

The Mean of Angles method requires measurement of angles between lines of sight from sampling points to their nearest two neighboring trees (Figure 1.3.). Therefore, it can be practical in field surveys since the sample of angles can be easy obtained. Point sampling procedures are also more practical than the selection of sample trees. In forest stands having randomly distributed individual trees, conducting measurements in degrees, angles would range from 0° to 180° and measurements would have uniform (i.e. even, flat) frequency distributions (Assunção 1994).

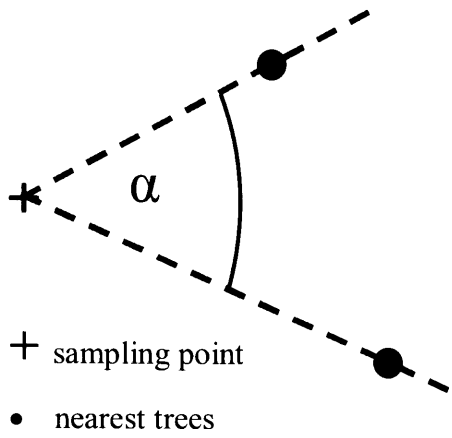



**Figure 1.3.** Measured angle "α" between lines of sight from sampling point to its nearest two neighboring trees

In addition to acquiring information of whether trees in forest stands are distributed randomly, we may wish to estimate departures from the randomness in either the direction of regularity or aggregation. Assunção (1994) has suggested that the expected mean value of measured angles in random populations is 90°:

$$MoA = \frac{1}{n}\sum_{i=1}^{n}\alpha_i \qquad (6)$$

where: $\alpha_i$ are measured angles and $n$ is a number of sampling points

Assunção (1994) has also suggested that the angles in forest stands having aggregated spatial pattern will tend to be smaller than expected under the CSR while opposite in regular populations. Examining some coppice forests having many sprouts per stump, and characterizing individual sprouts as individual trees, would probably induce the *MoA* to be significantly smaller than 90°. In forest plantations, where seedlings are usually planted in regular spacing, the *MoA* would be significantly larger than 90°. Measured angles in random populations do not depend on a relative density of individual trees. Therefore, unlike with the use of *c*-tree sampling or fixed-area sampling, measuring the angles can not be used in estimating the density of trees in forests.

## 1.4. Objectives

Surveying designs based on measurements of the distances and the angles are believed to have a potential use in many different applications and fulfill various objectives in a scientific research as well as in a practical forestry. It is believed that measuring both, the distances and the angles, can benefit to foresters in describing a state of forest resources. In particular, merits of using these methods are exceptional in assessing a state of forest regeneration and the two main parameters of its success, designated to as tree density and spatial pattern.

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 thesis is focused on explaining statistical properties of *c*-tree sampling. It is attempted to compare density estimators being proposed in past and to propose the best of them for the use in forest regeneration surveys. 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 the ability in stratifying populations of naturally regenerated saplings.

The *c*-tree sampling method was also proposed in the past to be used in indexing spatial patterns. One of specific objectives of the thesis was to test the performance of the $L_p$ spatial pattern index being proposed by Liu (2001) as the best-performed spatial pattern index derived for the *c*-tree sampling procedure.

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. Defining whether trees in forests are distributed at random or not may fulfill objectives of certain research. However, researchers as well as forestry practitioners are usually interested in indexing the degree of clustering or regularity being exhibited by individual trees. Specific objectives of the thesis include analysis of potential of the arithmetic mean of angles to serve as a practical measure of the degree of regularity or clustering.

Being aware of a statistical bias involved in density estimates assessed by the use of *c*-tree sampling and its dependence on exhibited spatial patterns of trees, it is attempted to increase a reliability of estimates by a combined use of the distances and the angles. 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.

## 2. Methodology

It can be generalized that each individual tree in forest can be represented by points in a plane area (Cartesian coordinate system). That allows us to map individual tree positions or to mimic real forests by simulating point spatial patterns. Methodology in the thesis was almost entirely based on simulated point populations. For example, simulation studies are indispensable in order to draw reliable conclusions about the bias and the variance of density estimates involved in the *c*-tree sampling. That was also necessary to test a performance of the Mean of Angles method or *c*-tree sampling in assessing the degree of regularity or clustering. All possible varieties and mixtures of spatial patterns and relative densities of trees in forests are almost impossible to consider. Here, only the most theoretically significant point populations are presented and that greatly reduced a volume of the thesis. In addition to a simulation study, the practical applicability of studied methods was tested in a one real forest stand.

Simulation studies were conducted using advances of the GIS. The GIS allows to automatically and accurately conducting measurements of angles, distances or counts per fixed-area plots. Angles were measured in degrees and in a continuous statistical scale with a measurement ranging from 0° to 180°. Distances were also measured in a continuous statistical scale and in all presented point populations distances were measured up to the 10th nearest point. Density estimates applying $c = 1$ sampling were omitted because the $(c-1)$ estimator could not be applied.

Simulated point populations, regardless of their spatial pattern or relative density, can be regarded as uniform and thus the edge-effect does not influence spatial pattern and per hectare density estimates. For example, simulated regular point populations can be considered as infinite in size. However, the size of simulated point populations needed to be finite in size because of the limit in a computing power. The measured

forest stand is also finite in size. Therefore, the buffer-zone needed to be set in order to ensure that the influence of the edge-effect is minimized for both purposes in indexing spatial patterns and in obtaining density estimates.

The bootstrap statistical technique (for example, Manly 1997) was applied as it can serve in evaluating the performance of density estimators in regard to the variance of estimates. It is known that density estimates can be obtained by a randomization of variables and the estimates would fit the normal frequency distribution (Efron 1981). Therefore, comparing observed variances involved in density estimates yielded by different estimators, or different methods, can serve in comparing their statistical performance. It is believed that such an approach is the best available and the most suitable to studying the variance involved in different estimators.

## 2.1. Simulation study

Many spatial processes proposed in the past attempted to mimic real distribution patterns of individual trees in forest stands. Some of them, like the Matérn process (Stoyan and Stoyan 1994), could be used to simulate clustered point populations. Various patterns created by inhomogeneous random spatial processes, or the Poisson cluster process, may also attempt to describe spatial patterns present in some real ecological populations (for example, Liu 2001). Individual trees in some forest stands may also exhibit similar spatial pattern to that of the CSR simulated by the homogenous random spatial process. Point spatial patterns can also be used to represent many other events in the forest area, such as distribution of clusters in coppice forests (Picard et al. 2005). Forest plantations can be established by planting trees with regular spacing in the form of a triangular network, regular square network, rectangular network or following some other regular, or irregular, pattern (Šumarska Enciklopedija III 1987). Regular patterns are usually associated to forest plantations. Moreover, influence of the competition for the space in naturally regenerated forest stands can lead to some form of regular spatial pattern, such that exhibited by old-growth trees with closed canopy (Moeur 1993).

Naturally regenerated juvenile trees may exhibit various mixtures of spatial patterns and relative densities. In some naturally regenerated stands, seeds can be randomly dispersed under the mother-trees cover. Spatial patterns of mother-trees, influence of a wind, water, gravity, animals and possibly other factors or combination of these factors can also lead to some form of dispersed seed pattern exhibiting properties of clustering (Bigwood and Inouye 1988). Spatial distribution of germinated seeds can highly depend on a relief and other site conditions, or it can be influenced by a graze or pathogens, and succeeded naturally regenerated trees can exhibit highly variable spatial pattern

distributions. Naturally regenerated juvenile trees may exhibit clustered spatial pattern, with clusters irregularly shaped and different in a size. Furthermore, artificial or natural disturbances may lead to forming some sort of clustered spatial patterns. Clustered spatial patterns can be exhibited even in forest plantations, being established by planting trees in regular spacing, where disturbances can form larger gaps.

It is beyond the scope of the thesis to present all different varieties in spatial patterns of trees. Even it may not be feasible to consider them all. Here, it is considered simulating the most significant theoretical point spatial patterns being classified to as regular, random or clustered. In addition, a new methodology to simulate clustered point spatial patterns is introduced and it is here denoted to as the Gap-process. It is certain that artificial or natural disturbances can have a large influence on exhibited spatial patterns of individual trees in forests. Introducing the Gap-process, it is attempted to mimic artificial or natural disturbances in forest stands. That was conducted simply by creating "host point populations" and than erasing points felled inside simulated fractals of area representing the disturbed area. The Gap-process can be recognized as a modified Gibbs field process. The Gibbs field process uses so-called spatial birth-and-death processes (Stoyan and Stoyan 1994). The Gap-process is simplified and it accounts only for a "spatial death" of points at the host point population.

### 2.1.1. Regular spatial patterns

Among various simulated point populations exhibiting regular patterns, theoretically most significant are presented in the thesis. One of these theoretically most significant regular point populations is the regular-triangle (Figure 2.1.a) point population simulated in a form of equal-sized triangles having a 10 meter distance between points. Point population simulated in a form of regular squares having a 10 meter distance between points is regarded as regular-square (Figure 2.1.b). Point population simulated along a rectangular network having a 1 x 4 meter sides is regarded as rectangular (Figure 2.1.c).

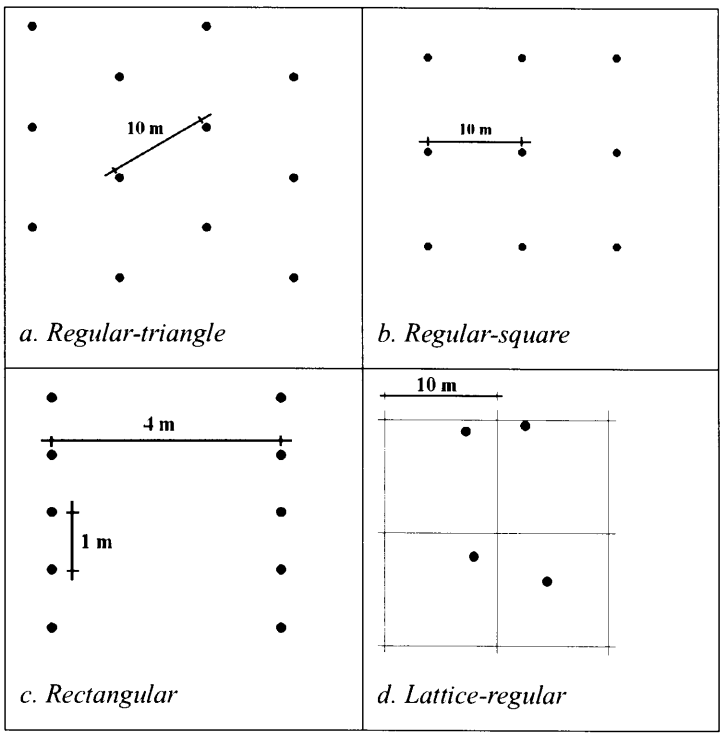



**Figure 2.1.** Theoretically most significant regular point spatial patterns

Foresters may not insist on planting seedlings with exactly equal spacing and such plantations could possibly have similar spatial properties to that of the lattice-regular point population (Figure 2.1.d) simulated by Engeman et al. (1994) or Liu (2001).

Furthermore, the lattice-regular spatial pattern can possibly be close to the spatial pattern of some even-aged forest stands. Such an example could be the case of old-growth trees with closed canopy (Moeur 1993). Here presented the lattice-regular point population (Figure 2.1.d) was simulated laying regular squares; these have 10 meter sides and points in each square were distributed randomly so the lattice contained one point per 100 $m^2$.

Here proposed the Gap-process was applied to above simulated point populations. Such a process can attempt to mimic disturbances in forest plantations. Here, one point population is presented and it mimics timber extraction routes in imagined forest plantation. Intensive management systems in forest plantations require planning of forest roads and timber extraction routes. Some management systems include thinning at regular spacing; for example each third row is cut down.

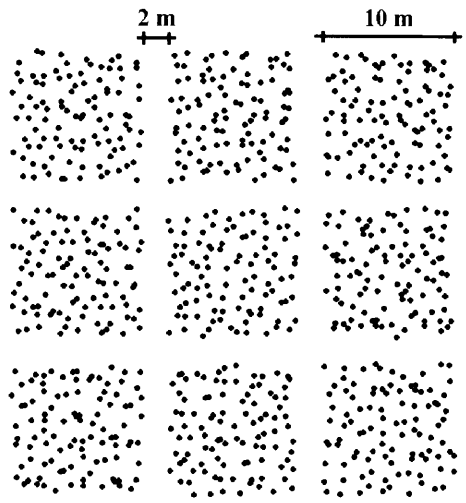



**Figure 2.2.** A part of the point population which mimic forest roads in plantations; regular-clusters

Here presented point population was simulated applying the Gap-process where the host-population was a lattice-regular point population. The mesh of this lattice-regular

point population was created by 1 meter equal sides and points in each square were distributed randomly so the lattice contained one point per 1 $m^2$. The paths being 2 m wide along 10 m interval between rows and columns were simulated and the points felled inside the paths were erased, producing the regular-clusters point population (Figure 2.2.).

### 2.1.2. Random spatial patterns

Probably the most studied and theoretically significant point population is that having a random spatial distribution of points in a plane. The uniformly random spatial pattern also serves as a dividing reference between regular and clustered point spatial patterns.

Random point spatial patterns can be efficiently simulated by the use of random number generators. Random point populations were simulated using a computer random number generator along the homogenous random spatial process. Assigning randomly derived numbers to the X and assigning other randomly derived numbers to the Y, in a homogenous Cartesian coordinate system ranging from 0 to 1, would result to a complete spatially random point population. Some statisticians could argue that random numbers generated using computers, randomly drawing uniformly distributed numbers ranged between 0 and 1, are not "perfectly" random but these practices have found a broad use in biostatistical analysis (Zar 1999).

Here presented random point population is simulated by randomly distributing 100,000 points on a 100 ha area (1,000 points/ha) in a Cartesian coordinate system (Figure 2.3.).

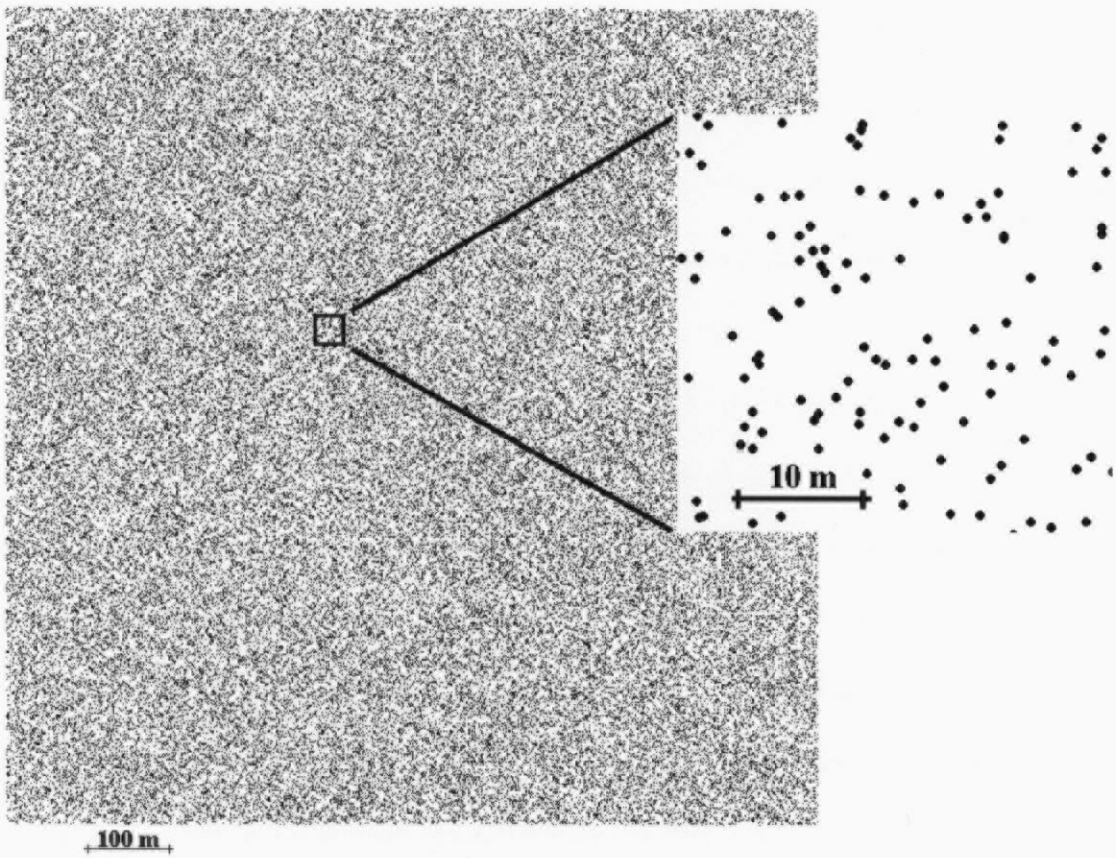



**Figure 2.3.** Simulated random point spatial pattern

### 2.1.3. Clustered spatial patterns

The Matérn process has a significant theoretical importance and here presented clustered point spatial pattern was simulated randomly distributing so-called mother-points, similarly to Picard et al. (2005). Here presented clustered point population having assigned only one point to each of mother-points and it have in average 100 points/ha or 50 clusters/ha (Figure 2.4.). Distances between points in each cluster are within 1 meter, ranging randomly inside the interval from 0 to 1 m. Point population clustered in such a way has also only theoretical value, similar to other clustered patterns created by the Matérn process. However, it can be considered that point populations simulated by the Matérn-process and having tightly adjacent individual points in clusters are theoretical representatives of clustered populations.

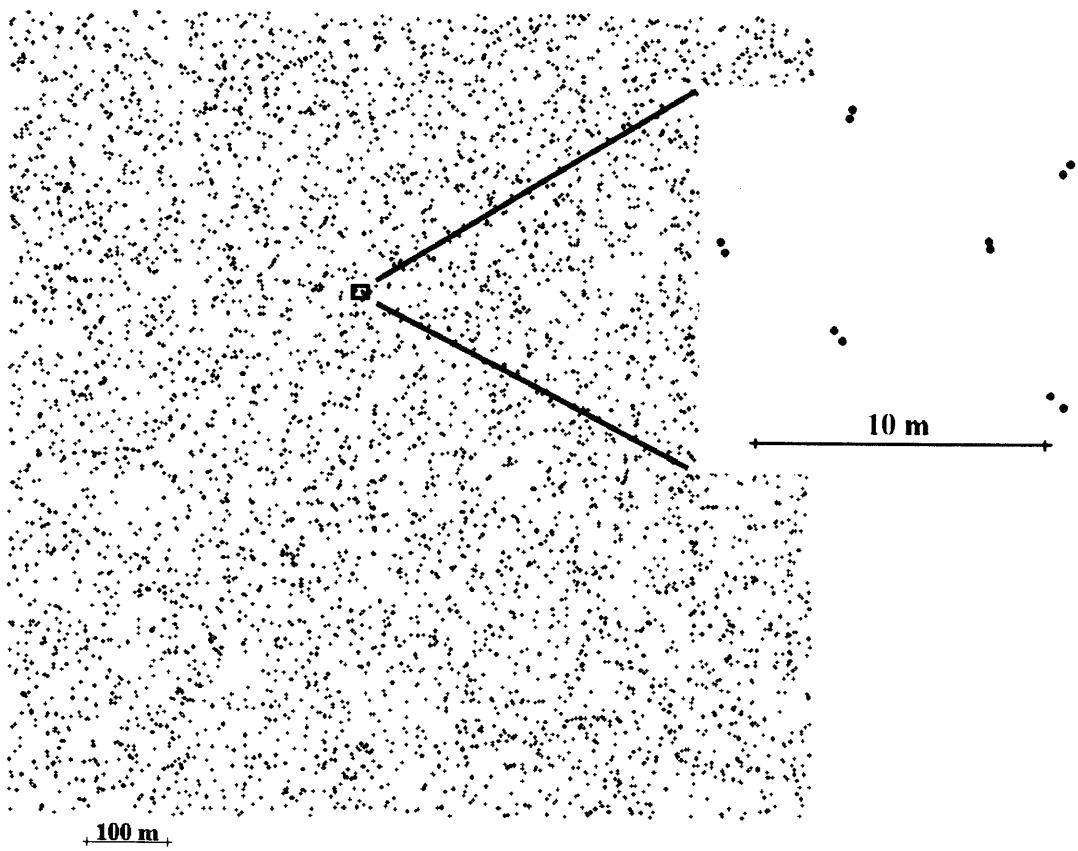



**Figure 2.4.** Simulated Matérn-clustered point population

Along to the the Matérn-process, here proposed Gap-process can also find the use in simulating theoretically clustered point populations and it also could be used to mimic spatial patterns exhibited by certain ecological populations. Here presented clustered point patterns simulated by applying the Gap-process have considered using the random point population (100,000 points on a 100 ha area) as the host point population. At the host point population, 1,000 points were randomly scattered and circular fixed-area plots having centers based on these 1,000 random points were drown; 1,000 randomly distributed circular fixed-area plots. Points of the host population which have felled inside the circular plot areas were erased. Three point populations having clustered spatial pattern were created by: setting the plot radius to 10 meters (Figure 2.5.; 10mGAP), setting the plot radius to 20 meters (Figure 2.6.; 20mGAP) and setting the plot radius to 30 meters (Figure 2.7.; 30mGAP).

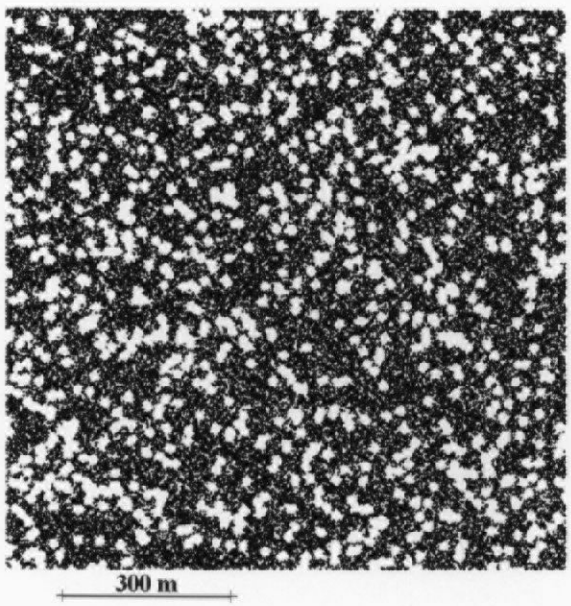



**Figure 2.5.** Simulated clustered point population by applying the Gap-process; 10mGAP

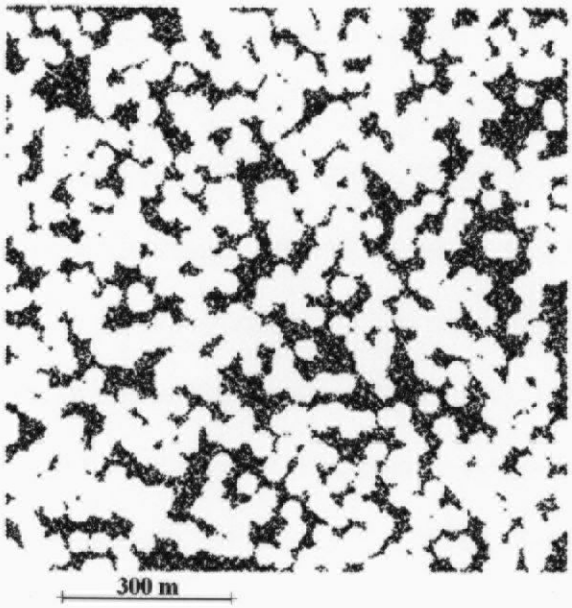



**Figure 2.6.** Simulated clustered point population by applying the Gap-process; 20mGAP


**Figure 2.7.** Simulated clustered point population by applying the Gap-process; 30mGAP

## 2.2. Study case of naturally regenerated *Chamaecyparis spp.* saplings

The compartment 100 of the Ogawairi national forest is consisted of three sub-compartments; sub-compartment 1 (2.93 ha) is located in the northern part of the stand, sub-compartment 2 (3.61 ha) in the central part and the sub-compartment 3 (3.64 ha) in the southern part of the compartment. Saplings sized from 1.5 to 5.0 meters in height were mapped (Cartesian coordinate system) at the sub-compartment 2 and the sub-compartment 3 (in total, 7.25 ha). Total number of saplings was 3877 (Figure 2.8.).

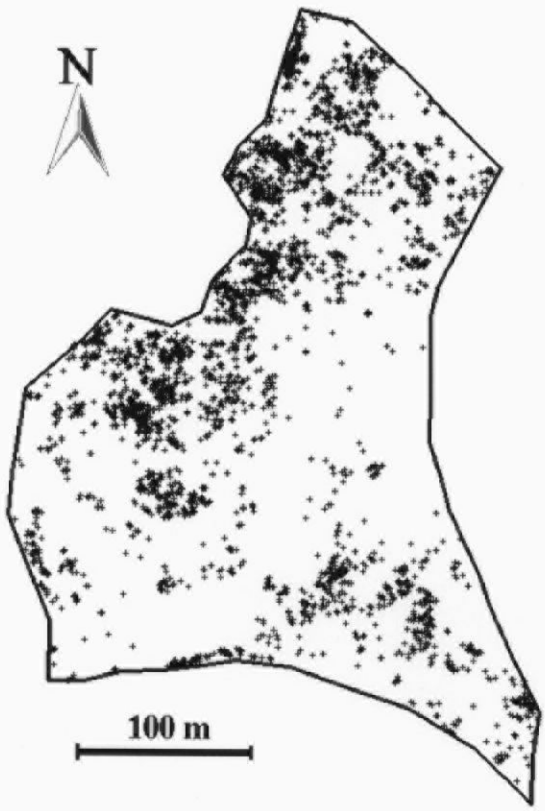



**Figure 2.8.** Mapped coordinates of saplings sized from 1.5 to 5.0 meters in height at the sub-compartment 2 and the sub-compartment 3 (compartment 100 of the Ogawairi national forest)

Simulation study was conducted in the GIS environment, randomly distributing

sampling points. Randomly distributed sampling points being less than 10 meters distant from the border line were excluded from the simulation (10 m buffer-zone). Furthermore, random sampling points, being closer to the border line than to their fourth nearest sapling, were also excluded. In total, 500 sampling points were distributed randomly (Figure 2.9.). Simulation study was designed to measure distances to nearest four saplings from these 500 random sampling points, to measure angles between lines of sight from sampling points to their nearest two neighboring saplings and to count saplings felled inside 1 m and 2 m radii circular fixed-area plots. The use of GIS has allowed fast and accurate measurements and thus it was very useful in accomplishing objectives of the thesis.

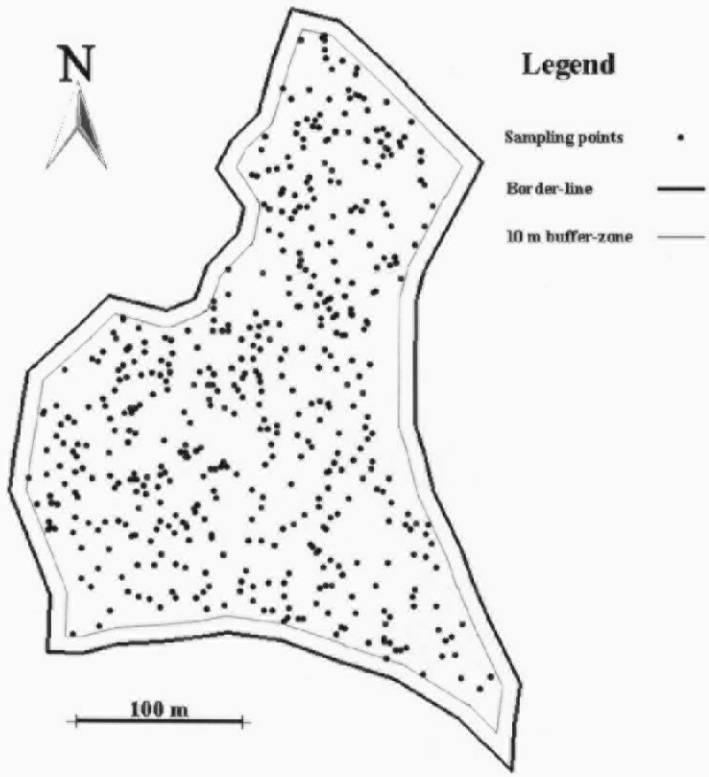



**Figure 2.9.** Randomly distributed 500 sampling points at the sub-compartment 2 and the sub-compartment 3 (compartment 100 of the Ogawairi national forest)

Systematical sampling procedures or clustered-systematical sampling procedures

can add a practical value to the forest inventory. Applying such a sampling design can serve to stratify the stand area by, for instance, setting aside square polygons containing no trees from those being densely populated. Such information is of a particular importance in supporting silvicultural operations or management decisions; for example, decisions regarding the supplemental planting. In the mapped population, simulation study was conducted applying the systematical mesh network in the GIS (20x20 m). Created systematical mesh network contained 144 square polygons; each square covers 400 $m^2$ area or 0.04 ha. Sampling points were distributed systematically, being located at centers of 144 square polygons (Figure 2.10.).

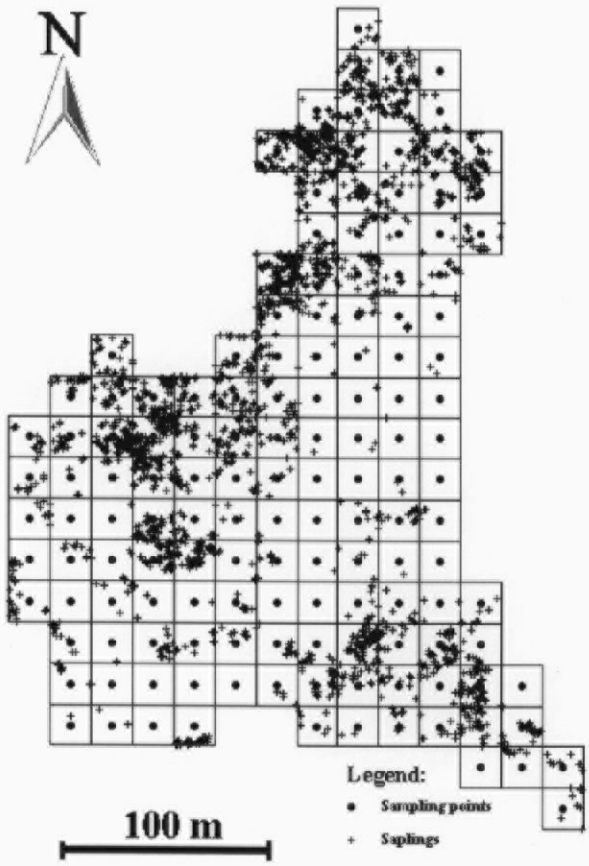



**Figure 2.10.** Saplings sized from 1.5 to 5.0 meters in height felled inside the systematical mesh network (20x20 m) at the sub-compartment 2 and the

sub-compartment 3 (compartment 100 of the Ogawairi national forest)

The true number of saplings sized from 1.5 to 5.0 meters in height felled inside the systematical mesh network (20x20 m) at the sub-compartment 2 and the sub-compartment 3 was 2788 or in average 484.1 saplings/ha. The stand area was stratified by setting aside square polygons containing less than two saplings from those containing two to four saplings and those being more densely populated. This methodology can provide us with information on the forest stand area where the regeneration did not succeed.

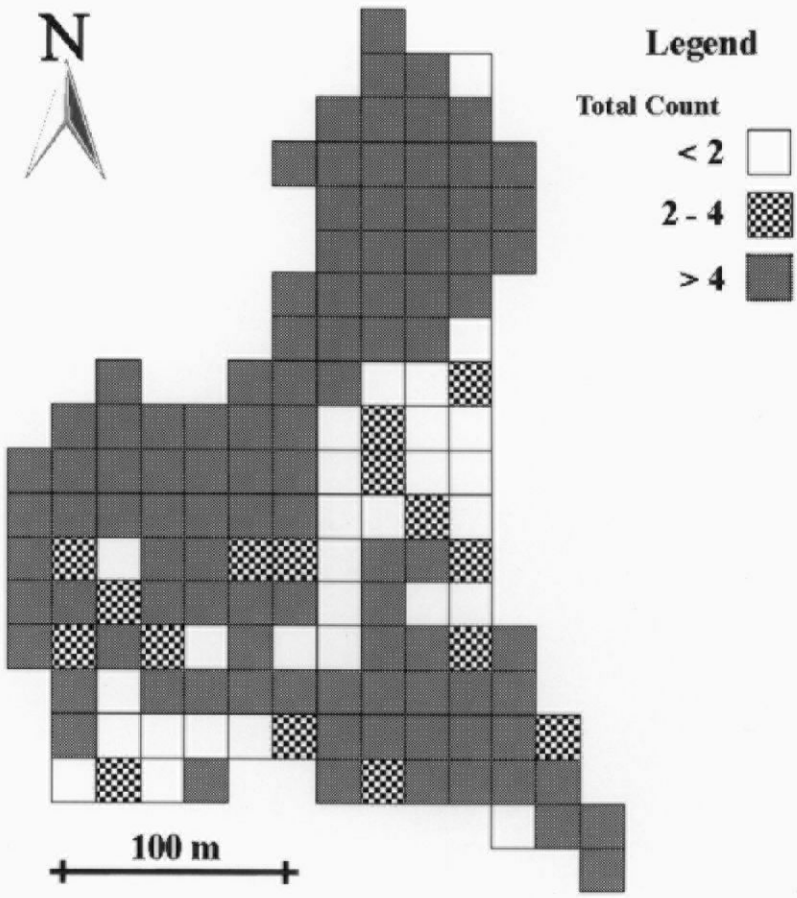



**Figure 2.11.** Stratified forest stand area by setting aside square polygons containing less than two saplings from those containing two to four saplings and those being more densely populated.

Inside the mesh polygons (0.04 ha area, 144 in total), 18 contained no saplings and 11 squares contained only one sapling sized from 1.5 to 5.0 meters in height respectively. Remaining 115 square polygons contained two or more saplings respectively (2777 saplings in total, 603.7 saplings/ha). There were 99 square polygons containing five or more saplings (2733 saplings in total, 690.1 saplings/ha) (Figure 2.11.).