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A Comparison Between Plot-Count and Nearest-Tree Method in Assessing Tree Regeneration Features

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Abstract

Assessing tree regeneration is important, in particular the proportion of saplings browsed due to the increasing number of ungulates. However, results of surveys differ depending on the method used. We investigated the differences between the plot-count method and the nearest-tree method for their use in tree regeneration inventories using simulations and field surveys at 11 study sites. The methods use differing references, i.e. number of trees vs. stand area. We focus in our comparison on aspects of practicability from a silvicultural point of view and not on comparing the estimators from a statistical point of view.

For simulations, three artificial stands were generated taking gaps and tree clusters into account. Therein seven equidistant grids (36-484 grid points) were used for both methods. The plot-count was applied using circular sample plots with a radius of 1.5 m. The nearest-tree method was applied using maximum search distances of 1.13 and 3.99 m, referring to stocking goals of 2500 and 200 trees ha^{-1}, respectively. Two to five times more trees were evaluated for the plot-count method. In contrast to the nearest-tree method, the plot-count method does not account for unstocked stand area when evaluating the stocking goal. The estimated proportion of damaged trees (plot-count method) was larger than the estimated proportion of stand area occupied by 'damaged' trees (nearest-tree method). The same was the case for the variation but the estimators of both methods are asymptotically unbiased.

For the 11 field surveys, results of 2 m circular sample plots are compared to the ones from the two nearest *Abies alba* saplings using a maximum searching distance of 10 m. Due to the large searching area, the density estimations of the nearest-tree method were more precise for low sapling numbers. The estimated proportion of browsed saplings highly differed from the area occupied by browsed *Abies alba* saplings.

The nearest-tree method is less laborious when measuring only the nearest tree independent of species and height class. Since an estimate of occupied stand area can be interpreted very intuitively, the nearest-tree method is particularly suitable to support silvicultural decision making in structured naturally regenerated stands.

Keywords: Forest Inventory; Silviculture; Regeneration Monitoring; Regeneration Sampling; Regeneration Survey

Introduction

Tree regeneration is a central element of sustainable forest management [1]. For silvicultural decision making, a forester relies on information about the status of tree regeneration such as size and species distributions or the frequency of frost or browsing damage [2]. Forest inventories based on field surveys can provide quantity-based or area-based (stocking) indicators for this purpose.

The plot-count method is commonly used all over the world with the main purpose to evaluate density, i.e., to obtain an estimate of the average number of saplings per unit area [2]. In such density-based tree regeneration assessments, individuals are counted, and every sapling within the sample plot of a fixed area and shape has to be evaluated regarding the criteria of interest. Tree density alone does not provide information on the pattern of sapling distribution in the area. Therefore, Cox [3] suggested presenting the results of the plot-count method using the so called "zero-plot-diagram" which is a diagram of the cumulative distribution function of the number of saplings per sample plot [4].

An alternative for regeneration assessment that allows evaluating the spatial distribution of saplings over the stand area are area-based methods [5,6] such as the stocked-quadrat method [7,8]. The stocked-quadrat method was developed to allow an estimation of the proportion of stand area that is stocked by "well-spaced" saplings. For each sample plot, it has to be determined if at least one sapling of pre-defined quality can be found. The quality criteria are mostly related to the health status of the saplings and/or silvicultural objectives (e.g., concerning tree species). The stocked-quadrat method follows a very practical approach. It is common in North America [2] and was also applied in tropical forest ecosystems [5]. However, it cannot be used directly to evaluate different criteria of the tree regeneration, e.g. to assess the frequency of browsing for different species.

By applying a minor modification, namely by evaluating the nearest sapling to the sampling point, it is possible to estimate the proportion of stand area that is stocked by tree regeneration of different criteria. This "nearest-tree method" was presented by Staupendahl (1997) as a novel method to evaluate specific characteristics of natural tree regeneration in German forests, and was later implemented for the 3rd Swiss National Forest Inventory [see 9,10]. However, it is still widely unknown in the international forestry literature [see 11-13]. MacLeod and Chaudhry [14] compared the stocked-quadrat to the nearest-tree method for estimating the regeneration density. They concluded that the distance approach with the nearest tree was more efficient because fewer samples were needed for the same level of accuracy [14].

To our best knowledge, a methodological comparison between plot-count and nearest-tree method in evaluating tree regeneration on the same dataset is missing so far. In this paper, we therefore compare the plot-count method and the nearest-tree method based i) on a simulation experiment and ii) on field surveys of 11 study sites that due to long term surveys were known to differ in sapling density and proportion of browsing [15]. The two methods use differing references of their estimator - number of trees vs. stand area; thus, the estimators are incomparable from a statistical point of view. We rather focused on the practicability from a silvicultural point of view, as little is known about the differences in interpreting the results of the obtained estimators. The focus was on investigating how the methods differ when used to quantify the proportion of features that could affect a young forest stand, i.e. target variables such as frost damage, insect damage, browsing, fraying etc.

Material and Methods

In the literature about forest regeneration, the small individuals of the regeneration layer are usually called "seedlings" or "saplings", depending on their height. In this paper, we use the shorter term "tree" for the simulation, as the methods presented here can be applied irrespective of the size of the regeneration.

Simulation Based on Three Generated Stands

The Simulated Stands

Three artificial examples of a naturally regenerated stand with the area of one hectare were generated by drawing tree coordinates within a 100 m x 100 m rectangle using a random number generator. A spatially-random distribution was chosen here so that patterns that naturally occur in real forest stands could not influence the estimations.

Example stand 1: 2448 trees were randomly and uniformly distributed over the stand area (Figure 1a). Fifty percent of these trees were randomly selected (Figure 1a, black dots), and it was supposed that this second group exhibited a specific feature that was not present in the first group of trees (grey dots). This could be any "binary" feature that is either present or not, e.g., frost damage, browsing, the tree belonging to a specific tree species or height class, etc. To enhance readability, the second group of trees is called "damaged trees" in this paper.

Example stand 2: the tree locations of example 1 were used and an unstocked gap was created by deleting all trees located outside of two segments of circles, one at coordinates (100/100) with a radius of 100 m and one at coordinates (0/0) with a radius of 20 m. To avoid an unstocked area at the border of the stand, additional trees were generated within a distance of 7 m from the left and lower stand border. The total number of trees was 2096. Again, fifty percent of the trees were randomly selected as the group of damaged trees (Figure 1d, black dots).

Example stand 3: the tree locations of example 2 were used as the undamaged group (Figure 1g, grey dots). The damaged group was generated by grouping additional 1749 trees into 50 small clusters exhibiting a greater local tree density than the rest of the stand (Figure 1g, black dots). The cluster radius was 2 m, and cluster locations were randomly selected at positions beyond the x- and y-coordinates of 25 m, in order to leave the gap free of trees. The total number of trees in example stand 3 was 3845, and the true value of the ratio of damaged trees equals 0.45 (1749 divided by 3845).

The Nearest-Tree Method

The nearest-tree method [16] is based on sampling the tree that is nearest to the plot centre. This tree has to be evaluated in terms of the characteristics of interest, in our case the 'damage' status (e.g. frost damage, insect damage, browsing, fraying etc.). As a measure of damage frequency for the whole stand, it is then possible to estimate the percentage of the stand area that is occupied by damaged trees.

Theoretically, the nearest-tree method is based on area estimation with systematic dot grids [see 17]. The stand area is subdivided into so called Voronoi-polygons or inclusion zones [18]. The inclusion zone associated with tree X comprises the part of the stand area that is nearer to tree X than to any other tree in the

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stand. The inclusion zone of tree X can be understood as the part of the stand area that is occupied by tree X. Thus, the stand area occupied by damaged trees is the sum of the inclusion zones of all damaged trees. The percentage of this area can be estimated using systematic dot grids: for each grid point, it has to be determined if it is located within the inclusion zone of a damaged or within that of an undamaged tree. It is unnecessary to determine the area or the shape of the polygon, as the definition of the inclusion zone directs the grid point to be located within the inclusion zone of its nearest tree. Thus, it is sufficient to search the nearest tree to the plot centre and determine its damage status. The percentage of stand area occupied by damaged trees can be estimated by dividing the number of grid points nearest to damaged trees by the total number of grid points within the stand. The standard error of this estimate can be calculated using the binomial variance formula [17].

For tree regeneration assessment, in terms of evaluating the fulfilment of a silvicultural stocking goal, a "maximum search distance" has to be implemented. In this way the stand area occupied by an individual tree cannot be larger than the area of a circle with a radius equal to that of the maximum search distance. Grid points where no tree can be found within the maximum search distance are located within that area of the stand which is not occupied by tree regeneration and are thus considered as unstocked, i.e. no tree [14]. The percentage of stocked stand area can be estimated by dividing the number of grid points for that a nearest tree could be found by the total number of grid points within the stand. For example, with a stocking goal of 2500 trees per hectare and assuming a uniform spatial tree distribution, one tree would occupy 4 m^2. In this case the inclusion zone of the individual-tree has to be limited to 4 m^2. This leads to a maximum search distance of 1.13 m. Similarly, for assessing a stocking goal of 200 trees per hectare, the inclusion zone is 50 m^2 and thus a maximum circular search distance of 3.99 m is needed. For this simulation study, the nearest-tree method was applied using these two maximum search distances. In Figure 1 the stand area occupied by the individual trees in the three example stands is shown for these two cases.

The Plot-Count Method

The plot-count method is based on counting trees within sample plots of a fixed size and shape. Due to its simple statistical concept and broad applicability, this method is very popular [19]. The frequency of damage can be evaluated with this method based on the ratio of damaged trees to the total number of trees [20].

Finding an appropriate plot size and shape is a long standing topic of forest science [20,21]. Different practical aspects relating to tree density and the spatial distribution of the trees as well as their environment, e.g., the amount of competing vegetation, must be considered. Both the amount of work and the error rate in the field assessment increase with increasing plot size, since the entire plot area must be searched for trees [19]. However, as it is not the aim of this study to address this topic, we decided to use a simple approach with about the lowest possible plot size that still allows a comparison with the simulations of the nearest-tree method. We used circular sample plots with a radius of 1.5 m. The number of trees per hectare, the ratio of damaged trees as well as the standard error of these measures were estimated using the common formulas for simple random sampling [see 22].

Sampling on Grids with Different Spacing

To investigate how the sample size influences, the estimates and standard errors, 7 equidistant grids with different spacing were used in each generated stand. The resulting number of grid points ranged between 36 and 484. At each grid point, the plot-count method and the nearest-tree method were applied as described above.

Field Surveys at 11 Study Sites

In order to investigate the influence of ungulate browsing on tree saplings on a regular basis, indicator areas have been established [23] and repeatedly monitored in the canton of St. Gallen (SG) in Switzerland. Such sites typically comprise a continuous forest area with different forest developmental stages and forest types. Each site contains a rectangular grid with a fixed grid size of 100 m between the circular sampling plots. The plot centres are permanently marked.

For this study, 11 sites were selected on a purposive basis in spring 2015 [i.e. the 11 sites with spring assessment in canton SG from 15]. Sites were selected that i) had seed-producing *Abies alba* trees in the canopy (at least 5% of canopy trees), ii) contained at least some sampling plots where *Abies alba* saplings were present and iii) which had very different densities of saplings and browsing intensities (in order to test the methods). On each site, 15-18 randomly chosen plots (see Table 3) were assessed in spring 2015 before budburst using the plot-count method and the nearest-tree method.

The plot-count method was executed on a circular plot of 2 m horizontal radius. This radius was chosen as this sums up to the 'optimum' sampling surface of 12 m^2 that was recommended by Eiberle & Lanz [20] for Swiss forests and is normally used by foresters during the surveys in such indicator areas [23]. For the nearest-tree method the two *Abies alba* saplings nearest to the plot centre were assessed and the measured distance to the saplings was noted. The maximal search distance from the plot centre was 10 m, resulting in a stocking goal of 32 trees per hectare in order to be able to make a statement also for admixed *Abies* saplings. For both methods, only *Abies* saplings between 10 cm and 130 cm tree height were considered and the leader shoot formed in the previous year was classified in two classes: 'unbrowsed' were *Abies* saplings that had no sign of browsing on their leader shoot or no leader shoot in that year (owing to older 'damage'), and 'browsed' were saplings of which the leader buds up to the whole of the annual increment had been browsed by ungulates. The same variables were calculated as for the simulated stands, naturally taking only into account the tree that was nearer to the plot centre for the nearest-tree method. In addition, with the two measured distances we calculated the sapling density based on the k-tree method [24], i.e. 1/(radius^2*π), where the radius is variable and depends on the distances:

radius = distance to nearest tree + 0.5 * (distance to second nearest tree – distance to nearest tree).

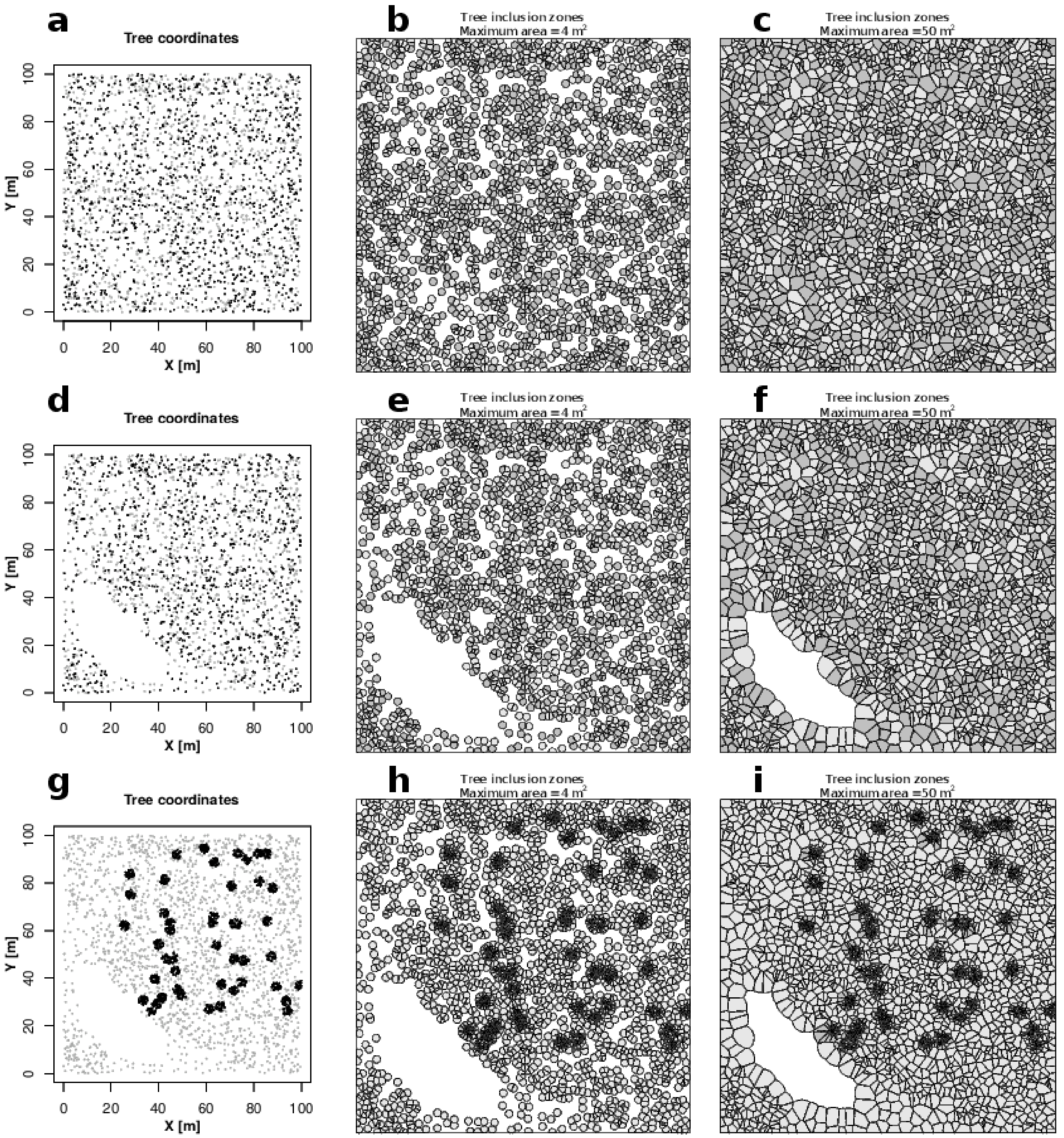

Figure 1: Tree coordinates (a, d and g) and individual-tree inclusion zones for the saplings in the example stands. Subfigures a-c, d-f and g-i refer to example stands 1, 2 and 3, respectively. Damaged trees are marked as black dots (a, d and g) or their inclusion zone painted in dark grey. The subfigures in the middle and right column differ only by the size of the tree inclusion zones. The white area in these subfigures is considered unstocked.

Results

Results of the Simulations

Example Stand 1

For the example stand 1 and the stocking goal of 200 trees per hectare (maximum distance to the nearest tree of 3.99 m, Figure 2c), the true proportion of total occupied stand area was 100 %. Since the two groups of damaged and undamaged trees exhibit the same local tree density in this example, the true proportion of stand area occupied by the damaged trees was 51.4 % (Figure 2c) and thus very near to the true proportion of damaged trees (50 %; Figure 2a). The slight deviation of 1.4 % was due to the fact that the trees were randomly assigned to a damage group. For the stocking goal of 2500 trees per hectare (maximum distance to the nearest tree of 1.13 m, Figure 2b), the true proportion of total occupied stand area was 62.6 %, and the true proportion of stand area occupied by the damaged trees was 31.7 %. This means that the stocking was too low in parts of the stand in order to meet the goal of 2500 trees per hectare. Not considering this unstocked stand area (i.e. omitting all plots with no nearest tree), the proportion of stand area occupied by the damaged trees was 50.6 % (31.7 divided by 62.6). Also this proportion is very near to the true proportion of the damaged trees due to the same local tree density of the two groups in this example.

Example Stand 2

For the example stand 2, the gap in the lower left corner of the stand lead to a reduction of occupied stand area as compared to the example stand 1. The true proportion of total occupied stand area was 94.2 % for the stocking goal of 200 trees (Figure 2f), and 54.8 % for the stocking goal of 2500 trees (Figure 2e). The true proportion of stand area occupied by damaged trees was 46.6 % and 27.3 %, respectively. As also for this example the local tree density of the damaged and undamaged trees did not differ (Figure 2d), the proportion of stand area occupied by damaged trees was near 50 % for both stocking goals if the unstocked area was not considered.

Example Stand 3

The proportion of total occupied stand area was 94.2 % with a stocking goal of 200 trees per hectare (Figure 2i) and thus the same as in example stand 2. Grouping the damaged trees into clusters with a larger local tree density than that of the undamaged trees in this example lead, however, to a considerably lower proportion of stand area occupied by the damaged trees (10.1 %, Figure 2i). For the stocking goal of 2500 trees per hectare, the proportions were 58.5 % and 8.4 % (Figure 2h). This difference in local tree density between control and damage group is not so clearly reflected in the proportion of damaged trees which is 45 % (Figure 2g) and thus very close to that in the other examples (Figure 2a and Figure 2d).

Comparison Between the Plot-Count and the Nearest-Tree Method

The two methods differed in terms of the number of trees that had to be evaluated (Table 1). Between 2 to 5 times more trees had to be evaluated for the plot-count method, depending on which maximum search distance was applied for the nearest-tree method. This was independent of the grid spacing, but naturally proportionally fewer trees had to be evaluated with a wider spacing.

Number of sample points	Nearest-tree method Maximum distance 1.13 m			Nearest-tree method Maximum distance 3.99 m			Plot-count method Radius 1.5 m		
Simulated example stand:	1	2	3	1	2	3	1	2	3
36	18	18	19	36	34	34	45	43	60
64	40	34	36	64	61	61	123	110	203
100	72	65	69	100	95	95	211	188	280
144	95	82	87	144	134	135	270	225	418
196	116	98	106	196	184	184	321	263	475
256	165	144	152	256	241	241	438	372	653
484	304	264	284	484	456	457	842	705	1299

Table 1: Number of evaluated trees by method and example stand for the 7 different sampling grids.

For the plot-count method, the resulting statistics are an estimate of the number of trees per hectare (Table 2) and an estimate of the proportion of damaged trees (Figure 2a, 2d and 2g). For the nearest-tree method, the resulting statistics are an estimate of the proportion of the total stand area that is stocked by trees and the proportion of stocked area by damaged trees (Figure 2b, 2c, 2e, 2f, 2h and 2i). The statistics varied for each example stand depending on the grid size, but for all example stands, both bias (i.e., the absolute value of the difference between estimate and true value) and standard error of the estimates decreased with increasing number of sample points. With the smallest grid size of 484 grid points, all estimates were near the true value.

Number of sample points	Estimated number of trees (std. err.)		
	Stand 1	Stand 2	Stand 3
36	1768 (170)	1690 (175)	2358 (499)
64	2719 (201)	2431 (201)	4487 (844)
100	2985 (162)	2660 (154)	3961 (446)
144	2653 (146)	2210 (139)	4107 (514)
196	2316 (111)	1898 (99)	3429 (396)
256	2420 (96)	2055 (90)	3609 (329)
484	2461 (68)	2061 (66)	3797 (255)

Table 2: Number of trees estimated using the plot-count method by example stand for the 7 different sampling grids.

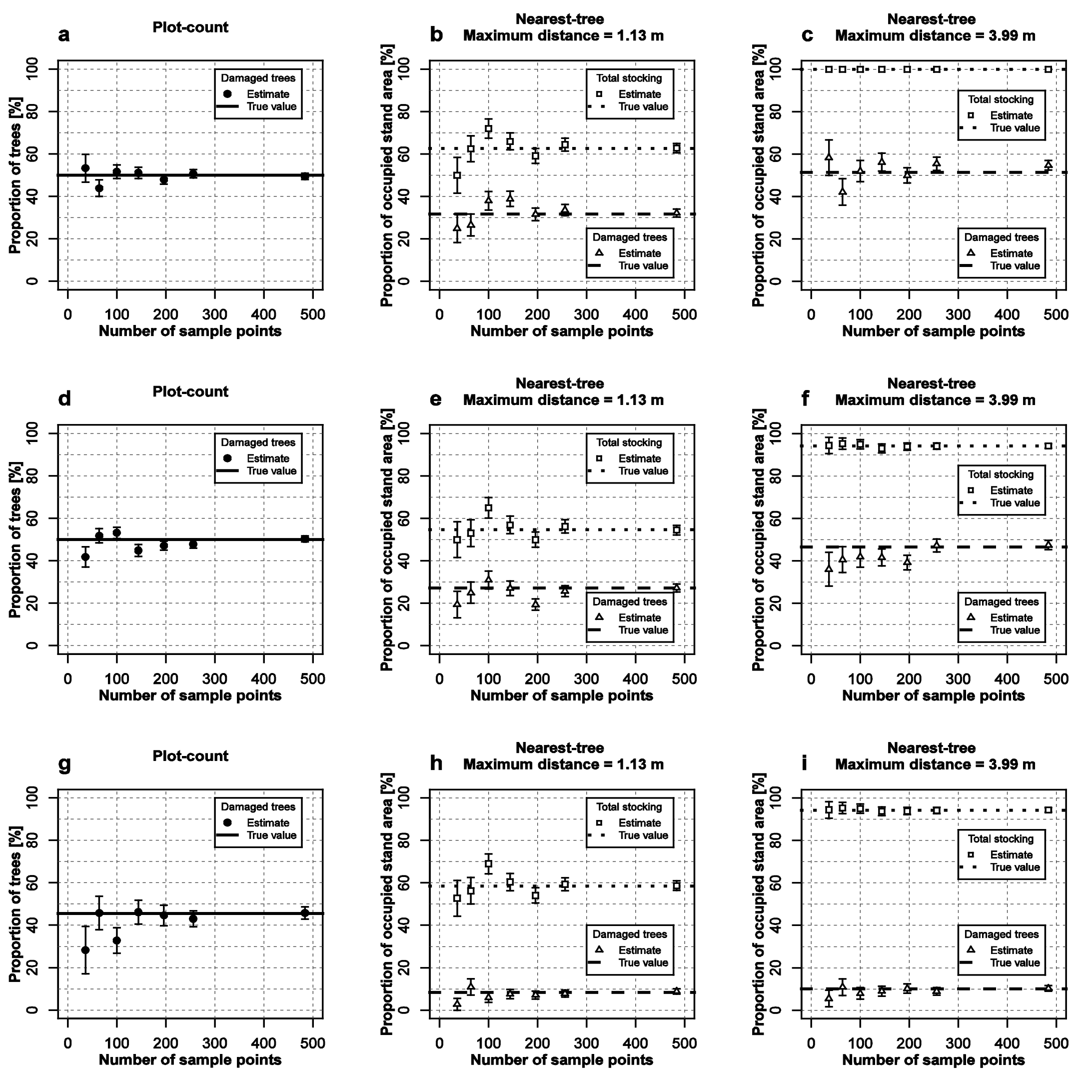

Figure 2: Proportion of damaged trees for the three example stands estimated using the plot-count method (a, d and g) and proportion of occupied stand area for the group of damaged trees and total, estimated using the nearest-tree method and maximum search distances of 1.13 m (b, e and h) and 3.99 m (c, f and i) over the number of sample plots. Subfigures a-c, d-f and g-i refer to example stands 1, 2 and 3, respectively.

The results for the two methods differ in terms of the evaluation of the fulfilment of the stocking goal in the example stand 3. According to the estimate of the number of trees by the plot-count method, both stocking goals of 200 and 2500 trees can be considered fulfilled (Table 2). However, according to the nearest-tree method, the stocking goal of 2500 trees per hectare is fulfilled only for between 53 and 69 % of the stand area (depending on the grid size used for sampling, Figure 2h). Also the stocking goal of 200 trees per hectare is fulfilled only for between 94 and 95 % of the stand area (Figure 2i).

Furthermore, the methods yielded different results regarding the frequency of damaged trees in example stand 3. The estimated proportion of damaged trees was between 28 and 46 %, depending on the grid size (Figure 2g), and was larger than the estimated proportion of stand area occupied by damaged trees which varied between 3 - 10 % (Figure 2h) and 6 - 10 % (Figure 2i) for the two stocking goals.

Results of the Field Surveys at 11 Study Sites

The median of the estimated number of *Abies* saplings per hectare for each plot was very similar using the plot-count method (Figure 3a) compared to the median of the density calculation based on the distances of the two nearest *Abies* saplings (Figure 3b). However, either 0 (sites 2, 6, 7 and 11) or at least 796 *Abies* saplings (sites 1, 4, 5, 8 and 10) were in average present on a plot with the plot-count, owing the 2 m radius. Based on the density calculations made with the nearest two *Abies* trees, all 11 sites had a density around (site 6 and 11) or above 100 *Abies* saplings per hectare (Figure 3b). The variation between the plots of each site was high for both methods as only 15-18 plots per site had been visited.

The proportion of occupied stand area varied greatly between the 11 sites. Five sites with apparently low densities of *Abies* saplings had rather a high proportion of occupied stand area (sites 1, 2, 4, 8 and 10, see Figure 3d). This illustrates that the scarce *Abies* regeneration was rather homogenously distributed over these sites. In contrast, the other four sites with low density estimations had also low proportions of occupied stand area (sites 5, 6, 7 and 11, see Figure 3d).

The estimated proportion of browsed *Abies* saplings (Figure 3c) - the 'browsing intensity' [20] - highly differed from the area occupied by browsed *Abies* saplings (Figure 3d) and from the proportion of stand area occupied by browsed *Abies* saplings (Table 3). Therein no clear density dependence was found, tough ecologically seen the largest differences were found for the sites 2, 6 and 7 which all had very low numbers of observed saplings estimated by both methods (Figure 3). However, once again 15-18 sites are too few for precise estimations, as the variation within each site was large (Figure 3 and Table 3).

Nr.	Site	Coordinates		Forest	N plot	Nearest-tree method	
		X	Y	Type		**proportion of browsed *Abies* saplings**	
1	Nieselberg (Zuzwil)	722800	258900	Fa	15	14.3	± 9.7
2	Altenberg (Degersheim)	729600	250000	Fa(AcFrTi)	16	7.1	± 7.1
3	Bernhardzellerwald (Waldkirch)	742900	258000	Fa(AcFrTi)	16	6.3	± 6.3
4	Wildberg (Jonschwil)	725700	252800	Fa(AcFrTi)	15	30.8	± 13.3
5	Hasenstrick (Goldach)	755000	258000	Fa	18	15.4	± 10.4
6	Moos (Buchs)	751600	223600	Fa-Ab(AcFrTi)	15	0.0	
7	Spaltenstein (Gams)	750300	231800	Fa-Ab(AcFrTi)	15	25.0	± 16.4
8	Laubwald (Amden)	734900	225700	Ab-Pi(Fa-Ab)	15	0.0	
9	Hofstetten (Hemberg)	730600	241200	Fa(Fa-Ab)	15	0.0	
10	Rumpf (Wattwil)	721100	238900	Fa-Ab	16	13.3	± 9.1
11	Neckerwald (Krummenau)	734600	236200	Ab-Pi(Fa-Ab)	15	0.0	

Table 3: Details of the 11 assessed sites in the field survey, including the coordinates and the prevailing forest types at each site (Acer-*Fraxinus-Tilia, Fagus, Fagus-Abies* and *Abies-Picea*). Nr. is the number used in Figure 3, N plot is the number of plots per site. Not considering the unstocked area, the proportion of stand area occupied by browsed *Abies* saplings [%] was calculated using the nearest-tree method.

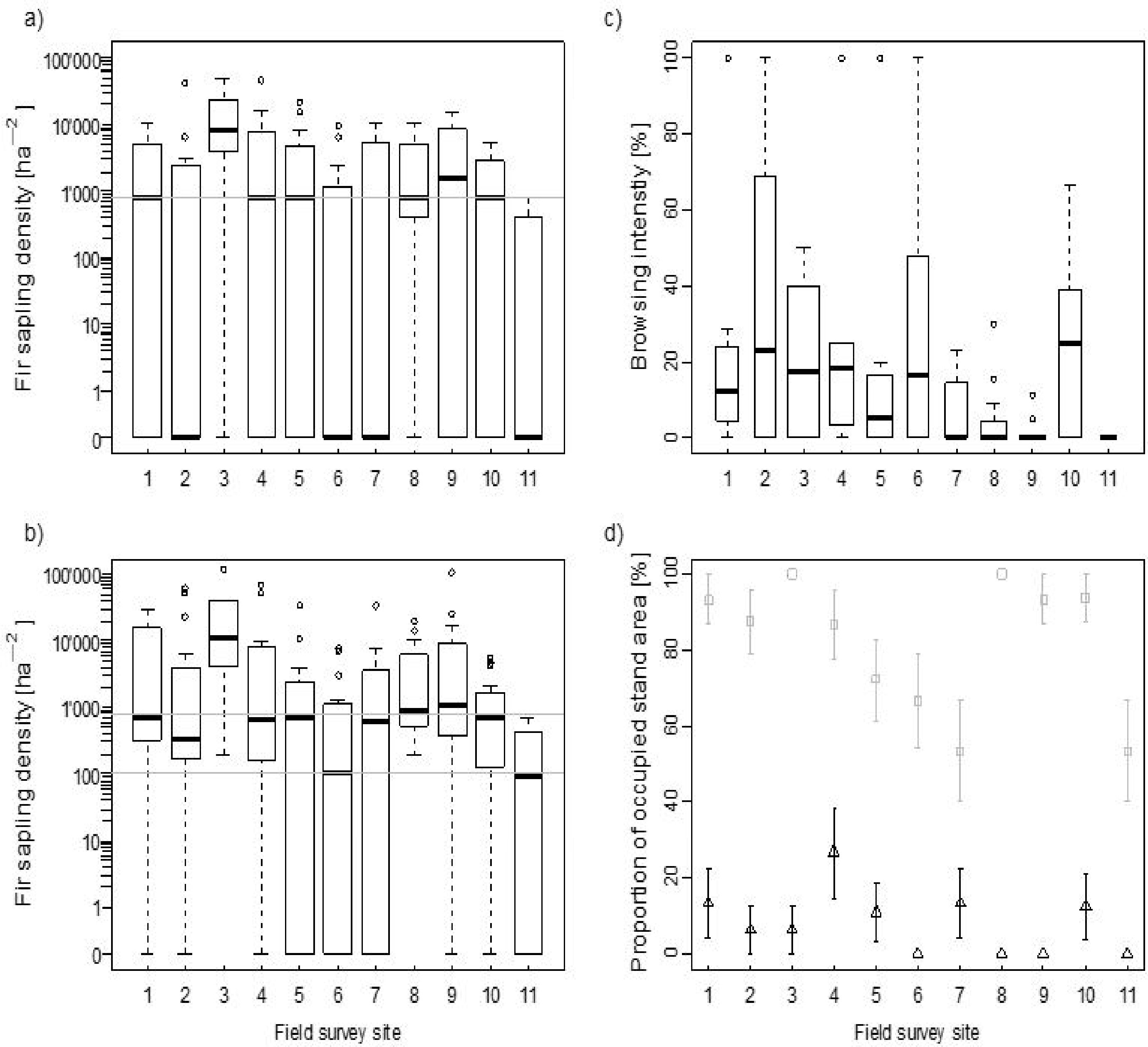

Figure 3: Results for the 11 field survey sites described in Table 3. *Abies alba* sapling density calculated based on the plot-count method (a) or the k-tree method with the distance of the two *Abies* saplings nearest to the plot centre (b). The proportion of browsed *Abies* saplings – the so called browsing intensity - based on the plot-count method (c) and proportion of occupied stand area (d) for the group of browsed *Abies* saplings (black triangle) and in total (grey square). For panels a-c) median (bold line), first and third quartile (bottom and top of the box) with whiskers at quartile ± 1.5 * interquartile range and individual points more extreme in value (circles) have been drawn using boxplot in default R code. For better visibility, in panel a) and b) a line is drawn at a density of 796 saplings.

Discussion

Comparison Between the Plot-Count and the Nearest-Tree Method

Both methods are asymptotically unbiased with regard to their respective estimators, i.e., the bias approaches zero with an increasing number of sample points (Figure 2). Thus, from a statistical point of view, both methods are equally 'correct'. There are, however, differences to notice from a practical point of view. First, for the plot-count method, a significantly larger number of trees have to be evaluated (Table 1), which makes this method both more expensive and error-prone. This is directly related to the amount of information that needs to be collected for each tree. Obviously, a larger mental concentration effort is needed to count trees by different tree species and damage types within circular fixed-area plots than to assess these characteristics only for the nearest tree to the sample point. Second, as it is the stand area that has to be sufficiently stocked according to the management objectives (i.e., stocked by future crop trees), measures that evaluate forest regeneration only based on number of trees are of limited use for silvicultural decisions [14]. The plot-count method did not account for the unstocked gap in the lower left corner of the simulated example stand 2. The nearest-tree method allows to estimate the proportion of stand area occupied (i.e., stocked) by tree regeneration. The gap in the lower left corner leads to the result that only about 95 % of the stand is stocked in compliance with the stocking goal of 200 trees per hectare. Such result can be spatially illustrated on a map by marking the coordinates of those sample plots that are located in the inclusion zone of a sapling.

In the case of different local tree density of the group of damaged and that of the undamaged trees (example stand 3), the plot-count and the nearest-tree method lead to different estimates of damage frequency. This result is due to the different reference units - number of trees vs. stand area. The local tree density of the damaged trees is larger than that of the undamaged trees in example 3; in this case (Figure 2g, 2h and 2i) the proportion of damaged trees (plot-count method) is bound to be larger than the proportion of occupied stand area (nearest-tree method). Vice-versa, the difference would be inverse if the tree density of the damaged trees would be lower than that of the undamaged trees. Since the damage status is a binary feature, one would just have to change the names of the groups to achieve the contrary result. We choose to use about 50% of damaged trees in our simulation examples, but the result of lower estimated proportion of occupied stand are than estimated proportion of damaged trees would be the same for other levels of damage proportion. We also intentionally choose a tight clustering of the damaged trees with a clear difference of local stand densities for the two groups because we wanted the effect of this circumstance to be clearly reflected in our results. In real stands, the clustering and differences in local browsing densities will vary on a small-scale, leading to results on the level of sites that are much more difficult to explain (see results from the 11 field study sites). A general pattern of a relation between tree density and browsing seems to be missing. Some studies found more browsing the fewer seedlings were present [9,25] and some others the more seedlings were present [15,26].

Role of the Maximum Search Distance

Due to the large searching area in our 11 study sites, the density estimations of the nearest-tree method were more precise for sites with low sapling numbers than the plot-count method with a radius of 2 m. Generally, stocking is affected by plot size and not by the shape of the plot [14]. Thus not the exact method but rather the radius or searching distances are crucial for the estimation of tree density when saplings are scarce. Obviously – but not further discussed here - the results will heavily differ if tree regeneration is assessed in all plots in contrast to only in sites were regeneration is needed [see 27].

For practical purposes, the choice of the maximum search distance should be based on the management objectives for the forest stand that is to be evaluated. A too large search distance as related to the stocking goal leads to an "overestimation" of the occupied stand area and vice versa. If a larger search radius should be used (e.g., in order to have a larger database for evaluation of damage to the tree regeneration), it is useful to measure and record the exact distance to the nearest plant(s) for each sample plot. In this way different search distances can afterwards be applied for solving different questions.

Role of the Grid Distance

The grid distance (i.e., the number of sample points) influences the bias and standard error of the estimates for both the plot-count and the nearest-tree method. Both bias and standard error decrease with an increasing number of sample points (Figure 2).

For the nearest-tree method, a too large grid distance in relation to the size of the occupied stand area can lead to instable estimates, as too few sample points fall within the inclusion zones of damaged trees. Figure 2 (middle and right column) shows that with fewer than 100 sample points the proportion of occupied stand area was often significantly over- or underestimated. Shifting such a coarse grid randomly could lead to a different result, depending on the spatial distribution of the damaged trees. As the workload per sample plot is comparatively low for the nearest-tree method, a much denser grid can be realized as compared to the plot-count method (but pay attention on the walking time between plots). The appropriate grid distance depends on the spatial distribution of the regeneration. The grid distance should be adjusted in order to get information of all target species, not only on the most abundant tree species [28]. Further research is required to find practical approaches for pre-estimating these parameters in the field. We assume that the less tree regeneration is present, the smaller should the grid distance be and the more uniform the trees and their specific binary features are distributed, the larger the distances can be.

Systematic Grid vs. Random Sampling

For fieldwork, a systematic dot grid is clearly more practicable than sample point locations distributed at random and independently over the sampling area. It is well known that applying systematic dot grids leads to more precise results than random sampling with the same number of sample points, but the standard error is generally overestimated with the traditional variance formula [17,29]. This latter problem is, however, negligible if the area to be estimated consists of many small sub-patches [17,29], which should be the case for the spatial distribution of natural tree regeneration that is further divided into different categories (e.g., browsing status, tree species, etc.).

Relation Between the Nearest-Tree Method and the Stocked-Quadrat Method

The stocked-quadrat method [7,8] was often used to estimate the proportion of stand area that is stocked by "well-spaced" trees. The term "well-spaced" refers to the stocking goal, and the size of the sample plot has to be chosen accordingly, with the same reasoning as previously described for the maximum search distance of the nearest-tree method. The stocked-quadrat method is very straightforward and thus easy to apply. However, the results can be misleading since the stand is evaluated only in terms of presence/ absence of trees that belong to the pre-defined group. All other trees are ignored. This means that the result obtained by applying the stocked-quadrat method could be that the stand is fully stocked by "well-spaced" trees, while in fact the majority of the stand area is occupied by a different group of trees. This can be problematic if the characteristics of the other group of trees could have a negative influence on the future development of the "well-spaced" trees; e.g., in the case of higher competitiveness. The nearest-tree method allows estimating the proportion of occupied stand area for different pre-defined groups [e.g. 4 height class for each tree species in the study of 15].

Combining the Nearest-Tree Method with Distance Sampling

For cases where also an estimate of the number of trees is of interest in addition to an estimate of occupied stand area, the nearest-tree method can be easily combined with distance sampling for density estimation [see our 11 field surveys and e.g. 30,31]. Distance sampling has been rarely applied in forest inventories - tough for example recommended for browsing surveys by Eiberle & Lanz [20] - since it is known to lead to biased estimates [1]. However, new estimators have been developed recently that showed promising results in comparative simulation experiments [24]. Using these estimators requires the distance to at least two (like in our 11 field surveys) or more trees per sample plot to be measured during fieldwork. The analyses concerning the nearest-tree method remain the same as for estimating the "overall" proportion of occupied stand area only the very nearest tree has to be taken into account. Depending on the amount of criteria of interest, e.g., if the two nearest trees have to be determined separately for several tree species and various height classes, this method can be just as laborious as the plot-count method in densely regenerated stands (own experience of A.D. Kupferschmid).

However, the nearest-tree method gives additionally the possibility to look closer to single trees. For example, tree height and height increment of the nearest tree per species and height class can be measured and the within-tree browsing intensity can be assessed separately for winter and summer browsing. With such an extra effort not only the proportion of stocked area and browsed trees can be estimated, but also the regeneration time span and the impact of browsing on the admixture of tree species [15]. We thus recommend combining the nearest-tree method with distance sampling and height increment measurements, in case the target is to monitor the browsing impact of ungulates on tree regeneration.

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