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Sampling forest tree regeneration with a transect approach

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Abstract. A new transect approach for sampling forest tree regeneration is developed with the aim to minimize the amount of field measurements, and to produce an accurate estimation of tree species composition and density independent of tree height. This approach is based on the "probability proportional to size" (PPS) theory to assess heterogeneous vegetation. This new method is compared with other approaches to assess forest regeneration based on simulated and measured, real data. The main result is that the transect approach requires about 50% of the time to assess stand density as compared to the plot approach, due to the fact that only 25% of the tree individuals are measured. In addition, tall members of the regeneration are counted with equal probability as small members. This is not the case in the plot approach. The evenness is 0.1 to 0.2 units larger in the transect by PPS than in the plot approach, which means that the plot approach shows a more homogenous regeneration layer than the PPS approach, even though the stand densities and height distributions are similar. The species diversity is variable in both approaches and needs further investigations.
Keywords regeneration, sampling, probability proportional to size, forest inventory.

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Introduction

Forests are dynamic and complex ecosystems, continuously changing under the influence of natural and human disturbances, such as weather events, insects and diseases, deer browsing or timber harvesting (Burschel & Huss 1997). Regeneration is the most dynamic phase of a forest's life-cycle. It is often characterized by a mosaic of small, densely vegetated areas and gaps which makes a representative sampling difficult. Regenerating forest is initially very rich in species, with tree heights varying strongly at a small spatial scale.

Including regeneration assessments into a forest inventory remains a challenging task, which is not only work-intensive, but also associated with a high degree of uncertainty. The current procedure of inventoring regeneration is based on fixed sample areas, often in the form of several rectangular or circular microplots, where all individuals of a certain size are sampled (whole the plot sampling: Branthomme 2004, Polley 2011, US Forest Service 2011). These plots are selected either by stratified sampling of certain conditions (Shatfort et al. 2007), or are fixed in their position in relation to the grid-based sampling of the canopy (Hessenmöller et al. 2011). However, the selection of fixed plot areas versus "probability-proportional-to-size" (PPS) is not the sampling strategy (grid versus stratified design), but the decision to use a variable geometry according to the size of the individuals versus a fixed geometry of a sample plot.

Here we introduce a new approach based on the PPS approach, which is based on the line intersect methodology (LIS). The Line Intersect Sampling (Wagner 1968) records the "hits" on pre-set designed lines, for example plant individuals which are intersected by the line-transect and which are evaluated as sample elements (e.g. Vries 1974, Hansen 1985, Stahl 2000). The initial idea of sampling heterogenous vegetation along transect lines is old, and it was originally termed as the "Buffon's Needle Problem" by George Louis Leclerc, Comte de Buffon (1707-1788). Warren & Olsen (1964) used the line transect to quantify wood quality in clear cuts. In vegetation science, the transect was used to quantify the species composition in heterogenous vegetation (Canfield 1941), and only recently the approach was used to quantify coarse woody debris (Roth et al. 2003, Böhl & Brändli 2007). The general problem emerges with LIS is the orientation of the transect in relation to the topography and wind direction (Roth et al. 2003). The size distribution of individuals can be recognized by LIS in small herbaceous vegetation, but finds its limits in tall intermingled woody vegetation. In contrast, the PPS method recognizes the size as an additional parameter, and in that tall individuals contribute to the sample if they hit the transect line. With increasing height of the individual, the probability increases to be included in the sample. Thus, the plot area increases with the dimension of the individuals. The PPS approach has been successfully applied by Bitterlich (Bitterlich 1948) to estimate the basal area of forest stands.

In the following paper we compare the PPS method with the plot based method to assess density, species composition and height distribution of tree regeneration, because the PPS method promises a major reduction of work time in the field, with an increased representativeness of the vegetation.

Materials and methods

The "Probability Proportional to Size" theory

The starting point of our method is the assumption that the growing space of a tree is approximately proportional to its height. Under natural field conditions, tree height of regeneration varies strongly, with most of the individuals being of small size. Thus, statistical data derived from the samples circular or rectangular plots have a reliability that is inversely proportional to the size of the tree. To overcome this weakness of conventional plot sampling we introduce the PPS-approach. This sampling procedure is based on a transect line, which should be pre-set by a grid-based inventory point. The height of all trees growing at a distance less than their height from the transect line are recorded. Thus, small trees represent a narrow rectangle and tall trees a wider rectangular. Therefore, the new approach overcomes the inherent problem of fixed plots with possible under-sampling of tall individuals. Here, we refer to tree regeneration of up to 3 m, even though the method per se is limited by the size of the individual.

The search area, A, of the transect approach depends on the maximum height (h_{max}) of a tree, the transect length (l), and on whether one or both sides of the transect are considered (S = 1 or 2). It is given by:

$$A = h_{\max} \cdot l \cdot S \tag{1}$$

Denoting the number of recoreded trees with height h by t_h,leads to the density

$$d_h = \frac{t_h}{h \cdot l \cdot S} \tag{2}$$

of trees with height h. The total density of trees $\hat{d}$ can be computed as

$$\hat{d} = \sum d_h \tag{3}$$

Further, we can compute the moments of the height distribution by:

$$\mu_1 = \sum h \cdot \frac{d_h}{\hat{d}} \tag{4}$$

$$\mu_2 = \sum h^2 \cdot \frac{d_h}{\hat{d}} \tag{5}$$

$$\mu_3 = \sum h^3 \cdot \frac{d_h}{\hat{d}} \tag{6}$$

This gives the mean (m), variance (σ) and skewness, γ of the height distribution as:

$$m = \mu_1 \tag{7}$$

$$\sigma = \mu_2 - \mu_1^2 \tag{8}$$

$$\gamma = \frac{\mu_3 - 3 \cdot \sigma \cdot m - m^3}{\sigma^{\frac{3}{2}}} \tag{9}$$

The relative error of any parameter can be derived as

$$rel.error = \frac{(predicted\ value - true\ value)}{true\ value} \cdot 100\% \tag{10}$$

The scattering of the mean value is expressed as a standard deviation.

The diversity of the experimental plots shall be evaluated using Pielou's eveness E (Pielou 1969) and the diversity index H (Shannon 1948), with the input variables R (number of trees species), n_i (number of trees of species i) and N (number of trees):

$$E = \frac{H}{H_{\max}} \cdot 100 \tag{11}$$

and

$$H_{\max} = \ln(R) \tag{12}$$

$$H = -\sum_{i=1}^{R} p_i \cdot \mathrm{h}\ p_i \tag{13}$$

$$p_i = \frac{n_i}{N} \tag{14}$$

Height distribution of regeneration

The method was tested on both simulated and field data. The height distribution is reported, subject to the restriction that the height of small trees in one age class is approximately normally distributed (Kramer & Akca 1994), even though this assumption does not apply to natural regeneration. However, as a result of intra- and inter-specific competition, the height distribution in natural regeneration approaches a normal distribution as the mean height increases (Fig. 1).

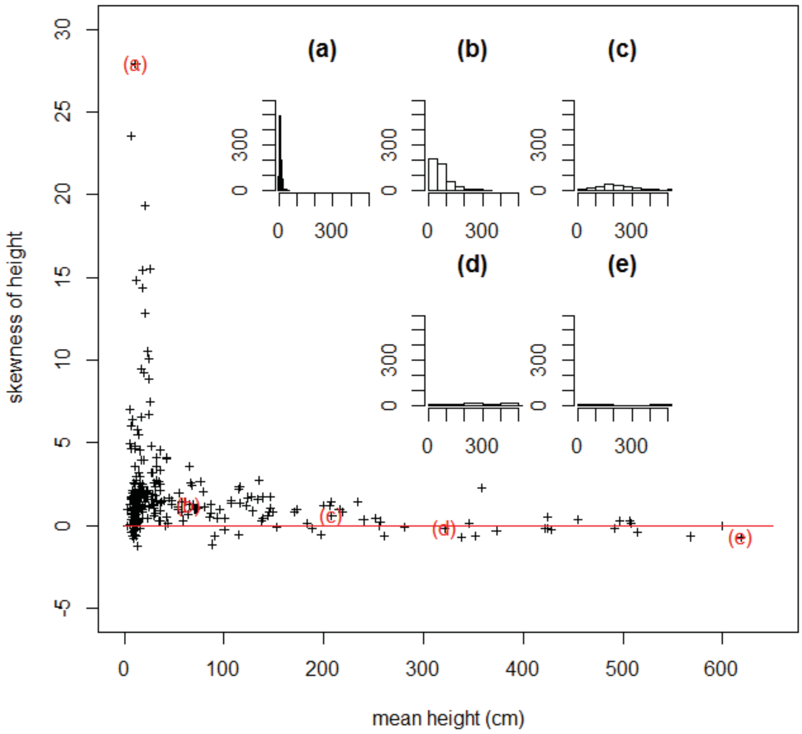

Figure 1 Skewness of height distribution and mean tree height in 265 experimental plots in Schorfheide-Chorin, Hainich-Dün and Swabian Alb. The plots' size is 5x5 m, the data were recorded in 2008. The plots are located in broadleaved and coniferous stands. The subplots inside shows exemplary the height distributions of 5 experimental plots (a) to (e). The skewness of the Gaussain normal distribution is null

Model application

To overcome the problem of skewness, we used three unimodal height distributions in the model simulations: (i) the Gaussian normal distribution and (ii) the uniform or rectangular distribution, (iii) the exponential distribution.

Although the rectangular distribution is not supported by field data, it represents an extreme case and should therefore also be tested.

In this model test, the height range is limited from 0.20 m to 2.00 m, even though in large scale inventories the transect should cover the whole range up to tree size (e.g. DBH = 7 cm). The size limitation of 0.2 to 2 m follows grid based forest inventories (Polley 2011). In the present simulation, the upper limit of 2.0 m is arbitrarily chosen and this height should be adjusted according to the definition of the lower limit of tree dimensions.

Simulated data

For testing the new estimators to distributed trees on 30 squares of 100 m side length, we used the software Stochastic Geometry STG 4.1 (Stoyan 1995)(Fig. 2, Appendix 1). The underlying processes are the random models by Bernoulli and Poisson, the hard-core models by Matern and the cluster models by Thomas (Stoyan 1995). The point density per square meter ranges from 0.0150 to 1.6000, with a median of 0.3459. To describe the spatial distribution of points, the index of Clark-Evans (Clark & Evans 1954), with edge correction after Donelly (1978) is used: each 10 squares show an aggregated (index value: 0.13 to 0.53), a random (index value: 1.0 to 1.07) and a regular point distribution (index value:

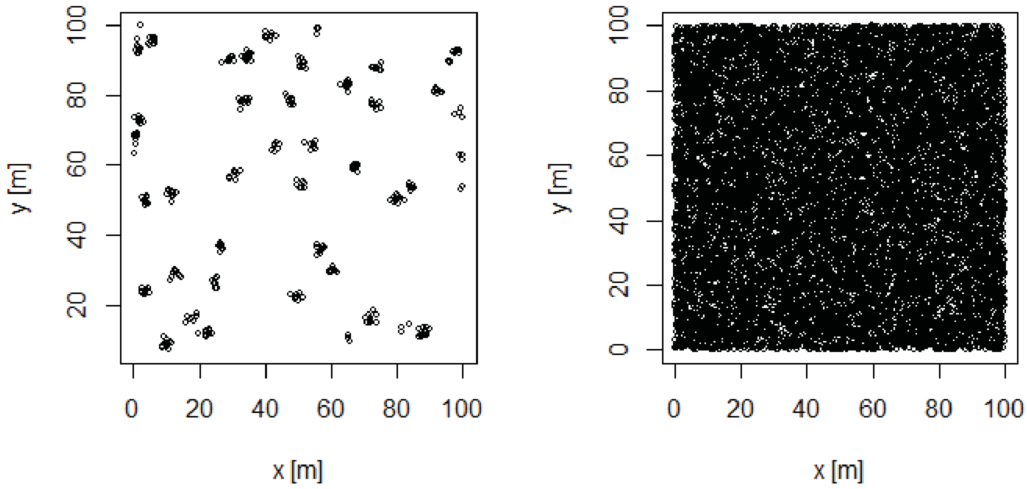

Figure 2 Two extremes of the 30 simulated stands. Left: 394 points with a Clark-Evans-Index of 0.24 (aggregated, No. 12 Appendix 1). Right: 16,000 points with a Clark-Evans-Index of 1.00 (random, No. 20 Appendix 1)

1.19 to 2.01)(Appendix 1). These pre-set ranges are guided by regeneration densities from a large-scale forest inventory in Germany (Hessenmöller et al. 2011).

Using these 30 point distributions, the three described height distributions and combinations of a transect length from 1 to 100 m and a number of transects from 1 to 25 per stand, 50,000 variants were selected. Every of these inventory variants were repeated 1,000 times. The modelled tree heights are limited to a range of 0.20 to 2.00 m (Fig. 3), and were created with the software R 2.14 (R Development Core Team 2011). The sample simulation was always on both sides of the transect line.

Experimental data

In parallel to the simulated transect inventories, we conducted inventories on rectangular and on circular plots. The inventory variants are identical to the transect inventories in height distribution and identical with respect to the number of circles. The circle radius was chosen so that area of the circle, and the search area of the transect *A* (s. Eq.1) have the same area (radius from 1.128 m to 22.280 m). The center of the circle is located at the starting point of the transect. The transect is always running in a random direction. To avoid problems at the boundary of the squares, we assumed a periodic forest, having this square as a fundamental domain.

Field measurements were made in four different forest stands in Thuringia, Germany. The first stand (Stand 1) is an uneven-aged *Fagus*-hardwood forest near the village of Rehungen (51.371 lat., 10.524 long., WGS84) in central Germany and the measurements were made in five regeneration plots of 2 x 4 m. All trees in the height range from 0.20 to 2.00 m were recorded with by tree species and tree height. One pre-set 4 m edge of the plot was used as transect line, where trees on one side of the line was recorded only.

The second stand (Stand 2) is a 130-years old mixes *Fagus-Picea* - forest, with horizontally and vertically structured natural regeneration of beech and spruce (Breitenbach: 50.6793 lat., 10.4934 long., WGS84). Three transects (lengths of 20 m, 20 m, 3 m) and three corresponding sample circles (radius of 5.05 m, 5.05 m, 1.95 m) were established.

The third stand (Stand 3) is a 110-years old *Picea* stand, with highly variable regeneration (Breitenbach: 50.6804 lat., 10.4968 long.,

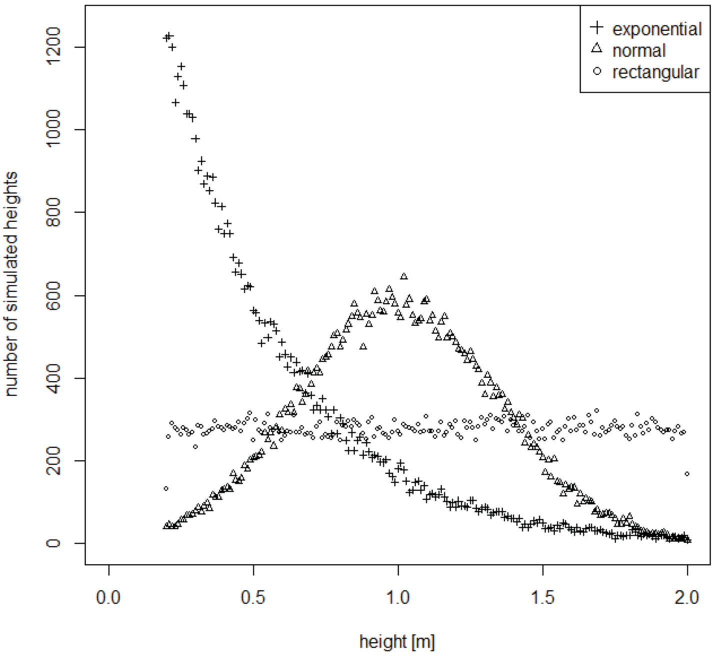

Figure 3 Distributions of simulated tree heights

WGS84). The regeneration can be found in spatially variable patterns, with nearly similar height. Three transects (lengths of 20 m, 10 m, 3 m) and corresponding sample circles (radius of 5.05 m, 3.57 m, 1.95 m) were investigated.

The fourth stand (Stand 4) is a stand which was affected by wind-throw (hurricane Kyrill) and a regeneration-stand with birch, pine, larch and spruce (Breitenbach: 50.68242 lat., 10.49556 long., WGS84). Three transects with 10 m lengths and three sample circles with 3.57 m radius were investigated.

On stands 2 to 4, both sides of the transect line were recorded. The tree position in relation to the transect (e.g. the distance on the transect) was additionally measured, in order to obtain a measure of the spatial distribution of the regeneration (i.e. Eveness, Pielou, 1969). The center of the circle is located at the starting point of the transect again and runs always in the North direction.

Trees up to two meters can easily be turned over and bent. Thus, without causing any damage one can rapidly check whether the height of an individual is bigger or smaller than the distance to the transect line. If the tree hits the line, the exact height must be measured and recorded. This process leads to significant shortening of the time spent for sampling in the field, because only a limited number of trees is measured, rather than monitoring all individuals on a given plot area.

Results

Results from simulations

In the following we use only modelled data, in which the model transects are compared with the total distribution of the model stand.

The transect approach provides an unbiased estimate. The relative error is on average 0.00478%, with extreme values of -19.73%, and +51, 92%. In comparison, the relative error using the sample circle method is 0.00559%, with extreme values of -24.38% and 21.90%. The largest discrepancies are between real and estimated values and are positioned above those offered by aggregate point distributions

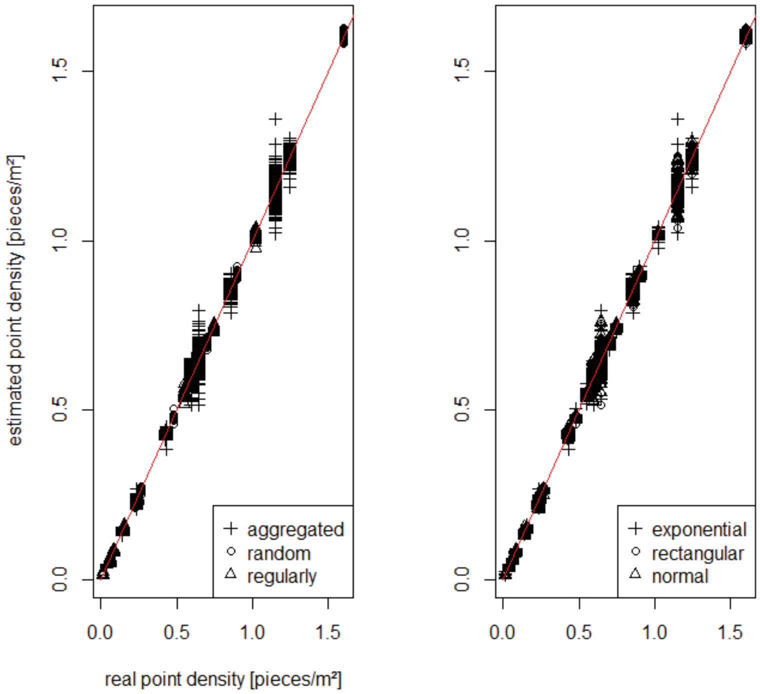

Figure 4 Results of testing the PPS-transect approach with 50,000 simulations. The x-axis is in each case the real density of points, and the y-axis, the estimated point density. In the left image, the point distribution types were specially emphasized, on the right the underlying distribution of the height of trees

with exponential height distribution (Fig. 4).

The transect approach requires a smaller number of sample trees to be measured, as compared to the sampling of a fixed area. In model simulations, in the case of an exponential height distribution, 28.34% (±0.78%) of the trees of the comparable sample circle inventory were required for height measurement, in the rectangular height distribution only 55.13% (±0.79%) and with normal height distribution only 50.23% (±0.76%) are measured. Across over all simulations, the transect method record 44.57 % (±11.66%) of the trees, which need to be recorded in a fixed sample circuit method of comparable area.

Comparison of the transect approach with real plot data

In stand 1, the transect approach was compared in the field with the rectangular plot measurements of 8 x 4 m area in a deciduous forest regeneration. The transect and the plot were measured using 2 m ranging poles marked at 50 cm intervals and one folding rule. The transect sampling took 7 to 30 minutes for each plot (Table 1), including the set up of the plot. On each experimental plot, there were only few border trees, whose distance from the transect line had to be measured exactly, in order to find out if the tree hits the transect or not. The high flexibility of the trees in the regeneration stage makes it possible to bend them over towards the transect line and to see if the tree is part of the transect sample or not.

The time required to take the data by the transect method is between 30 and 60 minutes, shorter than a conventional plot survey. The time-saving was largest with short regeneration, which, generally has a high density and require a lot of time in the whole plot surveys.

In the stands 2 to 4, the two sampling meth-

Table 1 Results of the regeneration inventory in the forest of Rehungen (Stand 1). The full recordings amount to an area of 4 x 2 m. Trees were recorded from 0.20 to 2.00 m height. The transect inventory took place on one side, the reference line was west. The plots A, B, C are inside a fence

	Unit	A	B	C	D	E
Density real	pieces/8 m²	241.0	193.0	132.0	190.0	264.0
Density predicted	pieces/8 m²	248.0	220.0	262.0	227.0	242.0
Density error	%	2.9	14.0	98.5	19.5	-8.3
Mean height real	cm	84.0	94.0	94.0	29.0	45.0
Mean height predicted	cm	85.0	79.0	61.0	29.0	44.0
Mean height error	%	1.2	-15.7	-35.2	1.6	-2.6
Proportion sampled trees	%	44.0	45.0	61.0	17.0	20.0
Time duration/transect sample	min	30.0	20.0	13.0	8.0	7.0

Table 2 Results of the regeneration inventory in Stand 2

		Sample circles				PPS-transects			
	unit	C1	C2	C3	C all	T1	T2	T3	T all
length	[m]					20.00	20.00	3.00	
radius	[m]	5.05	5.05	1.95					
measured trees	[pieces]	75	454	38	567	8	17	15	40
point density	[p/m²]	0.936	5.667	3.180	3.261	0.755	1.368	6.203	2.775
time duration	[min/sample]	NA	45	4	49*	NA	4	4	(8)*
time duration	[min/tree]	NA	0.10	0.11	0.09*	NA	0.24	0.27	(0.20)
tree height	[cm]	38.04 ± 18.13	37.37 ± 19.61	33.97 ± 9.99	36.46	30.38 ± 14.36	35.71 ± 13.78	44.60 ± 14.28	36.90
Species richness *R*		3	4	2	5	2	3	1	3
Shannon's index *H*		0.193	0.191	0.337	0.208	0.562	0.444	0.000	0.381
Pielou's eveness *E*		0.176	0.138	0.485	0.129	0.811	0.404	(0)	0.347

Note: * - two samples only

Table 3 Results of the regeneration inventory in Stand 3

		Sample circles				PPS-transects			
	unit	C1	C2	C3	C all	T1	T2	T3	T all
length	[m]					20.00	10.00	3.00	
radius	[m]	5.05	3.57	1.95					
measured trees	[pieces]	211	194	497	902	230	51	99	380
point density	[p/m²]	2.634	4.845	41.590	16.356	8.230	8.920	32.623	16.591
time duration	[min/sample]	30	19	36	85	41	8	14	63
time duration	[min/tree]	0.14	0.10	0.07	0.09	0.18	0.16	0.14	0.17
tree height	[cm]	81.49 ± 46.01	36.74 ± 23.38	41.32 ± 11.84	53.18	89.00 ± 43.76	35.76 ± 26.63	52.51 ± 10.07	59.09
Species richness *R*		4	7	4	7	8	3	4	9
Shannon's index *H*		0.288	0.657	0.118	0.322	0.310	0.725	0.211	0.449
Pielou's eveness *E*		0.208	0.338	0.085	0.165	0.149	0.660	0.152	0.204

Table 4 Results of the regeneration inventory in Stand 4

		Sample circles				PPS-transects			
	unit	C1	C2	C3	C all	T1	T2	T3	T all
length	[m]					10.00	10.00	10.00	
radius	[m]	3.57	3.57	3.57					
measured trees	[pieces]	31	174	81	286	9	44	15	68
point density	[p/m²]	0.774	4.346	2.023	2.381	0.708	3.309	1.370	1.796
time duration	[min/sample]	5	21	18	44	4	8	3	15
time duration	[min/tree]	0.16	0.12	0.22	0.15	0.44	0.18	0.20	0.22
tree height	[cm]	36.16 ± 20.65	70.87 ± 31.85	52.59 ± 23.79	53.21	80.89 ± 36.32	79.22 ± 33.10	62.07 ± 22.75	74.06
Species richness *R*		6	6	5	9	3	5	3	5
Shannon's index *H*		1.352	1.039	1.312	1.291	0.849	1.114	0.950	1.150
Pielou's eveness *E*		0.755	0.580	0.815	0.587	0.773	0.692	0.865	0.714

ods (i.e. the fixed sample area and the transect approach) are compared with respect to their results (see Tables 2, 3, 4). In almost all transects (8 of 9) were recorded fewer trees than in the comparable sample circle areas (Tables 2-4).

In summary, over three stands, the transect method collected 488 trees, using a total transect length of 106 m. This was compared with 1,755 trees on 424 m² sample circle area. Thus, the transect method is based on about a quarter of the whole plot tree population. This results in a much shorter time for investigation. The transect method required about 86 minutes for 8 double-sided transects (including the measurement of the position along the transect line), while the circular plot of comparable area required more than twice the time (178 minutes). A single transect-meter recording trees on both sides requires about 1 minute.

The detection of a single tree happens in the sample circle process faster, however, in this case 9.93 trees can be recorded in one minute, in the transect method there are 5.58 trees per minute.

Table 5 Comparing the estimated mean values of point density and tree height between the transect method and the sample circuites. The *t*-value is respectively non significand difference

	Point density	Tree height
Stand 2	0.836 (n.s.)	0.924 (n.s.)
Stand 3	0.988 (n.s.)	0.794 (n.s.)
Stand 4	0.677 (n.s.)	0.149 (n.s.)

Comparing both methods, there was no significant difference between the two methods with respect to stand density and mean tree height (Table 5). In the stands 3 and 4 using the transect method more tree species were recorded compared to the fixed plots (Tables 3,4). Looking at the number of trees per species, on average the transect method recorded 13 trees per species while the fixed plot, recorded 46 trees per species. By the relocation of the circle to an imaginary square, the tree species diversity of a population is better represented by a circle than by a rectangular plot. This is evident from Pielou's evenness (see equation 11). It is estimated in all three stands to be lower by each of the sample circles than by the transect approach (Tables 2-4). Even though the species diversity was similar in both approaches, the transect approach appear more likely to detect rare species, but this needs further investigations. This is confirmed by the fact that the fixed plots repeats measurements on the same species, while the transect approach distributes the measurements across the whole range species.

With increasing transect length or circle size area, there are more trees detected by the sample and the accuracy of the estimate increases, as the point density converges at a value (Fig. 5). This is particularly noticeable in the stand 2 in which the estimates of both 20m transects run well together in their total length (Fig. 5a). Similar results arise from the three transects in the stand 4 (Fig. 5c) and the two long transects in the stand 3 (Fig. 5b).

Discussion and conclusions

The PPS method applied along a transect emerges to be a more suitable methodology in describing tree regeneration than the fixed plot method. Thus, our study confirms earlier observations that transects are the appropriate tool to observe heterogeneous distributions, such as in dead wood (Böhl & Brändli 2007), species distribution (Kreeb 1983), and timber quality (Warren & Olsen 1964).

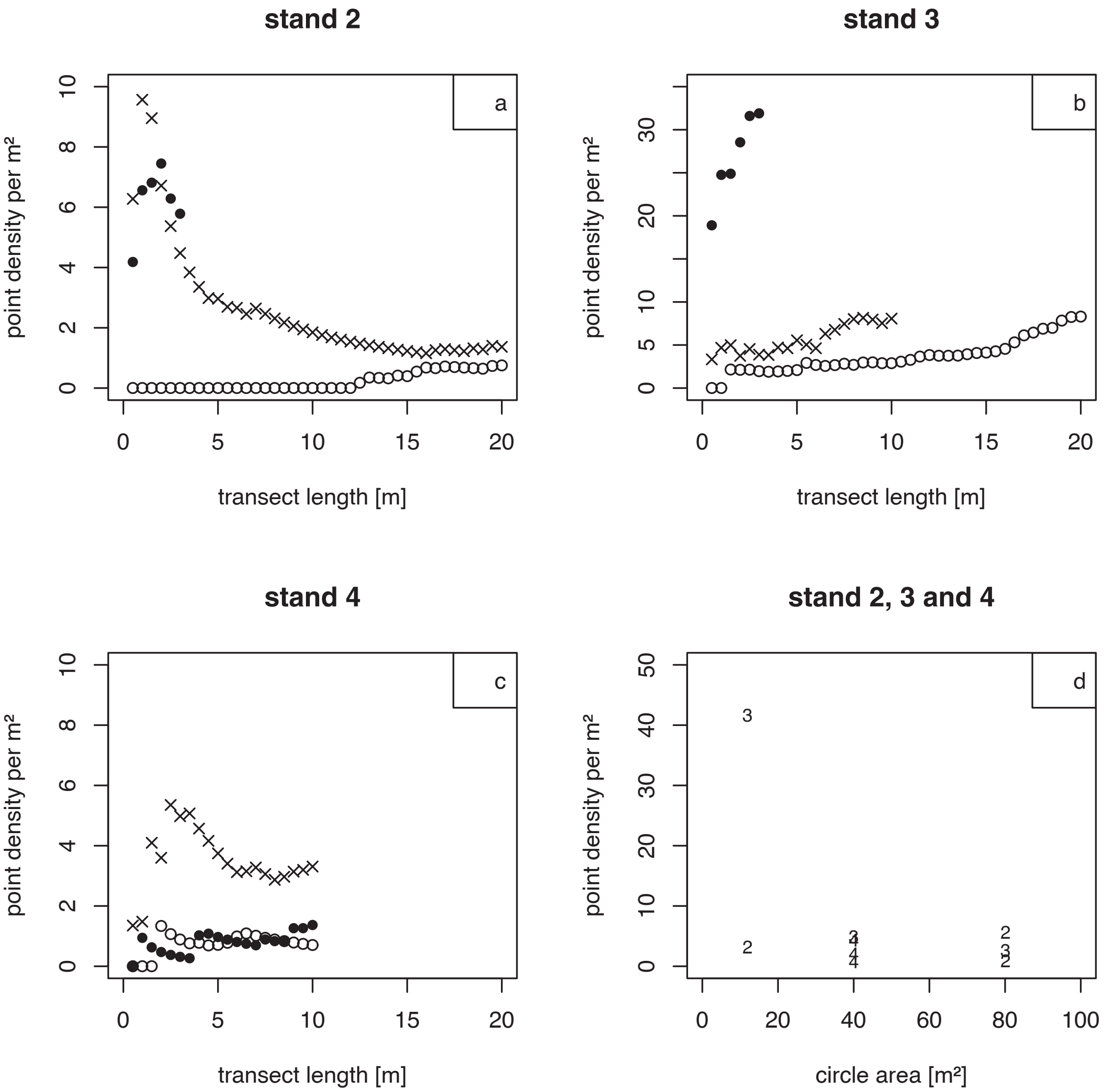

Figure 5 The influence of the transect length on the estimation of the point density. Figures a, b and c describe the relationship in the stocks 2, 3 and 4. Here each of 3 transects were recorded, the figure shows the evolution of the point density, as each transect will be extended by 0.5 m.
The figure d shows the results of the point density estimate by sample circles, the number describes the corresponding stand

One unresolved problem remains: namely to identify the optimum length of the transect. In the present study we relied on the length of the established plots, presently used to quantify regeneration. However, to reduce the measurements to a minimum, the transect length and also the plot size should be adjusted according to the height of regeneration. The transect length will also be different, if the aim is to study forest tree-species composition or damage by deer browsing. It would be advisable to estimate the total number of tree species in the study area, or total deer damage, and to adjust the transect length such that these parameters to be captured with the desired accuracy. However, the quantity is á priori unknown, and must be approximated by pre-investigations. A variable transect length based on tree species distribution or on clumping of regeneration is supported by the PPS method. This means that the transect has to be extended or reduced until the sample consists of a prescribed number of trees, based on the fact that the standard deviation of an estimate is approximately proportional to the square root of the number of observations. At this stage, more field data are required to develop an algorithm for this adjustment.

This study shows that this method quantifies forest regeneration concisely, based on a minimal number of sampled trees. The new method can be used to estimate the regeneration density, biomass and species richness, as well as tree damages. The transect-PPS approach is a monitors regeneration with increased efficiency (i.e. less work-time in the field) without bias. In comparison with fixed area plots, less trees are sampled for the same overall area of regeneration. The estimation of plant density, the height distribution and the tree species diversity generally is achieved to a high accuracy but requires further investigations.

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Appendix

Table 1 The 30 generated point distributions for simulations in virtual test stands

No.	X_{min}	X_{max}	Y_{min}	Y_{max}	Number of points	Clark & Evans index	Spatial pattern of points
1	0	100	0	100	9,000	0.996	random
2	0	100	0	100	150	1.027	random
3	0	100	0	100	2,259	1.026	random
4	0	100	0	100	7,436	1.217	regular
5	0	100	0	100	1,403	0.427	aggregated
6	0	100	0	100	4,267	0.532	aggregated
7	0	100	0	100	2,391	1.369	regular
8	0	100	0	100	4,798	1.002	random
9	0	100	0	100	6,379	0.997	random
10	0	100	0	100	7,000	1.005	random
11	0	100	0	100	2,398	1.000	random
12	0	100	0	100	394	0.244	aggregated
13	0	100	0	100	2,652	1.074	random
14	0	100	0	100	800	1.046	random
15	0	100	0	100	11,510	0.267	aggregated
16	0	100	0	100	4,320	0.463	aggregated
17	0	100	0	100	2,323	1.414	regular
18	0	100	0	100	8,533	0.251	aggregated
19	0	100	0	100	5,933	0.194	aggregated
20	0	100	0	100	16,000	0.996	random
21	0	100	0	100	10,201	2.012	regular
22	0	100	0	100	5,476	1.960	regular
23	0	100	0	100	1,521	1.930	regular
24	0	100	0	100	585	1.190	regular
25	0	100	0	100	150	1.540	regular
26	0	100	0	100	156	1.300	regular
27	0	100	0	100	845	1.433	regular
28	0	100	0	100	12,456	0.400	aggregated
29	0	100	0	100	6,432	0.130	aggregated
30	0	100	0	100	2,325	0.330	aggregated