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Continuous cover forestry: Which sampling method should be used to ensure sustainable management?☆

Mathias Leiter *, Hubert Hasenauer

Department of Forest- and Soil Sciences, Institute of Silviculture, University of Natural Resources and Life Sciences, Peter-Jordan-Str. 82, A-1190, Vienna, Austria

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ABSTRACT

The transformation of even-aged forests into continuous cover forests to improve resilience and to promote biodiversity in Central Europe necessitates a re-evaluation of forest sampling designs. This study examines the precision and accuracy of two widely used terrestrial sampling methods, namely Angle Count Sampling and Fixed Area Plot Sampling. By simulating multiple samples in typical well-established Plenter forests in Switzerland, we analyse the error components and variabilities of the different methods for three key stand parameters: stem number per hectare, basal area per hectare and annual basal area increment per hectare. Our results suggest that, depending on the parameter of interest, the standard deviation, and the acceptable margin of error, the number of needed sample plots exhibits a large variation. Since the key stand parameters for ensuring sustainability in Plenter forests are the stem number by diameter at breast height class and the basal area increment, our results suggest that a Fixed Area Plot with 300 m^2 circles is the best compromise between cost efficiency and precision for the sampled Plenter forest data. Alternatively, a Fixed Area Plot of 500 m^2 or a combined Angle Count Sampling method with a basal area factor of 4 m^2/ha and a 200 m^2 Fixed Area Plot may be considered.

1. Introduction

Historically, uneven-aged Plenter forest management was considered to be unprofessional because forest managers had difficulties controlling sustainability (Cotta, 1804). Plenter management was even prohibited in some parts of Europe (O'Hara et al., 2007; Schütz, 2001), out of fear of unrestrained and unsustainable harvesting. In contrast, even-aged forests were promoted as being sustainable (Hundeshagen, 1826), and they were easy to monitor as well as yield-tables based on empirical data had been developed to guide even-aged forest management (Tesch, 1980). With the industrialization during the 19th century, associated with a population increase, an enormous demand for forest resources became evident. Fast-growing tree species such as Norway spruce (*Picea abies* (L.) H. Karst.) and pine (*Pinus* spp.), growing in even-aged forests were promoted within and beyond their natural range (Spiecker et al., 1996). Today, many of these even-aged homogenous stands are transformed into more diverse forests such as Plenter forests (Griess et al., 2012; Pretzsch et al., 2013; Vacek et al., 2021), to increase the resilience and to promote biodiversity.

Plenter forests are a form of a selection cutting system, semi-synonymous with continuous cover forests, "Dauerwald", uneven-aged or multi-aged forests (Pommerening and Murphy, 2004). Depending on the initial stand, the transformation process towards a continuous cover forest takes several decades (Hilmers et al., 2020; Neumann et al., 2023; Reventlow et al., 2021; Sterba and Ledermann, 2006). With a change from even-aged towards uneven-aged Plenter forest management, the differences amongst forest stands of different age classes decline, but the variation within a given forest stand increases. Plenter forests cannot be stratified by age class. Thus, typical yield-tables developed for managing even-aged forest stand development increasingly diverge from the actual forest development, creating an old and well-known problem: How do we control sustainability in Plenter forests?

De Liocourt (1898), Kerr (2014), and Meyer (1933) describe sustainability in Plenter forests as the maintenance of a balanced diameter distribution and growing stock. Forest managers consider the distribution of DBH (diameter at breast height) classes as a valuable approach to control heterogeneous forest stands (O'Hara and Gersonde, 2004;

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* Corresponding author.
E-mail address: mathias.leiter@boku.ac.at (M. Leiter).

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Schütz, 1997). It can be seen as an equivalent to the age class distribution of even-aged forests, namely, a tool to analyse strategic objectives, i.e., sustainability (Schütz, 2001). The DBH class distribution takes the form of a negative exponential relationship (O'Hara and Gersonde, 2004; Schütz, 1997), also called the "reverse-J distribution", based on an ideal pre-defined DBH class distribution for a given Plenter forest stand. For large forest areas, the DBH class distribution of a regular even-aged forest may show similar behaviour to a single Plenter forest stand (Schütz, 1997). The q factor, a way to quantify this reverse-J curve was developed by Meyer (1943), is the ratio of trees in a DBH class next to the larger DBH class (Meyer, 1943). Only the number of trees exceeding this number of required trees per DBH class are harvested to maintain the Plenter equilibrium (O'Hara and Gersonde, 2004). Nevertheless, using only the q factor for estimating the sustainable development of an uneven-aged forest, my lead to considerable misinterpretations by forest managers, as the reverse-J distribution might not always be the optimal base-line scenario for uneven-aged management (O'Hara, 1996, 1998). Schütz (1997, 2001) argues that the estimation of n_{10}, the number of stems in the DBH class to reach 10 cm, plays a significant role in defining the Plenter equilibrium, since it determines the "ideal" number of stems in all the following DBH classes.

While n_{10} can be calculated as a function of the stand volume, it might be important to accurately estimate n_{10} when sampling in Plenter forests. The problem with getting an accurate representation of the DBH class distribution is that large samples are required (Janowiak et al., 2008), suggesting that other estimators for sustainable management in Plenter forests should be used as well. O'Hara et al. (2007) assessed sustainability by estimating stand density, tree species diversity, basal area increment, and stand structure (the horizontal and vertical distribution of trees), according to the criteria of the Montreal Process (Montréal Process Liaison Office, 2015). Growing stock, a measure for the light conditions, may also be a good indicator of sustainability, as it influences the regeneration process (Schütz, 1997).

Forest inventories are needed to provide information and to control sustainability with reasonable statistical precision as well as costs (Avery and Burkhart, 1994; Bitterlich, 1949). Compared to a full forest census, such as the control method used in the past (Biolley, 1920; Dvorak, 2000), forest sampling is less time consuming and cheaper (Dvorak, 2000; Kramer and Akça, 2002). The drivers of any sampling design are the expected variation and the precision which must be achieved. Many forest sampling processes have been developed (Bitterlich, 1984; Gregoire and Valentine, 2008; Grosenbaugh, 1958; Husch et al., 2003; Iles, 2003; Kramer and Akça, 2002), which may range from Fixed Area Plot Sampling (FAPS) or Angle Count Sampling (ACS), to different grid sizes and permanently or temporarily established plots for data recording (Avery and Burkhart, 1994). The result of any sampling process is always a mean value for a given parameter (e.g., basal area in m^2/ha or number of trees/ha) with the corresponding variation (standard deviation), which can be upscaled to the sampled forest area. The two common terrestrial forest sampling methods in Europe (Pucher et al., 2022; Vidal et al., 2016) are ACS and FAPS. ACS, also known as horizontal point sampling, variable-radius plot sampling, or Bitterlich sampling (Bitterlich, 1949), is a sampling method with variable plot size according to DBH. It is an application of selecting trees with a probability proportional to the DBH. The maximal distance a tree can have from the centre of the sampling point is the ratio of its DBH and the chosen basal area factor (BAF) (Grosenbaugh, 1958). The most used BAF in forest inventories in Austria and the national forest inventories of Austria and Germany is 4 m^2/ha (Bitterlich, 1984; Pucher et al., 2022; Vidal et al., 2016), indicating that a selected tree represents 4 m^2/ha in basal area. With declining BAF (e.g., 2 m^2/ha and 1 m^2/ha), the probability of a tree being sampled increases and thus more trees will be included at a given sampling point. FAPS defines a fixed circle or rectangle and every tree located in the plot is sampled with the same probability proportional to the frequency (Avery and Burkhart, 1994). A special variant of FAPS are concentric sample plots, which differ in size according to a selected threshold DBH but the same central point (Gabler and Schadauer, 2007). In this study, we decided not to include concentric sampling plots because the combination in size varies by the chosen DBH limit and thus there is a similarity to ACS. Common plot sizes for sampling forests may range between 200 and 500 m^2 (Pucher et al., 2022; Vidal et al., 2016). An important issue in securing sustainability in diverse forests is the collection of data to derive the sustainability indicators (Dvorak, 2000). Most sampling designs and statistical methods in Europe have been used in even-aged forests, as plenter forests covered only 400,000 ha in Central Europe (Schütz, 2001). Thus, an essential question remains: Are sampling methods commonly used in even-aged forests able to estimate stand parameters with sufficient precision and accuracy in Plenter forests?

This information is critical because the shift from uniform to diverse forests affects the distribution and variety of stand parameters (Oderwald, 1981): With increasing irregularity and clumping of trees within a stand, the variation between samples increases (Oderwald, 1981; Sukwong et al., 1971).

The purpose of this study is to analyse the variability, accuracy, and precision of the two different sampling methods commonly used for forest inventories (i) Angle Count Sampling (ACS) and (ii) Fixed Area Plot Sampling (FAPS) within an uneven-aged Plenter forest. We are specifically interested in assessing:

(i) The variability in sampling three key stand parameters: Stand density expressed as the stem number per hectare (N/ha), basal area per hectare (BA, m^2/ha), and the annual basal area increment per hectare (ABAI, m^2/ha/).
(ii) The precision of the resulting sampling estimates by tree population parameter, expressed as the confidence interval.
(iii) Finally, we provide examples for calculating the number of inventory plots by stand parameter according to the standard deviation and a predefined margin of error for an uneven-aged Plenter forest area.

2. Material and methods

2.1. Plenter forest data

For our study, we obtained the famous long-term Plenter forest research plots from Switzerland, established at the beginning of the 20th century and since then, managed accordingly. These forests are part of the Swizz Experimental Forest Management network (Forrester et al., 2021). For further details regarding the management of the plots, we refer to O'Hara et al. (2007) and Zingg et al. (2009, 1999). All trees have been mapped and monitored since their establishment, with a remeasurement interval ranging from 6 to 10 years. The dominating tree species are Norway spruce (*Picea abies* (L.) H. Karst.), silver fir (*Abies alba* Mill.), and European beech (*Fagus sylvatica* L.).

For our study, we selected nine stands with an identical eight-year remeasurement interval between two surveys. The DBH threshold of the field DBH measurements was set to 8 cm (Forrester et al., 2022), but some trees with a DBH ranging from 7 to 8 cm were also measured. We chose to include these trees in our experiment. For more details on the site characteristics, DBH class distributions and major tree species of the original Swizz Plenter forest stands see Table A.1, Fig. A.1, and Forrester et al. (2022).

2.2. Creation of the composite Plenter forest stand

We controlled potential edge effects due to irregularly shaped edges and unclear definitions of stand boundaries of the Plenter forest stands by creating a 50 × 50 m (= 2500 m^2) square at a random point inside the nine research plots. We only selected points that did not result in an overlap of the square and the edge of the stand. Next, we combined the nine squares into a new 150 × 150 m "composite Plenter Forest" of

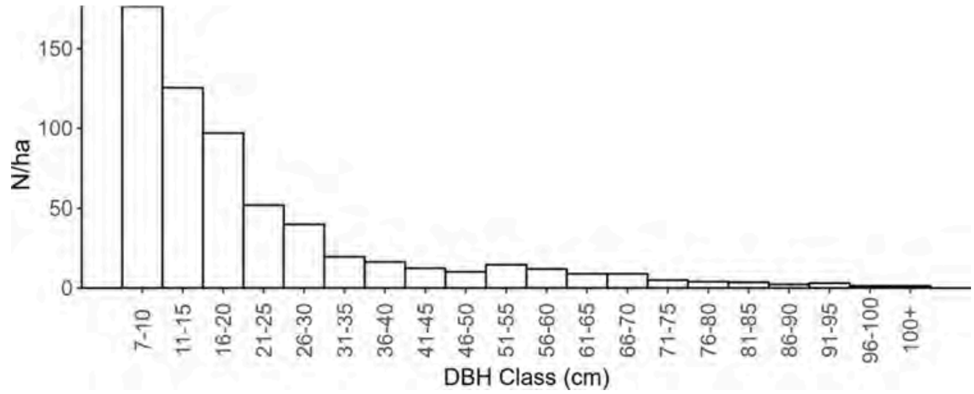

Fig. 1. Stem number (N/ha) versus diameter at breast height (DBH) for the composite Plenter forest created from 9 long-term Swiss Plenter forest research plots. The Plenter forest represents a well-balanced revers J-shaped distribution.

22,500 m^2 in size (see Fig. A.2) and compared the DBH class distribution of our composite Plenter forest to real Plenter forests.

2.3. Sampling in the composite Plenter forest stand

For any inventory, information on stem number, basal area, basal area increment, volume and, volume increment is essential to ensure sustainability. While in even-aged forests, a balanced age class distribution is commonly used as measure for sustainability (Hundeshagen, 1826) in Plenter forests, age classes are no longer detectable and thus increment becomes the key driver for ensuring sustainability (O'Hara et al., 2007; Schütz, 2001). Since volume and volume increment cannot be measured directly, we used basal area and annual basal area increment. This ensures that only measured data and no additional processing (e.g., to estimate volume) is needed.

In the analysis, we used three key stand parameters, (i) stand density expressed as stem number per hectare (N/ha), (ii) basal area (BA, m^2/ha) as the sum of the individual tree basal areas according to the DBH per hectare and (iii) the change in basal area – the annual basal area increment (ABAI, m^2/ha/year) – calculated as the mean basal area change for the selected 8-year growth period using the starting value method. For the ACS plots, ABAI was calculated as the change from time 1 to time 2, multiplied by the number of the estimated trees of that size at time 1, plus the BA from trees that entered the stand between time 1 and time 2. The ABAI of the FAPS plots resulted from the difference in BA between time 1 and time 2 plus the BA of the removed or dead trees. We chose the two most recent inventories of the stands that had a time gap of 8 years in-between. For the static parameters, such as stand density and basal area per hectare, we used the snapshots of the later inventory. To calculate the basal area increment, we used the snapshots at time 1 and repeated the sampling process at the same points in a snapshot at time 2.

For each sampling method, we analysed three sampling variants (= total of 6): (i) Angle Count Sampling (ACS) with a basal area factor (BAF) of 4 m^2/ha, 2 m^2/ha, and 1 m^2/ha, reflecting that with declining BAF the probability of trees to be included at a given sampling plot increases; (ii) Fixed Area Plot Sampling (FAPS) with plot sizes of 500 m^2 (Radius $r = 12.62$ m), 300 m^2 ($r = 9.78$ m), and 200 m^2 ($r = 7.98$ m). While for the FAPS, the radius of the plot area determines a fixed distance between the plot centre and each tree to be selected, ACS selects a tree to be sampled based on the proportion between the distance from the plot centre and the DBH of that tree. The BAF defines the proportion and thus the maximum radius (R_{Border}) for a given tree:

$$R_{Border}(m) = \frac{DBH\ (cm)}{2\sqrt{BAF}} \quad (1)$$

Where DBH is the diameter at breast height and BAF the chosen basal area factor. For example, at a BAF of 4 m^2/ha, a tree with a DBH=10 cm has to be within a distance from the plot centre of $R_{Border} = 2.5$ m to be selected, while the same tree recorded with a BAF of 1 m^2/ha, has a maximum distance of $R_{Border} = 5$ m, respectively. The maximum distance increases proportional with increasing DBH and decreasing BAF: For example, a tree with a DBH=60 cm and a BAF=4 m^2/ha, exhibits R_{Border}=15 m, and for a BAF=1 m^2/ha, the maximum distance would be $R_{Border} = 30$ m. To show the differences in the likelihood of a tree to be sampled between ACS and FAPS we calculated the probability of inclusion for the different DBH classes. For each of the six variants, we simulated 1000 inventory plots. The inventory plots were chosen randomly from an infinite set of floating circles and points inside the composite Plenter forest (Brus, 2022). To account for the underrepresentation of edge trees, when the centre of a sample cannot lie outside the stand, edge-correction was applied using the mirage method (Gregoire and Valentine, 2008; Schmid-Haas, 1969).

2.4. Analysis

The mean and the standard deviation (SD) for each of the three stand parameters per method and variation were calculated using the 1000 sampling simulations. Additionally, the mean number of sampled trees and its SD was calculated. We compared the sampling means of each method with "true" values from the census.

To analyse the sampling variability of the three key stand parameters, we compared the results of each of our 1000 sampling simulations with the "true" values from the census for each method (ACS vs. FAPS), variant and stand parameter, which can be expressed as:

$$\text{rel.deviation} = \frac{x_i - \mu}{\mu} \quad (2)$$

Where x_i is the units per hectare estimation of the stand parameters of the i th sample, and μ are the summed up stand parameters from the census ("true" mean) of the composite Plenter forest divided by the area of the composite Plenter forest. In the composite Plenter forest we found some trees with negative ABAI, resulting from errors of the DBH measurements but their impact was negligible.

The most common sampling designs in Central Europe for Angle Count Sampling (ACS) are using a Basal Area Factor (BAF) of 4 m^2/ha (Bitterlich, 1984; Pucher et al., 2022; Vidal et al., 2016). For Fixed Area Plot Sampling plot size of 300 m^2 (FAPS, 300 m^2), are common in Austria (Gschwantner et al., 2010). To keep the results concise, only these two out of the six available methods were used to compare the variability and accuracy by stand parameter and DBH class.

We were also interested in the differences in the required number of sampling points for assessing the stand density, BA, and ABAI by sampling method. We chose a confidence interval (CI) of 95%, which can be defined as

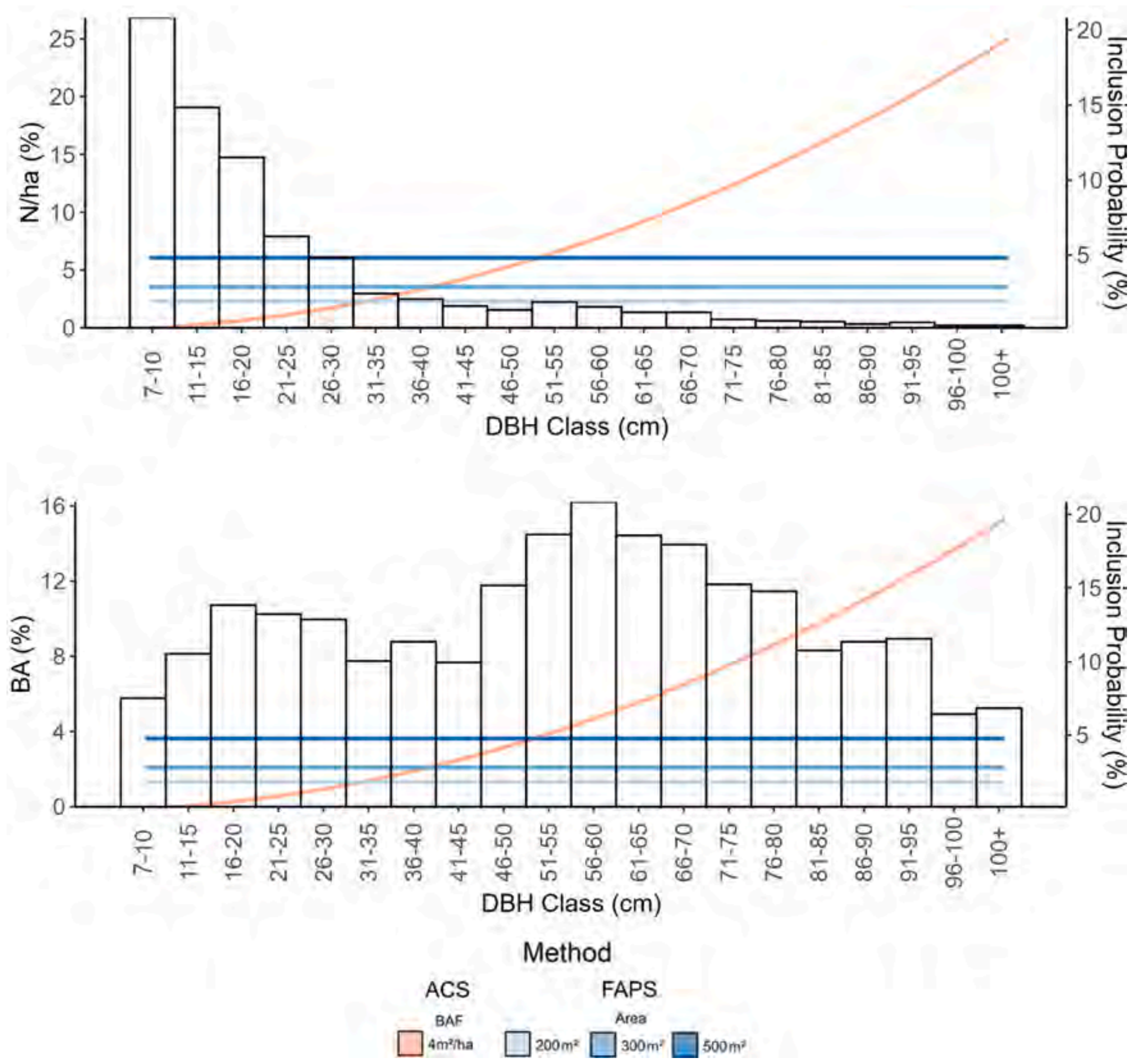

Fig. 2. Relationship of the stand density (N/ha) per DBH class and basal area (BA) m^2/ha per DBH class of the censused composite Plenter forest (see Fig. 1) versus the probabilities of trees to be recorded by DBH class if ACS with BAF=4 m^2/ha or FAPS with an area of 200 m^2, 300 m^2 or 500 m^2 is chosen.

Table 1
Overview of the mean and standard deviation (SD) of the estimates by Angle Count Sampling (ACS) using three different basal area factors (BAF) versus Fixed Area Plot Sampling (FAPS) with different plot sizes for stand density, basal area, and annual basal area increment (ABAI). Sampled trees are the number of sampled trees per sampling plot, and the census represents the "true" values of the 22,500 m^2 composite Plenter forest stand where every tree was recorded repeatedly. Lowest SD are indicated by bolt formatting.

Method	BAF/Area	Stand density *N/ha*		Basal area *m²/ha*		ABAI *m²/ha/year*		Sampled trees *N/plot*	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Census		614	–	40.1	–	1.03	–	–	–
ACS (m^2/ha)	1	622	336	40.0	**7.2**	1.02	**0.277**	40.0	7.2
	2	638	422	40.7	9.0	1.03	0.350	20.4	4.5
	4	600	486	40.8	11.6	1.07	0.484	10.2	2.9
FAPS (m^2)	500	613	**209**	39.9	13.2	1.03	0.295	30.6	10.5
	300	626	247	41.0	16.6	1.04	0.364	18.8	7.4
	200	622	271	41.4	20.1	1.05	0.463	12.4	5.4

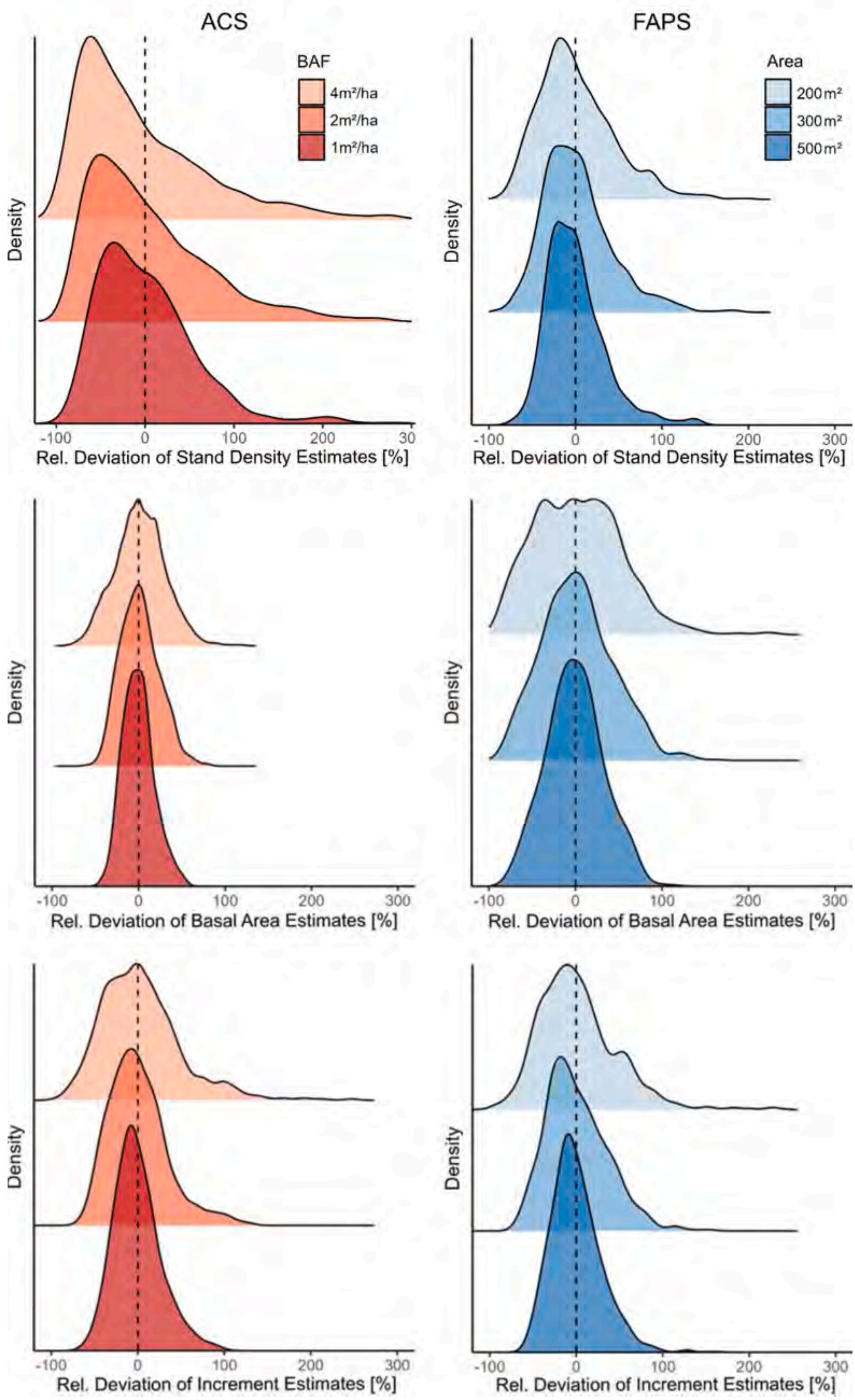

Fig. 3. Density plot of relative deviation (Rel. Deviation) of the sampling estimates of stand density (N/ha), basal area (m^2/ha), and annual basal area increment (m^2/ha/year) in% of the "true" mean from the census of the composite Plenter Forest. The density plots are based on 1000 simulations with Angle Count Sampling (ACS), choosing three different basal area factors (BAF) and Fixed Area Plot Sampling (FAPS) with three different sample plot areas.

Table 2
Comparison of the sampling estimates of stand parameters and standard deviations (SD) of Angle Count Sampling (ACS) with basal area factor (BAF) 4 m^2/ha and Fixed Area Plot Sampling (FAPS) with 300 m^2 plots for stand density and basal area after 1000 simulated sample points by DBH Classes < 81 cm DBH. Sampled are the number of measured trees per sampling plot and DBH class. The "true" value provides the results of the census of the composite Plenter forest. The method with lower SD per DBH class is indicated by bolt formatting.

DBH class	Stand density (N/ha)					Basal area (m^2/ha/year)					Sampled trees (N/plot)			
(cm)	True value	ACS Mean	SD_{ACS}	FAPS Mean	SD_{FAPS}	True value	ACS Mean	SD_{ACS}	FAPS Mean	SD_{FAPS}	ACS Mean	SD_{ACS}	FAPS Mean	SD_{FAPS}
7–10	176	181	380	169	**121**	1.13	1.18	2.44	1.09	**0.78**	0.29	0.61	5.06	3.64
11–15	125	103	209	121	**88**	1.62	1.34	2.71	1.57	**1.15**	0.34	0.68	3.63	2.65
16–20	97	94	131	93	**66**	2.28	2.22	3.08	2.20	**1.58**	0.56	0.77	2.79	1.97
21–25	52	56	86	54	**51**	2.04	2.24	3.41	2.11	**2.04**	0.56	0.85	1.61	1.54
26–30	40	40	53	42	**38**	2.35	2.34	3.14	2.50	**2.27**	0.59	0.78	1.27	1.14
31–35	17	19	31	19	**26**	1.60	1.52	2.53	1.54	**2.13**	0.38	0.63	0.57	0.77
36–40	16	17	28	16	**27**	1.82	1.86	3.05	1.82	**2.94**	0.47	0.76	0.49	0.80
41–45	12	13	**20**	13	22	1.76	1.88	**2.81**	1.81	3.11	0.47	0.70	0.38	0.65
46–50	10	11	**17**	11	20	1.82	1.94	**3.10**	2.02	3.69	0.49	0.77	0.34	0.61
51–55	15	15	**18**	15	25	3.15	3.16	**3.87**	3.26	5.35	0.79	0.97	0.45	0.74
56–60	12	12	**14**	12	21	3.14	3.19	**3.74**	3.17	5.57	0.80	0.94	0.36	0.64
61–65	9	9	**11**	9	17	2.66	2.69	**3.21**	2.67	5.11	0.67	0.80	0.27	0.51
66–70	9	9	**10**	9	18	3.18	3.19	**3.75**	3.32	6.53	0.80	0.94	0.28	0.55
71–75	5	5	**7**	5	14	2.01	2.10	**3.00**	2.25	5.63	0.53	0.75	0.16	0.41
76–80	4	4	**7**	5	15	1.88	1.73	**3.06**	2.17	6.87	0.43	0.77	0.14	0.44

$$CI = \bar{x} \pm E \quad (3)$$

where $\bar{x}$ is the sample mean and E is the margin of error, also known as the half-width of the confidence interval. E can be calculated using the following formula:

$$E = \frac{t_{\alpha/2,n-1} \times SD}{\sqrt{n}} \quad (4)$$

where t is the t-value with a probability of α=0.05 and n-1 degrees of freedom, SD is the standard deviation of the sample mean and n the sample size. After rearranging Eq. (4) the number of sampling points at a given margin of error E can be calculated as:

$$n = \left(\frac{t_{\alpha/2,n-1} \times SD}{E}\right)^2 \quad (5)$$

With this equation it is easy to calculate the needed sample size. In Section 3.3. we provide an example based on the application of Eqs. (3) to (5) and assumed a margin of error E of 10% of the mean for α=0.05. The statistical software R (R Core Team, 2022) was used to build and run a sampling simulation tool and to carry out the analysis. All graphs were created using the R-package ggplot2 (Wickham, 2016).

3. Results

The created composite Plenter forest area is well-balanced expressed by the typical revers-J-shaped distribution of the stem number versus DBH class (Fig. 1, Fig. A.1).

The main differences in probability of a tree to be included in a sample vs. DBH class between the compared sampling methods Angle-Count Sampling (ACS) and Fixed Area Plot Sampling (FAPS) is shown in Fig. 2., which shows DBH class distribution using the data of Fig. 1, the distribution of BA, and the probability of trees to be selected according to the chosen sampling method.

3.1. Variability in sampling estimates by stand parameters

ACS covering three different basal area factors (BAF=4 m^2/ha, 2 m^2/ha, and 1 m^2/ha) as well as FAPS with circular plot sizes 200 m^2, 300 m^2 and 500 m^2, exhibited unbiased mean estimates. Compared to the "true" values from the census of our composite Plenter forest, no substantial differences are detectable for the stand density, basal area (BA) and annual basal area increment (ABAI) (Table 1). However, substantial differences in the corresponding standard deviations (SD) and mean number of trees sampled per plot for the different methods are evident (Table 1).

For stand density, the ACS variants exhibited larger SD versus the FAPS variants (see Table 1), combined with a high proportion of negative relative deviation, as sampled N/ha is not normally distributed (see Fig. 3). The stem number by DBH class for ACS with a BAF=4 m^2/ha is unbiased. However, we see a high SD in low DBH classes and a declining trend in variation with increasing DBH (Table 2).

The mean in stand density from the FAPS plots exhibits only half of the SD versus the ACS samples (Table 1) and is nearly normally distributed with a tendency towards a small negative relative deviation for the 200 m^2 FAPS (Fig. 3). Comparing the variation by DBH (Table 2) for the example ACS with BAF=4 m^2/ha and FAPS with 300 m^2, shows that the SD for N/ha by DBH class is higher for smaller DBH classes and, interestingly, SD is less than half for mean N/ha sampled on the FAPS plots versus ACS plots with a BAF=4 m^2/ha in the lowest DBH classes (Table 2).

The SD of the sampled BA and ABAI exhibits a declining trend with increasing plot size (Table 1). This was expected because with decreasing BAF (2 m^2/ha and 1 m^2/ha) the plot size increases and more trees are selected and thus the variation between sample plots declines. The same is evident for the increasing plot size of the FAPS. Both parameters are unbiased for the different sampling methods (Table 1). The DBH class analysis shows that the SD for lower DBH classes is lower for all estimates in FAPS compared to ACS (Table 2). With both methods, SD gets lower with higher DBH classes. The SD for the DBH class from 36 to 50 cm is approximately the same for both methods. After that mark, ACS results in lower SD.

From Tables 1 and 2, as well as from Fig. 3, we learn that different sampling methods strongly affect the variability and the frequency of the relative deviation of the sampling estimates from the stand parameters. The higher the mean number of sampled trees, the smaller the deviations and the smaller the SD (see Fig. 3 and Table 1).

3.2. The precision of the resulting sampling estimates by stand parameter

According to the standard deviation and the acceptable margin of error E, a strong nonlinear relationship between the expected margin error E and the number of sample plots is evident (Fig. 4). The results of the relationship between the margin of error vs. the number of sampling points by sampling method and stand characteristics is shown in Fig. 4 and $E = 0$ represents the "true" mean from the census.

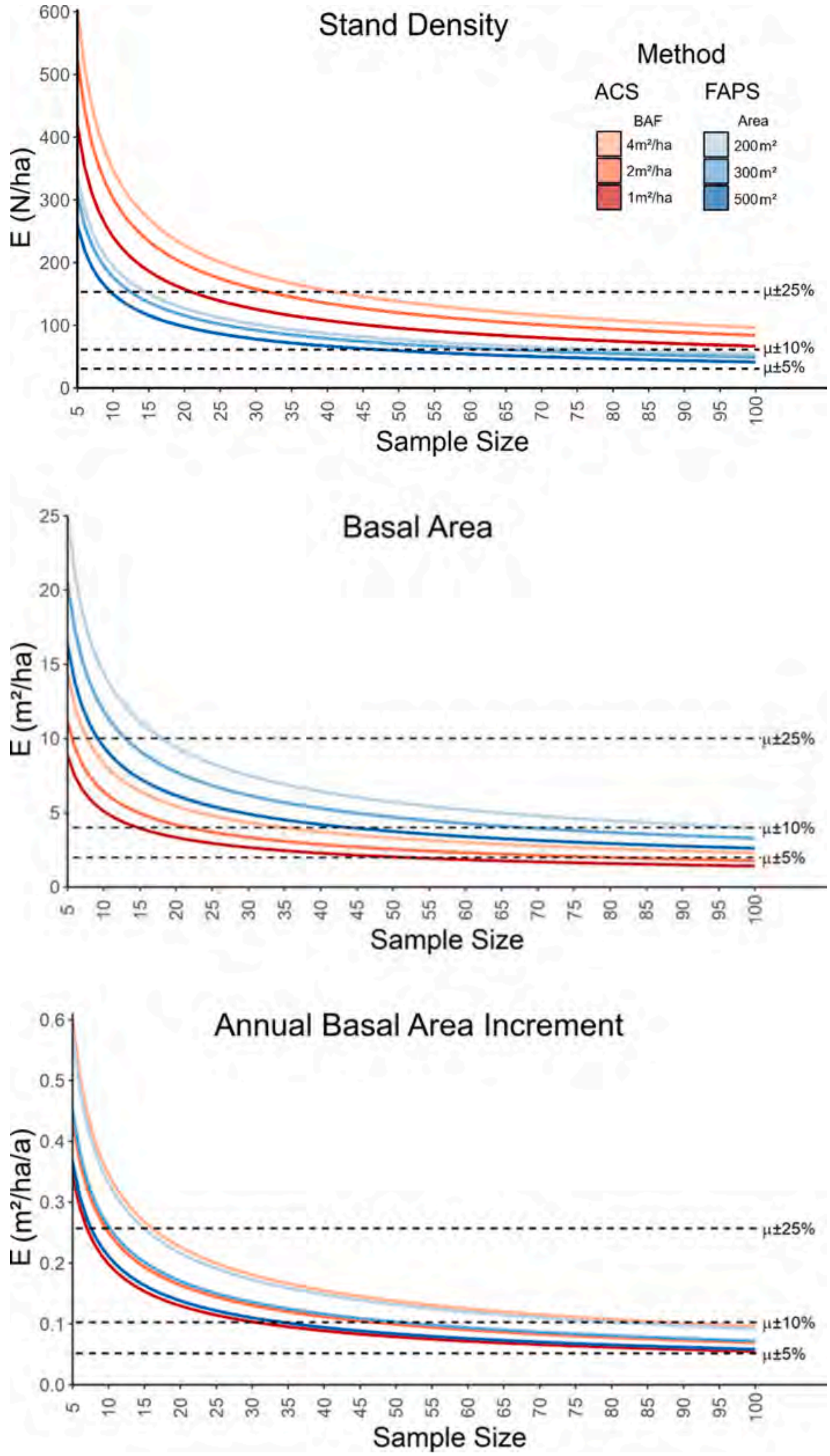

Fig. 4. Relation between the half-width of the 95%-confidence intervals (*E*) of stand density, basal area, and annual basal area increment estimates and sample size for Angle Count samples (ACS) with different basal area factors (BAF) and Fixed Area Plot samples (FAPS). The dotted lines ending in μ ± 25%, 10% and 5% show *E* in percentage of the "true" mean μ from the census.

Table 3
Estimated sample size *n*, for an acceptable 10% margin of error *E* from the true mean μ for (i) stand density, (ii) basal area and (iii) annual basal area increment for angle-count-sampling (ACS) with different basal-area-factors (BAF) of 1 m^2/ha, 2 m^2/ha, and 4 m^2/ha, as well as the fixed-area-plot-sampling (FAPS) with 200 m^2, 300 m^2 and 500 m^2 plot area. Sampled trees represent the estimated total number of trees that need to be sampled, with the estimated sample size *n*. Note that the true mean values from the recorded permanent Swiss Plenter forest research plots are N/ha = 614 for stand density, 40.1 m^2/ha for basal area, and 1,03 m^2/ha/year for annual basal area increment.

Method	BAF/ Area	Stand density (N/ha)					Basal area (m^2/ha)					Annual basal area increment (m^2/ha/year)				
		Mean	SD	Acceptable error *E*	Estimated sample size *n*	Sampled trees	Mean	SD	Acceptable error *E*	Estimated sample size *n*	Sampled trees	Mean	SD	Acceptable error *E*	Estimated sample size *n*	Sampled trees
ACS (m^2/ ha)	1	622	336	61.4 (10%)	**118**	4720	40.0	7.2	4.01 (10%)	**16**	640	1.02	0.277	0.1 (10%)	**31**	1240
	2	638	422	61.4 (10%)	**184**	3753	40.7	9.0	4.01 (10%)	**23**	470	1.03	0.350	0.1 (10%)	**47**	959
	4	600	486	61.4 (10%)	**244**	2488	40.8	11.6	4.01 (10%)	**35**	357	1.07	0.484	0.1 (10%)	**88**	898
FAPS (m^2)	500	613	209	61.4 (10%)	**48**	1470	39.9	13.2	4.01 (10%)	**45**	1377	1.03	0.295	0.1 (10%)	**35**	1071
	300	626	247	61.4 (10%)	**65**	1222	41.0	16.6	4.01 (10%)	**69**	1297	1.04	0.364	0.1 (10%)	**51**	959
	200	622	271	61.4 (10%)	**78**	967	41.4	20.1	4.01 (10%)	**99**	1228	1.05	0.463	0.1 (10%)	**81**	1004

3.3. Calculating the number of sample plots (Examples)

From the previous results, we can derive the number of sampling points required to achieve a given precision according to the chosen sampling approach (ACS vs. FAPS). Here, we provide a practical example needed for designing a forest inventory of a hypothetical Plenter forest holding. Table 3 shows the results for the calculated number of sample plots required by sampling method and the stand parameters (i) stand density, (ii) basal area, and (iii) annual basal area increment.

Example 1. *Calculation of the number of sample plots for α=0.05 for the stand density, choosing FAPS 500 m² (sample size is always rounded up):*

Step 1: $n = \left(\frac{t_{\alpha/2,n-1} \times SD}{E}\right)^2 = \left(\frac{1.96 \times 209\ N/ha}{61.4\ N/ha}\right)^2 = 45$

Step 2: Adapt the t-value to the resulting sample size $t_{\frac{\alpha}{2},\ 45-1} = 2.02$

Step 3: Recalculate the resulting sample size until $n = \left(\frac{2.02 \times 209\ N/ha}{61.4\ N/ha}\right)^2 = 48$

Example 2. *If we increase the desired margin of error E from 10% to 20% (α=0.05) the corresponding sample size for stand density (FAPS 500 m²) would be:*

Step 1: $n = \left(\frac{1.96 \times 209\ N/ha}{122.8\ N/ha}\right)^2 = 12$

Step 2: Adapting the t-value to the resulting sample size $t_{\frac{\alpha}{2},\ 12-1} = 2.2$

Step 3: Recalculate the resulting sample size until $n = \left(\frac{2.2 \times 209\ N/ha}{122.8\ N/ha}\right)^2 = 15$

Example 3. *The sample size n is given, and the margin of Error E is of interest using the same example as above:*

$$E = \frac{t_{\alpha/2,\ n-1} \times SD}{\sqrt{n}} = \frac{2.02 \times 209\ N/ha}{\sqrt{48}} = 60.9\ N/ha \text{ or about } 61\ N/ha$$

$$E_{in\%\ of\ \bar{x}} = \frac{61\ N/ha}{614\ N/ha} = 9.94\% \text{ or } 10\%$$

The practical examples (Table 3) for calculating the necessary number of sampling points according to the expected within stand variation and a pre-defined acceptable margin of error *E* shows large differences in the resulting number of sample plots by method and stand parameter. Note that in the example, we assume a relatively high precision with a confidence level of 95% at α=0.05. If we increase the margin of error *E* from 10% to 20% of the true mean, the number of sample plots can be substantially reduced (see Table 4).

4. Discussion

An important issue in designing forest inventories is finding a balance between the variability of the sampling estimates of stand parameters e.g., stand density, basal area (BA) or annual basal area increment (ABAI), and the precision, expressed as the acceptable margin of error or defined confidence interval, since they determine the number of required sampling plots. The applied forest management directly impacts the forest sampling design, as the standard deviation and therefore the sample size (see Eq. (5)) is strongly affected by the heterogeneity of the forest stands. For example, in an even-aged forest, one would expect that at the stand level the random variation of the recorded basal area and basal area increment is smaller vs. a Plenter forest. Additionally, the key sustainability indicator of an even-aged forest is a balanced age class distribution (Hundeshagen, 1826). Therefore, a lower

Table 4
Estimated needed sample size *n* for acceptable margin of error *E* at 10% and 20% from the mean of the corresponding stand parameter and for α=0.05 with t-value adjustment for angle-count samples (ACS) and fixed-area-plot samples (FAPS) with different basal area factors (BAF) and plot areas for stand density per hectare, basal area per hectare and annual basal area increment per hectare.

Method	BAF/Area	Stand density (N/ha)		Basal area (m^2/ha)		Increment (m^2/ha/year)	
		n with E = 10%	*n with E = 20%*	*n with E = 10%*	*n with E = 20%*	*n with E = 10%*	*n with E = 20%*
ACS (m^2/ha)	1	118	32	16	9	31	11
	2	184	48	23	10	47	14
	4	244	63	35	12	88	24
FAPS (m^2)	500	48	15	45	14	35	12
	300	65	19	69	20	51	16
	200	78	22	99	27	81	23

accuracy in ABAI or stand density is less important in even-aged management. In Plenter forests sustainability indicators differ from age class forests and increment becomes the key driver for monitoring sustainability (O'Hara et al., 2007; Schütz, 2001). A high random variation of the recorded increment information results either in a decline of the precision or will require a higher number of inventory plots which is costly (Gambill et al., 1985). Furthermore, the DBH class distribution is an important indicator for ensuring a balanced Plenter forest system (O'Hara, 1998; Schütz, 1997), e.g., the reversed-J-shaped relationship between N/ha and the DBH.

4.1. Stand density

FAPS (Fixed Area Plot Sampling) provides more accurate and precise estimates for stand density (N/ha) vs. ACS (Angel Count Sampling), see Table 1, Table 2, and Fig. 3 (see also Bitterlich, 1984; Matérn, 1972; Packard and Radtke, 2007; Piqué et al., 2011; Schreuder et al., 1987; Scott and Alegria, 1989). This is important, since the accurate assessment in the number of smaller trees as well as regeneration is essential for ensuing management options to maintain the Plenter equilibrium (Schütz, 1997).

4.2. Basal area

ACS (Angle Count Sampling) and FAP (Fixed Area Plot Sampling) provide accurate estimates (Table 1 and Fig. 3) for basal area (m^2/ha), but ACS is more precise (Matérn, 1972; Oderwald, 1981; Packard and Radtke, 2007; Piqué et al., 2011; Schreuder et al., 1987; Scott and Alegria, 1989; Sukwong et al., 1971; Whyte and Tennent, 1975), also for Plenter forests because a larger proportion of trees is recorded with increasing DBH (Fig. 2). This provides a higher precision in the resulting estimations for both (i) even-aged forests and (ii) Plenter forests (Hasenauer and Eastaugh, 2012).

4.3. Annual basal area increment

FAPS (Fixed area Plot Sampling) provides accurate and precise estimations (Table 1 and Fig. 3) for annual basal area increment (ABAI) defined as the mean annual net growth in basal area (m^2/ha/year), see Scott (1998, 1989). However, Hasenauer and Eastaugh (2012) argued that ACS might be as precise as FAPS when using appropriate increment calculation methods, such as the "starting value method". Our results confirm that both ACS and FAPS perform equally well in estimating ABAI, if the "starting value method" is used (Table 1, Fig. 3, and Fig. 4). For further details concerning all three increment calculation methods: (i) starting value, (ii) difference, and (iii) end value method as well as the associated changes in the error behaviour, we refer to Hradetzky (1995) and Eastaugh and Hasenauer (2013).

4.4. Sample size

Since forest inventories are labour intensive and costly (Gregoire and Valentine, 2008; Iles, 2003), the balance between the SD of a given sampling estimate of a population parameter and the precision needed will derive the data recording costs (Iles, 2003), as it determines the sample size. Therefore, the relationship between sample size and the margin of error is important for selecting the best and/or most efficient inventory method (Fig. 4). The accurate assessment of the periodic increment rates as well as the development of relationship between N/ha versus DBH (revers J-shaped Plenter curve as shown in Fig.1) is of high practical relevance to ensure sustainability (O'Hara et al., 2007; Schütz, 1997). Any over- as well as under-cutting will change the balance of a Plenter forest equilibrium and an even-aged forest will develop (Hasenauer, 2006). As seen in Fig. 4, the needed sample size to reach a certain precision, depends on the chosen sampling method. The number of sampled trees (see Table 3) can be seen as a proxy for the costs of a sample.

4.5. Practicality of the sampling methods in Plenter forests

The ACS (Angle Count Sampling) method assumes the visibility of all trees on a given sample plot, and non-visibility is a major concern (Kramer and Akça, 2002; Laar and Akça, 2007; Ritter et al., 2013; Schreuder et al., 1993; Zöhrer, 1973). This is relevant for highly heterogeneous forest stands (Laar and Akça, 2007), with undergrowth and high stem numbers (Zöhrer, 1973) as it is the case in Plenter forests. Missing trees as well as mistakenly excluded trees from a sample, results in biased estimations of forest stand parameters (Eastaugh and Hasenauer, 2013; Laar and Akça, 2007; Zöhrer, 1973). Therefore ACS with a low basal area factor (BAF) may lead to missing trees and consequently to biased estimations.

Our results indicate that the most efficient sampling method is FAPS with 300 m^2 plot size because expected precision and the needed stem number to be sampled is balanced (Table 3). Alternatively, a FAPS of 500 m^2 or a combined ACS with a BAF=4 m^2/ha and a 200 m^2 FAPS may be considered, e.g., on the FAPS plot the N/ha is recorded, and the ACS is used to estimate basal area as well as ABAI (Annual Basal Area Increment). This combination would result in good estimates of (i) stand density, (ii) basal area, and (iii) basal area increment (Table 3 and Fig. 4). All other tested variants are too expensive because either the data recording is too costly (see ACS with BAF=2 m^2/ha and 1 m^2/ha in Table 3) due to high number of trees (Bitterlich, 1984), or the results may not reach the requested precision.

5. Conclusion

Sustainable Plenter forest management requires accurate and precise estimates for the stem number development and the harvestable increment. In our study we combined nine long term Plenter forests from Switzerland to assess the error components by sampling method (Angle Count Sample (ACS) vs. Fixed Area Plot Sample (FAPS)) for typical mixed Norway spruce, silver fir, and European beech Plenter forests. The edge effect was controlled by applying the mirage method, an approach which may lead to an increase in the standard deviation (SD). Jensen's inequality (Jensen, 1906) of large sample sizes may also increase the SD, but the overall results are unbiased. Based on the acceptable error margin by stand variable and the expected SD, the number of samples required can be calculated. Note that the SD may vary by species composition and for forests in transition where the Plenter equilibrium has not been reached yet.

Two questions are important: (i) which sampling method should be chosen, and (ii) how many sampling points are required by sampling method and chosen required precision to control sustainability. The difficulty in making this decision is that for each variable the best sampling method is different (Table 3) and the decision about the required sample plots for a given Plenter forest management unit is always a compromise between expected standard deviation for a given stand parameter and the acceptable margin of the error.

In Plenter forests stand some stand parameters are related to increasing DBH, e.g., volume and basal area. These parameters are better covered by ACS, while parameters associated with declining DBH, e.g., stem number, tree mortality, and regeneration, are more effectively covered with FAPS. Both methods (ACS vs. FAPS) are suitable for estimating annual basal area increment. We consider FAPS 300 m^2, FAPS 500 m^2 or alternatively a combination of FAPS 200 m^2 and ACS BAF 4 m^2/ha to be the best sampling methods for controlling sustainability in Plenter forests. Depending on the sampling method (ACS vs. FAPS and the different variants), the acceptable margin of error *E* from the "true" mean (e.g., 10%), and the grid design (e.g., number of plots per hectare) the required sampling points for ensuing sustainable management for a given Plenter forest management unit can be calculated.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix

Table A.1,Fig. A.1,Fig. A.2

Table A.1
Summaries of the plots and site characteristics for the nine Swiss Plenter forests plots used to create the composite Plenter forest. Latitude/Longitude, elevation, precipitation, and mean temperature were taken from Forrester et al. (2022). Basal area and stand density are taken from the inventory year time 2. The main tree species are Norway spruce (NS), silver fir (SF), and European beech (EB).

Plot Nr.	Latitude/Longitude (°)	Elevation (m)	Precipitation (mm/year)	Mean temperature (°C)	Size (ha)	Basal Area (m^2/ha)	Stand Density (N/ha)	Main Tree Species	Inventory Year (time 1)	Inventory Year (time 2)
1,019,000	46.81/7.60	575	1048	9.0	1.99	44.3	599	NS, SF	1991	1999
1,027,000	46.88/7.69	861	1369	7.2	1.99	38.2	486	SF, NS	1988	1996
1,028,000	46.87/7.69	920	1437	6.8	1.18	37.9	687	SF, NS, EB	1988	1996
1,041,000	46.48/7.21	1294	1507	5.5	1.50	33.4	536	SF, NS	1987	1995
1,042,000	46.48/7.21	1185	1453	6.0	2.00	36.6	669	SF, NS	1987	1995
1,046,000	46.80/7.73	930	1375	7.1	2.00	45.4	594	SF, NS, EB	1988	1996
2,034,000	46.88/6.56	970	1442	6.8	0.97	42.4	856	EB, SF, NS	1990	1998
2,035,000	46.88/6.56	983	1431	6.9	1.98	40.8	636	EB, SF	1990	1998
2,047,000	46.84/7.76	1060	1517	6.3	2.47	42.5	529	SF, EB	1987	1995

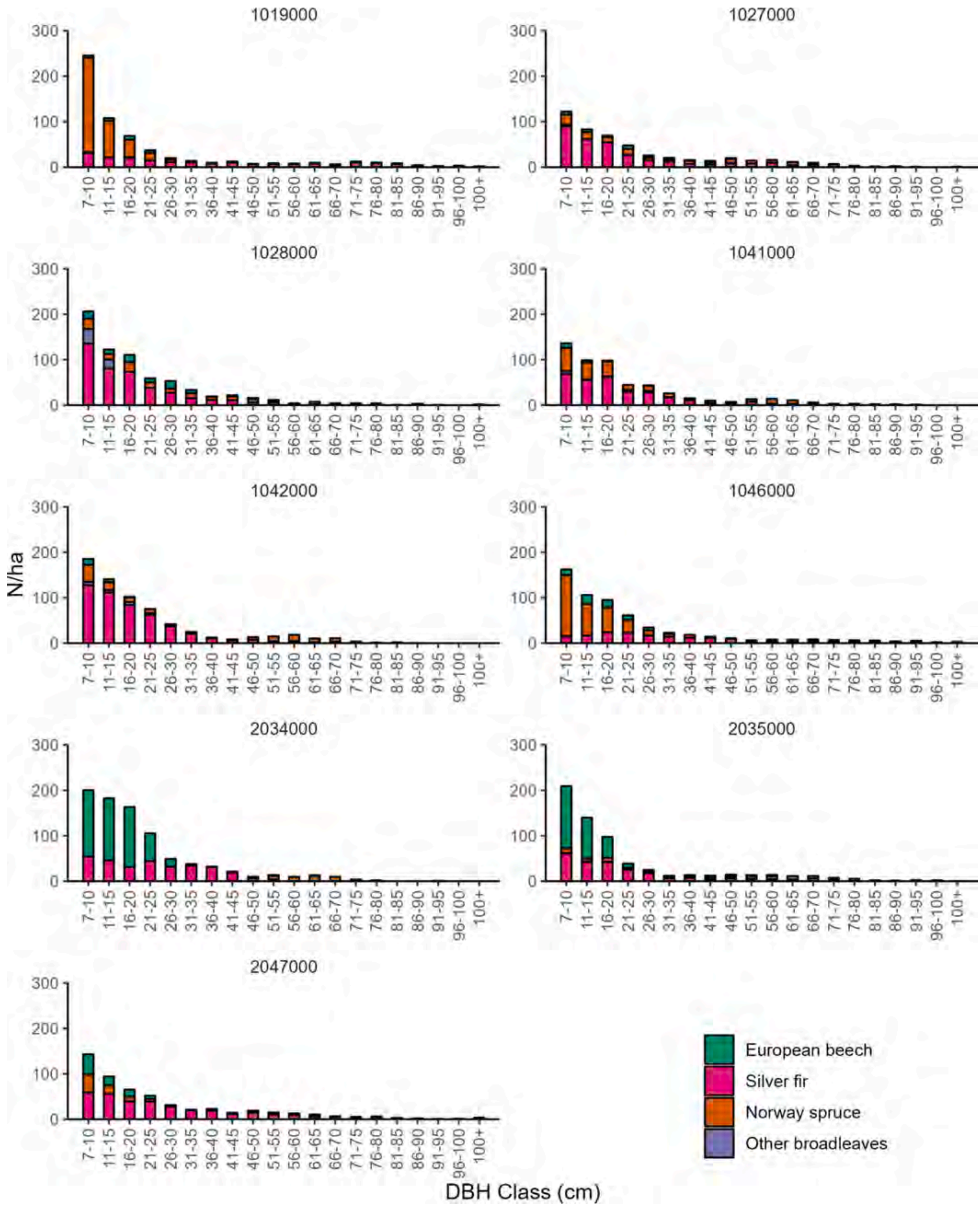

Fig. A.1. Stem number (N/ha) versus diameter at breast height (DBH) class distribution of the nine Swiss Plenter forests plots used to create the composite Plenter forest and their respective tree species compositions.

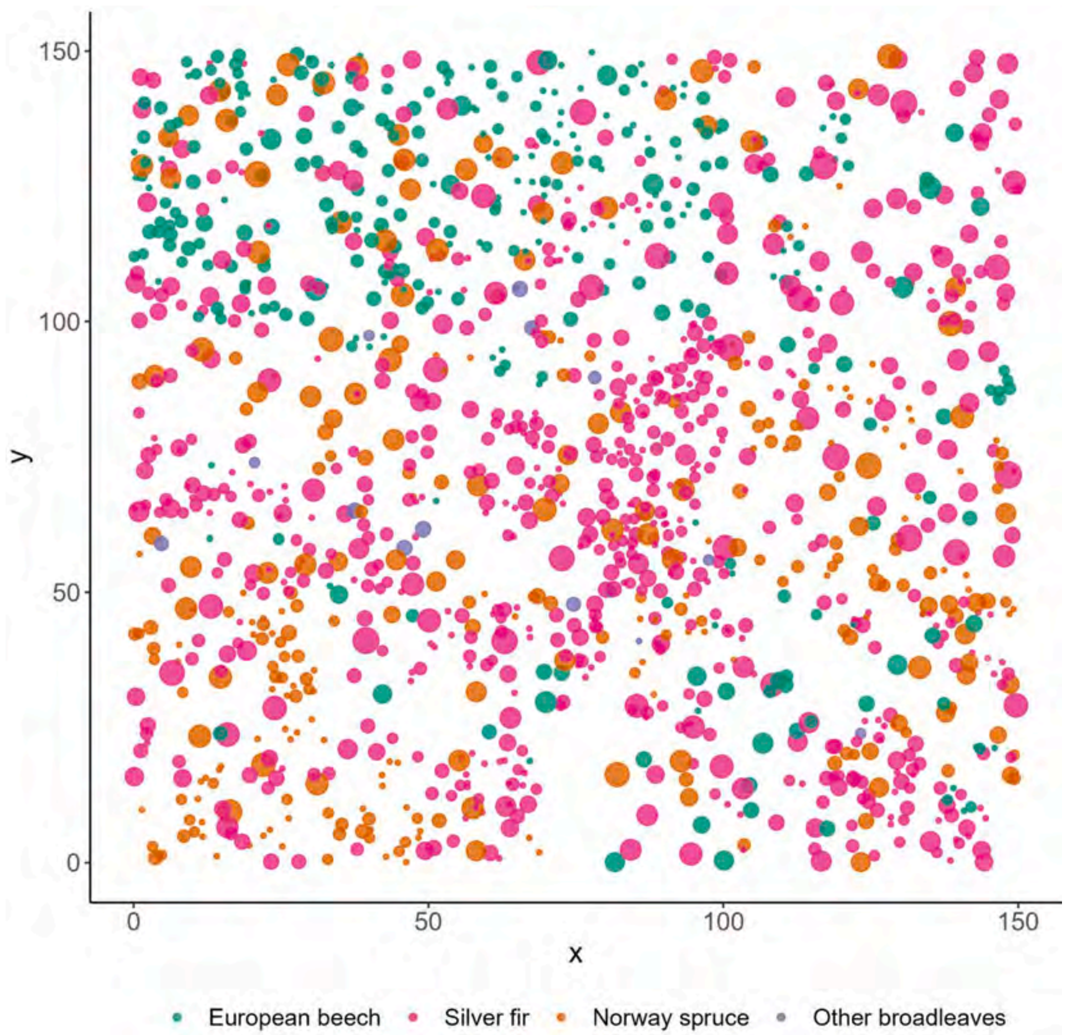

Fig. A.2. Stem-map of the 150 × 150 m composite Plenter forest. The size of the trees scales with DBH class.

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