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ORIGINAL PAPER

The impact of precision of tree position measurements and different plot designs on the estimates of tree level production and diversity parameters

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Abstract

Sample plots are basic units of statistical forest inventories. The choice of their shape and size, and sampling methods have changed over time due to economic constraints, efficiency and changes in human demands on data about forests. In the presented study we analysed the impact of three different sampling units: fixed-area plots, fixed-different-area plots, and nested concentric plots, on the estimates of tree level production and diversity parameters. These sampling units were measured during the regional inventory at the University Forest Enterprise of Technical University Zvolen, Slovakia, which was repeated four times (1986, 1992, 1998, 2012). Within each inventory plot, all positions of trees were repeatedly and independently measured three times (1986, 1998, 2012) by different operators using different tools. From these data we quantified the error of tree position resulting from human and technological factors and analysed its impact on the estimates of tree level diversity and production parameters. The selected parameters were: number of trees, stand basal area, standing volume per hectare, number of tree species and number of vertical tree layers. The results indicate that the plot design primarily affects ecological characteristics of forests. Fixed-area plots seem to be the most suitable sampling unit from the point of multi-criteria evaluation of forest status and forest change.

Key words: sample plot; forest inventory; monitoring; sampling simulation; sampling error

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1. Introduction

Forest inventory has a long tradition that dates several centuries back. The interest in inventory methods started in the late 18th century when the gaps in forest survey methods were identified (Fuchs 1993). In the 19th century, a complete census was usually performed (Kangas & Maltamo 2006). The development of statistical inventory methods started at the beginning of the twentieth century, when the first regional and national forest inventories were performed in Finland and Norway (Kangas & Maltamo 2006). About twenty years later, the progress in the development of forest inventory and monitoring methods was initiated in the USA (Stott 1947) followed by the works in Switzerland (Schmid 1963). While at the beginning, forest inventory was primarily aimed at gathering the information about the production parameters of stands (Rego et al. 2005), in the 80s of the last century their ecological functions started to become more important in the developed part of the world, due to which the inventoried information spectrum has expanded (Söderberg & Fridman 1998). Hence, nowadays national forest inventories are becoming more comprehensive surveys of natural resources (Corona & Marchetti 2007). In addition, while originally the aim of forest inventories was to obtain the information about the actual state of the ecosystem, over time determining the net change of an ecosystem and explaining its development has become the main task (Scott 1998).

As the amount of information gathered during forest inventories increased, sampling designs have become more complex and sophisticated. While originally forest inventory was based solely on field data acquisition, recent trends are to combine field sampling with other data sources, particularly remote sensing methods (Tomppo et al. 2008), but also geographical information systems, digital elevation models, etc. (Wezyka et al. 2005). These data sources enable rapid data acquisition and reduce inventory costs (Katila 2004). Fieldwork itself has been enhanced by satellite positioning systems

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(GPS), automatic measuring devices, e.g. terrestrial laser scanner (Holopainen & Kalliovirta 2006), field computers and wireless data transfer (Holopainen et al. 2005). Due to this development, nowadays there are numerous approaches of forest inventory and monitoring applied at local, regional, and national scales (Kangas & Maltamo 2006).

The changes in acquisition methods often lead to the changes in the applied sampling or plot design (Tomppo et al. 2010). Such changes during successive inventories may affect the precision and the accuracy of the evaluation of temporal development of examined parameters. Subsequently, the accuracy of inventory data may have a significant impact on management decisions and planning (Islam et al. 2009) and models derived from these data (Lichstein et al. 2014).

Hence, the goal of the work was to analyse the effect of two kinds of sampling errors on tree level production and diversity parameters. From production parameters characterising a forest tree level we selected number of trees, stand basal area and stand volume. From diversity parameters we chose simple measures characterising tree species richness and stand vertical diversity that are easy to quantify and simple to interpret, since several studies have pointed at the shortages of explaining the values of commonly applied diversity indices (e.g. Jost 2006; Morris et al. 2014). Hence, as a tree species richness measure we selected the most commonly used number of tree species. Stand vertical diversity was quantified using the number of vertical tree layers, a frequently used measure of forest structure in national forest inventories (Winter et al. 2008), and the proportion of vertical layers calculated as a ratio between the number of trees representing one vertical layer and the total number of trees per plot. The first type of errors represents the random error of tree position measurements as a result of imprecise determination of distances inside inventory plots. The second type of errors occurs if the sampling design is changed in successive inventories. Our aim was to examine if these types of errors have a significant impact on the estimates of tree level production and diversity parameters.

2. Materials and Methods

2.1. Inventory Area

The presented study is based on the data from four successive regional forest inventories performed at the University Forest Enteprise (UFE) of Technical University Zvolen in the years 1986, 1992, 1998, and 2012. Currently, the enterprise covers 9,937 ha. The largest part of the forests (80%) belongs to a category of forests for special purposes, primarily for education and research activities. Elevation of the enterprise ranges from 250 to 1,050 m above sea level.

Mixed spruce–fir–beech, pure beech and mixed oak-beech stands are most common forest stands in the area. Overall, deciduous species dominate (mainly common beech (*Fagus sylvatica* L.), oak (*Quercus spp.*) and hornbeam (*Carpinus betulus* L.)) over coniferous ones, represented mainly by Norway spruce (*Picea abies* Karst.), silver fir (*Abies alba* Mill.) and Scots pine (*Pinus sylvestris* L.).

2.2. Inventory Design

The inventories were performed at tracts laid in a square (2 × 2 km) lattice over the whole area of the forest enterprise (Fig. 1). Each tract is 100 × 200 m large, and is composed of maximum six sample plots with 100 m distance between the neighbouring plots in the tract (Fig. 1). Hence, it is a systematic cluster sampling design, where tracts represent clusters of sample plots. In 1986, the tracts and sample plots were permanently established if situated on forest land. In total, 27 tracts and 121 sample plots were established at the time of the first inventory of UFE. The tracts or plots which were located outside the forest land were not established.

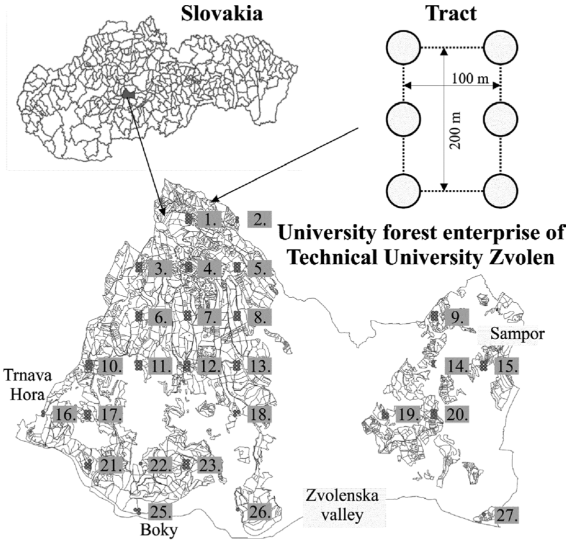

Fig. 1. Location of the University Forest Enterprise of Technical University Zvolen and the distribution of sample plots over the area.

All inventories were carried out on circular plots, but the plot design changed in time. During the first and second inventories in 1986 and 1992, sampling at each sample plot was performed on circular plots of different size from 200 to 500 m^2 (hereafter as fixed-different-area plots) depending on the stand density and stand growth stage. The radius of each sample plot was determined in the field to include in the measurements approximately 20 trees with diameters at breast height equal to or greater than 7 cm over bark (Batcheler & Craib 1985; Šmelko 1986). During the third inventory performed in 1998, five nested concentric sample plots (hereafter as concentric plots) were used. On each plot, a group of trees with a predefined size was measured as defined below (Šmelko 2000): (i) trees with tree height <1.3 m on

1 m^2 square; (ii) trees with tree height >1.3 m and diameter at breast height (dbh) <8 cm on circular plots with radius r = 2.52 m (i.e. area 20 m^2); (iii) trees with dbh from 8.1 to 16.0 cm on circular plots with radius r = 5.64 m (100 m^2); (iv) trees with dbh from 16.1 to 28.0 cm on circular plots with radius r = 7.98 m (200 m^2); (v) trees with dbh above 28.1 cm on circular plots with radius r = 12.62 m (500 m^2).

The last inventory in 2011/2012 was performed on circular plots with a fixed radius of r = 12.62 m (hereafter as fixed-area plots). Within this inventory all trees with dbh equal to or greater than 7 cm over bark were measured on the plots.

2.3. Real Data of Tree Positions

Tree positions, i.e. the distance and the bearing to a tree from the plot centre, were repeatedly and independently measured during three inventories in 1986, 1998 and 2011/2012 by different operators. The measurements of positions were performed only for the trees with dbh exceeding a certain threshold (7 cm in 1986 and 2011/2012, and 8 cm in 1998). In 1992, only the positions of ingrowth trees, i.e. trees with dbh below 7 cm at the first inventory but greater than 7 cm at the time of the second inventory, were measured, while the positions of other trees were taken over from the first inventory in 1986. In the first inventory, tree distances from the plot centre were measured using a measuring tape. In the last two inventories in 1998 and 2011/2012, hypsometers Vertex I and III were used for measuring the distances of trees from the plot centre with 1% accuracy of distance measurements, respectively. The bearings to trees from the plot centre were measured using a survey compass Keuffel & Esser Co New York with a precision of 1°.

2.4. Simulated Data

To quantify the effect of sampling design and the error of tree positions on the selected tree level diversity and production parameters, we generated forest stands, each 1.44 ha large, using STRUGEN structural generator (Pretzsch 1993) implemented in SIBYLA growth simulator (Fabrika 2005). For the generation of the stands, we used basic stand parameters, i.e. mean stand diameter, mean stand height, stand age taken from yield tables of Halaj & Petráš (1998). First, individual tree diameters were generated using Weibull function. This was followed by the generation of tree heights from modelled height curves. Then, tree crown parameters were generated on the base of tree diameters and heights. At the end, tree positions were generated within the modelled area of 1.44 ha. The size of the generated stand was set to 1.44 ha to enable systematic sampling without autocorrelation effects between the plots.

In total we generated 99 stands that represented 3 categories of stand vertical diversity (low, moderate and high), 3 categories of tree species richness and 11 decennial age classes starting from 40 to 140 years. The categories of stand vertical diversity were derived from the variability of tree diameters, because of the high correlation between tree diameter and height, defined by the coefficient of variation with the values for low, medium and high variability equal to 15%, 35%, and 50%, respectively. This approach is implemented in the structural generator used for generating stand structure. Tree species richness categories were defined as low, moderate and high if stands consisted of 3, 6, and 9 tree species, respectively, following the work of Merganič & Šmelko (2004). Age categories can be taken as a surrogate of stand density following the premise that the number of trees per hectare as a measure of stand density decreases with the increasing age.

The stand structure of each modelled stand was randomly generated 15 times using the same initial stand characteristics (i.e. mean diameter, mean height, stand volume of individual species). In each modelled stand, 9 inventory plots were systematically distributed over the whole area of the stand. The distance between the neighbouring plots was set to 45 m, which is greater than the minimum grid spacing of 20 m required for excluding the autocorrelation effects between the plots (Motz et al. 2010). It means that each combination of categories (richness × vertical diversity × age) was represented by 135 plots (i.e. 9 plots × 15 generations). At each simulated inventory plot, we applied the above-defined three plot designs that had been used in the regional forest inventories of the University Forest Enterprise, i.e. fixed-different-area plots, concentric plots, and fixed-area circular plots. For each inventory plot and the applied plot design, we calculated the selected tree level production and diversity parameters: number of trees per hectare, stand basal area and standing volume per hectare, tree species richness measure defined as a number of tree species per plot, and two vertical diversity measures defined as a number of vertical layers per plot and a proportion of vertical layers calculated as a ratio between the number of trees representing one vertical layer and the total number of trees per plot. The borders between the vertical layers were defined using the ratios of the maximum tree height in the stand: 90%, 80%, 60%, and 30%, i.e. each forest stand was divided into five vertical layers (0 – 30%, 30 – 60%, 60 – 80%, 80 – 90%, 90 – 100%). The values of the parameters were used for the subsequent analyses described in Methods.

2.5. Methods

2.5.1 Errors of Tree Position Measurements

Due to the repeated measurements of tree positions in successive inventories, it was possible to analyse the error of tree positions resulting from human and technological factors and the random error. The analysis was performed only for the trees with the measured positions from the plot centre, i.e. the trees with diameter at breast height equal to or greater than 7 cm over bark. The trees smaller than 7 cm were excluded from the analysis.

The analysis of tree positions was performed in Mathcad (PTC 2011) and GIS software called SAGA (Bock et al. 2008) as follows. Each inventory was represented by one layer of the vector data of tree positions. The trees measured in the first inventory in 1986 were assigned tree numbers starting from 1. The trees in successive inventories were assigned tree numbers using an algorithm programmed in Mathcad that checked if the following conditions were met: (1) the difference in their position between the particular inventory and the preceding inventory within the plot was less than 0.5 m, (2) the tree species was the same in both inventories, (3) the diameter at breast height determined in the successive inventory was equal to or greater than the diameter measured in the preceding inventory. Each tree that was linked to the tree from the previous inventory was assigned the same tree number. If the tree did not meet the above-mentioned criteria, it was assigned a new tree number that did not occur in the preceding inventory. In the next step, the inventory layers were overlapped in SAGA environment and the assigned tree numbers were visually checked and harmonised. This harmonisation was driven and controlled by an operator with regard to the inventory plot design, assigned tree species and diameters at breast height in individual inventories.

Afterwards, the differences in tree positions of the same tree between the individual inventory years were calculated. In total, we analysed 2,932 pairs of tree positions. From the individual differences we calculated the average difference as an arithmetical mean of all differences, which represented the systematic error of the measurements, i.e. bias, and their standard deviation (SD), which represented the variability of the differences, and hence the random error of tree position measurements. Afterwards, we divided the values of differences into twenty-six 0.5 m wide distance classes, and for each distance class we calculated its standard deviation. In the next step, we calculated relative standard deviations (RD) as a ratio between the standard deviation of the particular distance class and the distance from the plot centre (DIST). Subsequently, the regression analysis was applied to describe the relationship between RD and DIST. Thus, we obtained a function RDm = f(DIST), where RDm is a modelled relative standard deviation, which was used to calculate a modelled standard deviation SDm = RDm × DIST. The values of SDm were used in the subsequent analyses as they specify the uncertainty belt around the plot border.

2.5.2 Impact of Random Error (SDm) of Plot Radius on Tree Level Production and Diversity Parameters

In the case of the trees located within the uncertainty belt around the plot boundary defined by the random error of tree position measurements (i.e. plot radius ± SDm) it may happen that the trees that are already outside the plot are measured as if they were inside the plot, or vice versa the trees that are situated inside the plot near the plot border are excluded from measurements. Due to this, the plot values of tree level diversity and production measures may be under- or overestimated. Hence, the impact of the random error of tree position measurements calculated from the successive inventories of UFE on the values of tree level production and diversity parameters was examined using the simulated forest stands. The analysis was performed at a plot level, i.e. at each inventory plot inside the generated forest stands we compared the "precise" values of the examined parameters with the values obtained when the random error of the plot border was included.

The impact of the random error of tree position measurements on the tree level diversity and production parameters was examined within individual tree species richness categories, vertical categories, and age classes with multivariate analysis of variance (MANOVA) using Statistica software (StatSoft 2011). This analysis allowed us to examine also their mutual interactions between the individual factors and their interactions with the applied plot design.

2.5.3. Impact of Plot Design on the Estimates of Tree Level Production and Diversity Parameters

The sampling was analysed from the point of the impact of the applied plot design and the stand structure on the values of the selected tree level production and diversity parameters.

The effect of the inventory plot design was analysed by taking fixed-area circular plots as a basis and comparing the other two samplings with fixed-area circular plots. First we calculated the differences between the values of a particular parameter obtained from fixed-different-area plots or concentric plots and the values obtained at fixed-area circular plots. Negative differences represented underestimation of a particular parameter, while positive differences indicated their overestimation using a specific plot design in comparison to fixed-area circular plots. From these differences, average differences and their confidence intervals were calculated and tested if they were significantly different from zero.

3. Results

3.1. Errors of Tree Position Measurements

The calculated average bias from 2,932 analysed tree pair positions was equal to 6 cm. This value means that the positions of the same tree measured at two inventories differed by 6cm on average. The random error of tree position measurements represented by standard deviation (SD) of average difference was ±28 cm. This error is the measure of precision of individual tree position measurements. The analysis of the standard deviations at different distances from the centre of the inventory plot (at 0.5m wide classes of distances) revealed the increasing trend of standard deviation towards the plot border. The values of relative standard deviation (RD) decreased with the increasing distance from the plot centre following a non-linear trend. The derived model RDm = f(DIST) had the following form:

$$RDM = 1 - e^{(-0.1085\ *\ 0.8849^{DIST})} \qquad [1]$$

and $R^2 = 0.76$. This equation was used to calculate the modelled standard deviations SDm for the specific plot radii. The impact of this error was analysed in the next step using the simulated data.

3.2. Impact of Random Error of Plot Radius (±SDm) on Bias of Tree Level Diversity and Production Parameters

The analysis revealed that the random error of the plot border did not significantly affect the estimates of tree level diversity if fixed-area and concentric plots were used. MANOVA results showed that the interaction of the plot design and the categories of vertical diversity had a significant impact on the tree species richness measure at 95% significance level (F = 2.67, p = 0.03). The results indicated that when fixed-different-area plots were used for sampling, there was a tendency to overestimate the tree species richness measure in the stands with low vertical diversity, while in the stands with moderate vertical diversity we observed a tendency to its underestimation.

In the case of the number of vertical layers, the error of the plot radius did not significantly influence its estimates obtained from the fixed-area plots. MANOVA results revealed that the number of vertical layers was not significantly affected by the main factors separately, but by their interactions, namely: (i) the interaction of plot design and categories of vertical diversity (F = 3.37, p = 0.009), (ii) the interaction of age categories, vertical diversity categories and plot design (F = 1.65, p = 0.006), (iii) the interaction of age categories, tree species richness categories and vertical diversity categories (F = 1.45, p = 0.03). According to the results, there was a tendency to underestimate the number of vertical layers in the stands with moderate vertical diversity if concentric plots were used for sampling, and in the stands with high vertical diversity if fixed-different-area plots were applied.

Similarly, the error of plot radius did not significantly influence the estimates of the proportion of vertical layers if sampling was performed on fixed-area plots. However, if concetric and fixed-different-area plots were used, significant overestimation of the proportion of vertical layers was found. The overestimation was most pronounced in most frequent vertical layers. MANOVA results showed that the three main factors: age category, vertical layer and plot design significantly affected the estimates of the proportion of vertical layers. The impact of the vertical layers and plot design was significant at 99% significance level (F = 22.15 and F = 20.16, respectively with p = 0.000).

In the case of the tree level production parameters, the error of plot radius did not cause a bias in the estimates obtained from fixed-area plots, but caused their significant overestimation in the case of concentric and fixed-different-area plots. However, according to MANOVA analysis, no factors had a significant impact on the estimates of the selected production parameters.

3.3. Impact of Random Error of Plot Radius (±SDm) on Variation of Tree Level Diversity and Production Parameters

The precision of tree species richness was not found to be affected by the random error of the plot radius, but the relative change of the precision of the vertical diversity measure and production parameters fluctuated between −69% and +266% depending on the examined parameter (Table 1) and other factors. The precision of tree species richness was primarily affected by vertical diversity, while the precision of the vertical diversity measure was mainly affected by age category and the occurrence frequency of height layers. The precision of the production parameters was mainly affected by the plot design and age class.

3.4. Impact of Plot Design on the Estimates of Tree Level Diversity and Production Parameters

As shown in Fig. 2, plot design significantly affected the estimates of tree species richness characterised by the

Table 1. Effect of the random error of plot radius (±*SDm = f(DIST,RDm)*) on the precision of examined parameters.

Group of parameters	Parameter	Relative change of parameter precision [%]	
		Min	Max
Species diversity	Number of tree species	−3	+3
Vertical diversity	Proportion of a vertical layer	−5	+69
	Number of vertical layers	−18	+15
Production	Number of trees per hectare	−69	+15
	Basal area per hectare	−68	+266
	Standing volume per hectare	−69	+264

of tree species. Both concentric and fixed-different-area plots significantly underestimated the measure of tree species richness in all categories of vertical diversity, all categories of species richness, and almost all age classes. The underestimation of the number of tree species was greatest in young stands with high level of species richness. With the increasing age, the underestimation was significantly reduced, and in the stands older than 110 years the estimates of tree species richness became unbiased if concentric plots were applied. The estimates of the number of tree species from concentric plots were slightly better than the estimates obtained from fixed-different-area plots. The maximum differences were equal to −3 and −4 tree species, for concentric and fixed-different-area plots, respectively, indicating that the tree species richness measure estimated from sampling based on concentric or fixed-different-area plots was only 66% or 55% of the number of tree species on the site, respectively.

Similar effects of the plot design were shown in the case of vertical diversity characterised by the average number of vertical layers (Fig. 2). Both concentric and fixed-different-area plots significantly underestimated this vertical diversity measure in all categories of vertical diversity, all categories of species richness, and almost all age classes. In the case of fixed-different-area plots, the underestimation was greatest in young stands and decreased with the increasing stand age (Fig. 2). When sampling was performed at concentric plots, the best estimates of the number of vertical layers were in middle-aged stands. Similarly to tree species richness, the estimates of the number of tree layers from concentric plots were better than those from fixed-different-area plots.

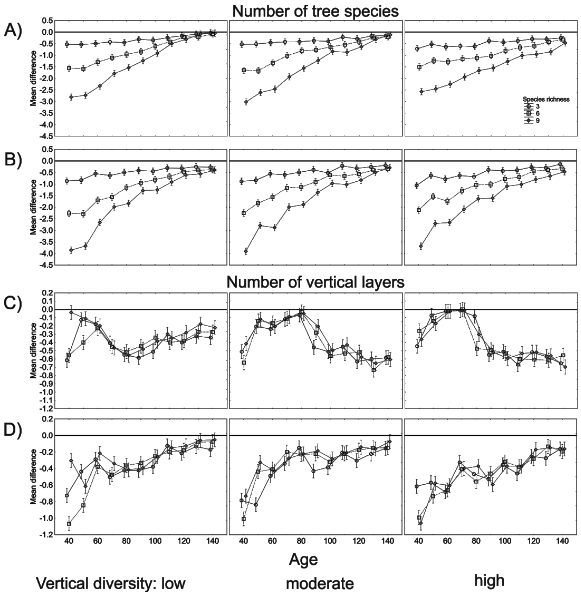

Fig. 2. Differences between the estimates of the number of tree species (A, B) and the number of vertical layers (C, D) at concentric (A, C) or fixed-different-area (B, D) sample plots and the estimates at fixed-area sample plots in categories of species richness (three lines), vertical diversity and age classes.

The analysis of the impact of the applied plot design on the proportion of vertical layers showed that the estimates obtained from concentric and fixed-different-area plots were significantly different from the values quantified at fixed-area plots in the 2nd and 4th vertical layers. The proportions of the other three vertical layers were not influenced by the applied plot design. Similarly, the estimates of the production parameters were not significantly affected by the applied plot design, although sampling at concentric plots had a tendency towards an overestimation of all examined parameters, while sampling at fixed-different-area plots tended to slightly underestimate the parameters.

4. Discussion

In repeated inventories, the position of trees is usually measured only once when the tree is measured for the first time. During the successive inventories, the tree is identified on the base of its polar coordinates, i.e. its bearing and the distance from the plot centre measured before, and only the values of tree parameters are updated. Such an approach ensures that the same trees are identified during every inventory and only ingrowth is added to the list. However, tree position measurement may also be affected by errors resulting from human and/or technological factors, such as imprecise identification of the plot centre, experience with the applied technology, but also from environmental conditions, e.g. slope of the terrain, undergrowth disrupting the laser beam, etc. The data used in the presented study allowed us to analyse such errors because a non-standard approach of re-measuring the polar coordinates of trees was applied in three repeated inventories of the University Forest Enterprise. The results revealed that the overall average bias of tree position measurements between the two independent inventories was 6 cm. This value is not relevant from the practical point of view, and can be neglected.

The random error of tree position measurements fluctuated from 2 to 5% depending on the tree distance from the plot centre. This error may cause problems mainly around the plot border, where it may happen that the trees that are already outside the plot are included in the plot measurements, or vice versa the trees that are situated at the plot border inside the plot are not measured. In the case of circular plots, the problems which trees are inside and which are outside the plot border can also result from the fact that the plot boundary is curved (West 2009). Nevertheless, the analysis of the impact of this random error on the plot values of diversity and production parameters revealed that it does not significantly affect the examined parameters if fixed-area plots are used for sampling. If concentric or fixed-different-area plots are applied, significant bias of production parameters and diversity measures was found. However, the magnitudes of the detected bias were small, and can be from the practical point of view neglected. Although the random error of the plot radius did not have a profound impact on the absolute values of the examined parameters, it influenced their precision (Table 1). Particularly, the precision of the quantified production parameters was significantly affected by the random error of the plot radius, which can lead to incorrect interpretation of inventory and monitoring results.

The analysis of the applied plot design on the production and diversity parameters revealed that the plot design did not have a significant impact on the estimation of production parameters. This corresponds with the previous findings of the works comparing different plot designs (Schreuder et al. 1992). However, from the biodiversity point of view, the results showed that the plot design significantly affected the estimates of both tree species richness and vertical diversity. Concentric and fixed-different-area plots significantly underestimated the number of tree species per plot (Fig. 2). This is caused by the fact that both concentric and fixed-different-area plots cover a smaller number of individuals and/or a smaller plot area in comparison to fixed-area plots. The number of species is known to have a strong positive relationship to the size of the sampled area (Cam et al. 2002). According to Brose et al. (2003), observed species richness is always smaller than true species richness, while the difference between them depends on the sampling intensity and the evenness in species´ abundances.

Motz et al. (2010) compared the estimates of different diversity indices from fixed area sample plots and angle count methods and concluded that fixed area plots are more suitable for consistent estimation of tree diversity. Our results showed that fixed area sample plots are also superior to concentric and variable-size plots (Fig. 2), particularly if biodiversity quantification is one of the main inventory aims.

Permanent fixed-area plots should also be preferred if the main focus of monitoring is on the change of an ecosystem rather than its state (Scott 1998), because such a plot design allows to identify all components of change (Poso 2006). In addition, the impact of possible underlying mechanisms causing the change can be deduced from the information obtained from repeated observations of the same sample (Nusser et al. 1998). From the practical point of view, circular fixed-area plots are easy to establish (West 2009), and simple to measure (Poso 2006). Although their time costs are double the costs of angle count methods and by 12 – 30% greater than the costs of concentric or fixed-different-area plots (Šmelko 2013), fixed-area plots are more efficient for estimating increments of e.g. basal area (Poso & Waite 1995), because calculation problems of concentric or angle count plots related to the compatibility of the successive measurements are excluded (Poso 2006).

On the base of the presented results we can state that the plot design may significantly influence the evaluation of ecological characteristics, which can negatively affect the assessment of their temporal development using the continuous monitoring data. Fixed-area plots seem to be the most suitable sampling units from the point of multi-criteria evaluation of forest status and forest change.

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