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How to Evaluate Downed Fine Woody Debris Including Logging Residues?

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Abstract: Volume or biomass estimates of downed woody debris are crucial for numerous applications such as forest carbon stock assessment, biodiversity assessments, and more recently for environmental evaluations of biofuel harvesting practices. Both fixed-area sampling (FAS) and line-intersect sampling (LIS) are used in forest inventories and ecological studies because they are unbiased and accurate methods. Nevertheless, most studies and inventories take into account only coarse woody debris (CWD, >10 cm in diameter), although fine woody debris (FWD) can account for a large part of the total downed biomass. We compared the LIS and FAS methods for FWD volume or biomass estimates and evaluated the influence of diameter and wood density measurements, plot number and size. We used a Test Zone (a defined surface area where a complete inventory was carried out, in addition to FAS and LIS), a Pilot Stand (a forest stand where both LIS and FAS methods were applied) and results from 10 field inventories in deciduous temperate forest stands with various conditions and amounts of FWD. Both methods, FAS and LIS, provided accurate (in trueness and precision) volume estimates, but LIS proved to be the more efficient. Diameter measurement was the main source of error: using the mean diameter, even by diameter class, led to an error for volume estimates of around 35%. On the contrary, wood density measurements can be simplified without much influence on the accuracy of biomass estimates (use of mean density by diameter class). We show that the length and number of transects greatly influences the estimates, and that it is better to apply more, shorter transects than fewer, longer ones. Finally, we determined the optimal methodology and propose a simplification of some measurements to obtain the best time-precision trade-off for FWD inventories at the stand level.

Keywords: fine wood; downed woody debris; biomass estimates; forest inventory; line intersects; fixed-area sampling

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1. Introduction

Logging operations, both thinning and final fellings, usually leave varying amounts and types of residue on the forest floor, including large and small downed woody debris containing small-diameter tree branches, twigs, leaves, stumps, roots, tree-tops and bark. All of this logging residue is generally non-merchantable. Nevertheless, the increased concern of climate change has led many countries to sign commitments aiming to increase the share of renewable energies in the total energy mix, and to rank wood energy in first place to reach this goal. Consequently, mechanically harvesting coppice, low-value stands and logging residues for woody biomass energy production has become more attractive.

After fuelwood harvesting operations, on average, 40–50% of the biomass is left on the ground in the form of logging residues, as reported in recent reviews on boreal and temperate forests [1,2]. Nevertheless, Thiffault, Barrette [2] observed wide variations: from 11% to 96%, depending on the field trial. The country of study was the main factor explaining these variations; Nordic countries, i.e., Sweden and Finland, had a higher average recovery rate (72% of the logging residues harvested) than the other countries, including France. A recent study showed that a third of the study sites had less than 20% of wood residues left on the ground [3]. The second most significant factor was type of harvest: whole-tree harvesting was more efficient than slash recovery [2]. Many logging companies prefer mechanized whole-tree harvesting due to economic constraints (including low biofuel prices), even in broadleaved stands where excavators with shear-blade or disc-saw heads are used. Such harvesting techniques improve forest biomass recovery, and at the same time, dramatically reduce logging residues, with potential negative impacts on biodiversity, soil fertility and tree productivity [1,4–8]. To prevent this impoverishment, many countries have established guidelines to limit the exportation of logging residues [9–12] by defining the volume, or biomass, of fine woody logging residues to leave on the ground. To determine whether these practical recommendations are being applied, it is necessary to estimate the quantity of residues actually left after fuelwood harvesting based on an inventory of all type of woody debris on the ground both before and after harvest.

Woody debris -including downed logs, deadwood, downed wood and logging residues- can be divided into two classes: coarse and fine woody debris. Coarse woody debris (CWD) consists of fallen trees, downed logs, large lying dead branches and large fragments of wood found on the forest floor. Fine woody debris (FWD) consists mainly of fine branches, twigs and small fragments of wood, also found on the forest floor. Generally, FWD is comprised of pieces less than 10 cm in diameter and CWD of pieces equal to or larger than 10 cm in diameter, and often longer than 1 m [13,14]. Nevertheless, as there are no internationally recognized common criteria for separating these two debris classes [15]; the limit can vary according to the country or the objective of the study. For example, CWD can be less than 10 cm in diameter in National Forest Inventories: the most common minimum diameter is around 7–8 cm [16] (France 7.5 cm, USA 7.6 cm, England 3 inches), but smaller diameters are also used, as in Switzerland (5 cm) or Belgium (6.4 cm).

FWD (defined here as pieces less than 7 cm in diameter) accounts for more than 40 % of the total deadwood volume [17]. Not taking these fine woody pieces into account would, therefore, lead to an underestimation of the total deadwood volume; indeed, Teissier Du Cros et al. recommend tallying all woody pieces, with a minimum diameter approaching 0, to accurately assess total woody debris [17]. In addition, both FWD and CWD play a key role in many aspects of ecosystem functioning: e.g., they participate in the carbon pool and nutrient cycling, and provide habitat for many invertebrates, some vertebrates, lichens, mosses, fungi and liverworts [18–23]. Therefore, it is important to accurately estimate all sizes of woody debris, even the smallest (with a diameter approaching 0) when monitoring and auditing harvesting practices according to state recommendations or guidelines for biofuel harvesting.

Unfortunately, no standardized method of estimating woody debris exists, and fine debris is often excluded from inventories [14,16]. Among the many existing sampling methods used to estimate the amount of deadwood, two are the most commonly applied, for both FWD and CWD: fixed-area sampling, or FAS, [24] and line-intersect sampling, or LIS [25]. FAS was the first method ever used to sample downed woody debris. It consists in tallying downed woody pieces within a large, pre-defined area. Later on, the size of the sampling plots was reduced and smaller plots, called quadrats, are now preferred. The effect of quadrat number and size has been assessed in studies on CWD [26]. Today, many national inventories have adopted FAS for snags and CWD (e.g., Belgium, Spain, Lithuania, Sweden and the United Kingdom), while LIS is used in France, Switzerland, the USA, Canada and Slovakia. LIS is also preferred by the research community studying CWD, though it is sometimes complemented with a FAS quadrat for the smallest woody debris (e.g., the Integrated Carbon Observation System, ICOS network). The LIS method is based on a probability proportional-to-size sampling design that selects downed woody pieces crossed by fixed-length transects. Warren and Olsen [27] first applied the LIS technique to estimate logging residue in New Zealand. Since plot sampling is time-consuming, they decided to reduce the plot width to a line. This approach assumes that the volume of wood on the line represents the volume in the surrounding area. They developed a volume-per-unit-area formula but their methodology still required a separate field test. Van Wagner [28] then designed a new method where only the diameter of each piece intersected by the transect was needed to determine total volume, and de Vris [29] expanded the LIS theory and proposed various LIS estimators. Based on this work, Brown [30] wrote the first handbook for inventorying downed woody material. Subsequently, different authors examined transect shape (equilateral triangle, L shape, a single line, etc.), studied the effect of the orientation of the pieces of wood on estimations, and generalized LIS for pieces of any shape [31–34]. Other improvements to the LIS method for CWD were proposed by reviewing parameter estimates, associated formulas, details of field measurements and the presentation of bias [25,34–37].

In practice, these methods are typically applied to estimate the fuelwood in natural forests to assess fire risk or to estimate downed deadwood for biodiversity in the framework of the National Forest Inventory [38–40]. Although LIS was originally developed for all sizes of wood [30], only a few countries with a downed-wood inventory sample FWD [16], and then sometimes not the smallest pieces. Indeed, the french inventory disregards pieces under 2.5 cm in diameter [36], although it is one of the most exhaustive national inventories. Only the US samples all pieces with no minimum diameter (the first size class is 0 to 0.62 cm) [16]. Finally, studies recommend assessing the precision of this method for very fine debris by setting up a pilot study to determine optimal length and number of transects for each new objective or stand type [39].

Therefore, in our study, we sought to improve the estimation of total FWD by: (i) comparing the LIS and FAS methods, (ii) evaluating the influence of some main parameters (diameter, wood density, number and size of the plot) on volume or biomass estimates, and (iii) determining the optimal sampling design for FWD. We used a Test Zone (a defined surface area where a complete inventory was done), a Pilot Stand (a forest stand where various measurements were carried out to compare the LIS and FAS methods), and results from several other forest stands with various conditions and amounts of FWD. Finally, we propose an optimized LIS method for inventorying FWD.

2. Materials and Methods

In the present study, CWD refers to pieces more than 7 cm in diameter. This limit corresponds to the minimum diameter of merchantable wood in France and is commonly used as the reference maximum diameter for FWD [16]. We then divided FWD into two size classes: large fine woody debris (LFWD), for pieces from 4 to 7 cm in diameter, and very fine woody debris (VFWD) for all pieces less than or equal to 4 cm in diameter. We sampled all the pieces on ground, both on the soil surface, and those mixed with the litter, but excluded pieces of wood that were extensively decayed or buried in the soil. We compared our estimates for VFWD from FAS (quadrats) or LIS (transects) in a Test Zone and a Pilot Stand. In the Test Zone, we further compared the two methods against a reference value obtained by sampling all the pieces on a limited area (Reference Strips). Each unit of implementation of FAS or LIS is called a plot, which may either be a quadrat or a transect. We also estimated the amount of VFWD plus LFWD according to the FAS and LIS method in the Pilot Stand and the Forest Stands. We assessed estimate bias either in the Test Zone or the Forest Stands.

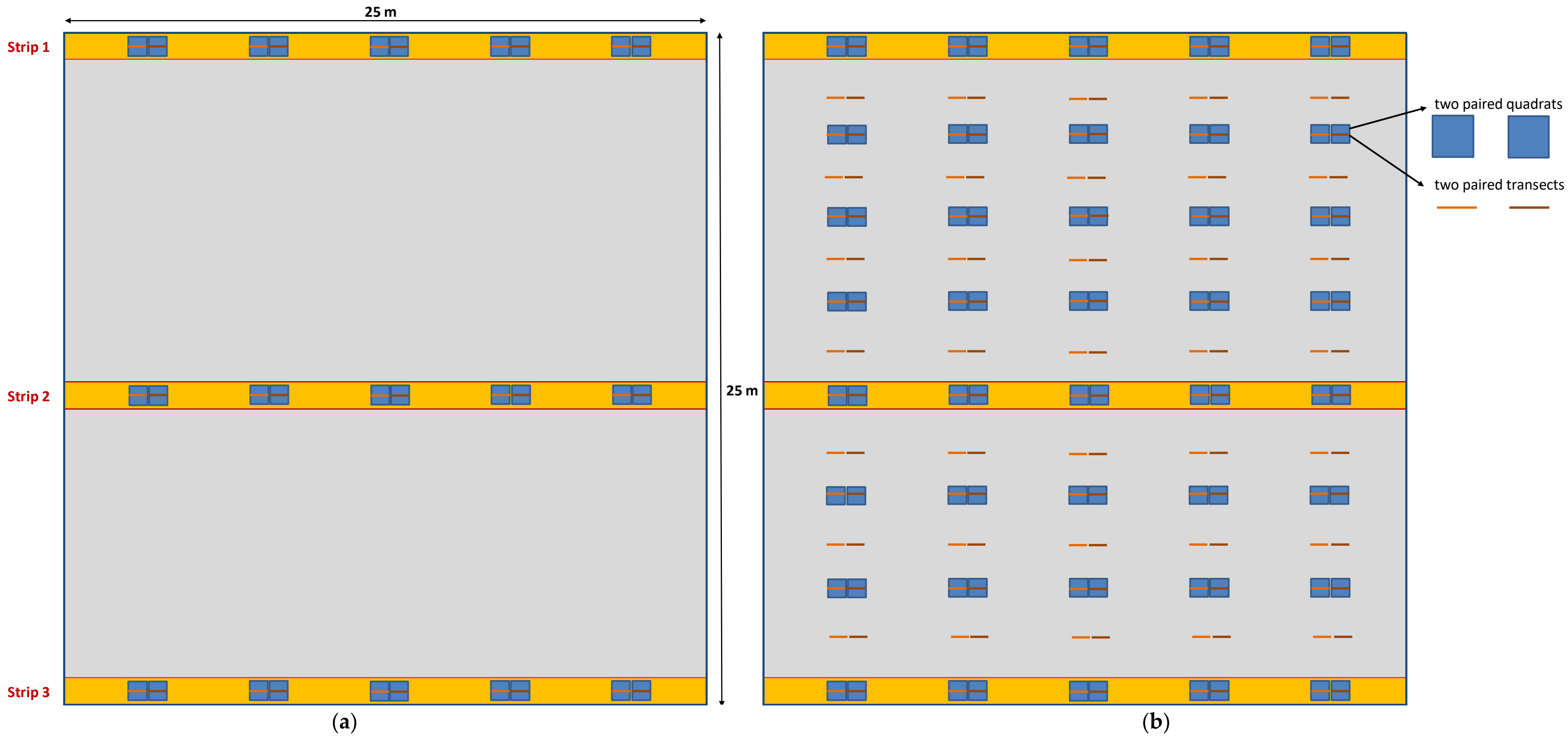

Figure 1. Schematic representation of the Test Zone and the sampling done: (**a**) comparison of line-intersect sampling (LIS) (two 0.7 m transects paired per plot, orange-brown lines, for a total of 30 transects) and fixed-area sampling (FAS) (two 0.46 m^2 quadrats paired per plot, blue squares, for a total of 30 quadrats) with a Reference Strips (orange rectangles), (**b**) estimation of biomass on the whole area of the Test Zone.

2.1. Description and Measurements in the Test Zone

The Test Zone was a square forest area of 625 m^2, set up in a stand composed of a hornbeam coppice (*Carpinus betulus*) with oak standards (*Quercus petraea*) where we applied the two methods, LIS and FAS, and then compared them to a complete inventory carried out on three "Reference Strips". The Reference Strips, located inside the Test Zone, were thoroughly sampled for all woody debris. The surface of each Reference Strip was 25 m^2 (1 m wide and 25 m long). We carried out an imbricated VFWD sampling (Figure 1a) with transects and quadrats located in pairs within the Reference Strip. First, we proceeded with the LIS protocol. We tallied all woody pieces intersecting 30 transects of 0.7 m regularly distributed over the surface of the strips (10 per Reference Strip, Figure 1a). Second, in exactly the same place as these transects, we sampled 30 quadrats (square plots of 0.46 m^2 each) following the FAS method. All woody debris found in the quadrats was collected and brought to the laboratory for measurements. Global dry weight of all the woody pieces was grouped by quadrat. We measured the diameter of all the sampled pieces (N = 2253) and the length and dry weight (oven-dried at 65 °C for 5 days) on a subsample (N = 374, 17% of all the pieces) in order to calculate woody-debris density (Density = Mass/Volume). Third, to establish reference values, all wood debris present in the three Reference Strips was collected and weighed fresh. A random sample of the woody pieces from each strip was oven-dried to obtain the percentage of humidity; this value was used to calculate total dry woody biomass at the strip level.

We used the results obtained from the strips as our reference parameters, or true values, against which we evaluated the performance of LIS and FAS (see Section 2.5). Their performance was also tested against the number of transects and quadrats sampled. To do so, we set up 120 supplementary transects and 50 supplementary quadrats regularly distributed over the Test Zone (Figure 1b) where we counted the number of pieces per transect and measured the total dry weight of all the pieces per quadrat. A grand total of 150 transects and 80 quadrats were sampled (Figure 1b) following the procedure described above.

2.2. Description and Measurements in the Pilot Stand and the Forest Stands

Our study was conducted in eight broadleaf temperate stands in the Center of France (slope < 3%). There were differences in soil characteristics, understory vegetation, species and basal area as well as quantity of woody debris but the stands were chosen to be representative of deciduous stands where whole tree harvesting is practiced to obtain fuelwood.

One site was chosen for the Pilot Stand and stands at the seven other sites (hereafter referred to as "Forest Stands") were used for field data and method optimization. All the sites were located in a temperate plain forest, and were larger than 1 ha (1.15 to 24.35 ha). The stands were composed predominantly of sessile and pedunculate oak (*Quercus petraea* and *robur*), hornbeam (*Carpinus betulus*), chestnut (*Castanea sativa*) and aspen (*Populus tremula*), and were mostly managed as coppice with standards. The mean total stand basal area was 36 m^2 ha^{-1} $\pm$ (min = 23; max = 54). Some stands had undergone a clear cut while others had been only partially cut (only the coppice was harvested). The mean total harvested basal area was 24 m^2 ha^{-1} (min = 11; max = 46) and the mean basal area of the standards (unharvested) was 13 m^2 ha^{-1} (min = 0; max = 35). Two of the Forest Stands were measured before and after harvesting, and six others only after. Overall, we carried out 10 woody debris inventories.

For the Pilot Stand, we compared the FAS and LIS methods only for VFWD, based on sampling carried out just before whole tree harvesting. Twenty-three plots over 2.2 ha were studied. First, we applied LIS (number and diameter of all pieces intersected by the 0.5-m transect) and then FAS (collection of all pieces present on a quadrat of 0.46 m^2), as described above (Section 2.1).

For the Forest Stands, we applied the LIS method after whole-tree harvest for eight sites and before harvest for two sites, for a total of 10 field campaigns. For each campaign and each site, we conducted LIS method along 25 transects of 20 m (total length = 500 m).

We laid a tape mesure on the ground (20 m) and measured the diameter with an electronic caliper of each debris piece intersecting the tape. The LFWD (4–7 cm) and CWD (>7 cm) was tallied over the whole transect length, while the VFWD (<4 cm) was tallied along two separate 0.5-m sections along each transect. Every VFWD piece in the first section, and a sample of larger pieces, were collected and taken to the laboratory to measure length, diameter and dry weight. These measurements allowed us to determine the wood density (Density = Mass/Volume, Equation (2)) for each piece collected. We further tested whether using mean values for diameter and density of FWD, either per transect or per site, had an influence on the estimates.

For LFWD, the position of each piece along the transect was also recorded. To test the influence of transect length on the accuracy of the estimate, we subdivided the 20 m transects into 1 m sub-segments. The data from the sub-segments could then be analyzed cumulatively to examine the effect of transect length and calculate optimal transect length and number.

2.3. Volume and Biomass Estimates

For the LIS method, we used the Huber formula [25] to calculate the total volume of woody debris on the studied area, as follows:

$$\text{Huber's formula}: \ V = \frac{\pi^2}{8 \times L} \times \sum_{j=1}^{m_i} d_{ij}^2 \tag{1}$$

V: woody debris volume, $m^3\ ha^{-1}$
L: total length of the transect, m
d: diameter of the wood pieces at the intercept, cm
where the indices i and j denote respectively the sample plot and piece number; m_i is the number of pieces that intersect the transect(s).

For the FAS method used in the Test Zone and the Pilot Stand, we collected all woody debris inside the 0.46-m^2, quadrats and dried it. Similarly, for the woody debris sampled in the Reference Strips in the Test Zone, the percentage of humidity of the samples grouped by quadrat was used to calculate the dry weight of the total biomass measured in the field. For both FAS and the Reference Strips, the data are expressed in $t\ ha^{-1}$.

To compare results from the two methods, the estimates must be expressed in the same physical quantity. For all the woody debris (or all the debris in a subsample), we measured diameter, length and dry mass. Then, we used the mean density (Equation (2)) of the woody debris collected in the FAS design to transform the biomass measured from $t\ ha^{-1}$ to volume in $m^3\ ha^{-1}$ (Equation (3)). The density can vary greatly according to tree species, piece diameter and decay rate.

$$D = \frac{1}{n} \sum_{j=1}^{m_i} \frac{M_{ij}}{V_{ij}} \tag{2}$$

D: mean density of the woody debris collected
M_{ij}: mass of each piece, g
V_{ij}: volume of each piece, cm^3
n = number of pieces measured

$$B = V \times D \tag{3}$$

B: woody debris biomass, $t\ ha^{-1}$
V: woody debris volume, $m^3\ ha^{-1}$
D: mean density of woody debris collected

2.4. Method Efficiency

We tracked the total fieldwork time spent for the FAS and LIS methods, and for the Reference Strips, in the Test Zone, and for the FAS and LIS methods in the Pilot Stand.

For the FAS method, the fieldwork consisted of installing the quadrat on the ground, cutting off the pieces exceeding the boundaries of the quadrat, sorting out the woody debris from the litter and dead or living vegetation, and collecting all the pieces within the quadrat. For the LIS method, we laid a a string on the ground (0.5 m) and measured the diameter with an electronic caliper of each debris piece intersecting the string. Sampling the woody debris for the laboratory measurements was also included. Calculations were not included in the fieldwork time.

For the Reference Strips, the fieldwork time corresponded to sorting out the woody debris from the litter and dead or living vegetation, and collecting all the pieces inside the Strip. A string marking the boundaries of each strip had been installed before and was not included in the total time. Weighing the collected debris in the field was also excluded, as it was negligible in comparison to the other field activities.

In the Pilot Stand, setting up the plots and carrying out measurements in the laboratory were also recorded. The set-up required measuring the distances between plots and plot azimuths to guarantee a good distribution of plot positions throughout the study area. The laboratory work included the time taken for the measurements on the woody pieces: length, diameter, fresh and dry weight when necessary. Drying time was not included.

2.5. Accuracy Assessment and Statistical Analyses

For VFWD, we compared the FAS and LIS methods and evaluated their accuracy in relation to two factors: trueness in the estimate (compared to the Reference Strips), and precision as reflected by the mean coefficient of variation (CV = standard deviation/average) or the percentage of deviation from the mean estimate. Furthermore, we tested the influence of sample size and sample number on the precision of the estimates. Observed data were used to launch Monte-Carlo simulations for 1 to 100 samples in order to determine the change in precision with the number of samples. We used a non-linear model fitted on observed data to asses changes in precision with transect length.

In order to compare LIS, FAS, and inventory in the Reference Strip, we used our density values to transform the data for volume or biomass (biomass = volume $\times$ wood density). We used an analysis of variance (ANOVA) to compare estimates from the FAS, LIS methods and inventory in the Reference Strip. To compare FAS and LIS, either in the Test Zone or in the Pilot Stand, we used a paired *t*-test, since both methods were applied at both plot types. All statistical analyses were done with the Statgraphics Centurion XVI software.

3. Results

3.1. Accuracy and Efficiency of the Line-Intersect Sampling (LIS) and Fixed-Area Sampling (FAS) Methods for Very Fine Woody Debris (VFWD, Diameter < 4 cm)

3.1.1. Comparison of LIS and FAS Volume Estimates

For the Test Zone, we compared the woody debris volume estimates from the LIS and FAS methods to the actual volume from the Reference Strips where all VFWD woody debris pieces were collected and weighed (Figure 1a, mean woody debris density was used to transform biomass into volume). The results showed small amounts of VFWD, around 2 m^3 ha^{-1}, and no significant difference (ANOVA, p = 0.31, n = 3) was observed between either of the two methods and the results on the Reference Strips (Table 1).

Similarly, in the Pilot Stand, comparing the FAS and LIS methods showed no difference (paired-t test, p = 0.73, n = 23). The estimated woody debris volume for the whole stand was 6.0 m^3 ha^{-1} and 6.3 m^3 ha^{-1}, respectively for FAS and LIS.

Table 1. Comparison of the VFWD volume (pieces < 4 cm) collected according to the fixed-area sampling (FAS), line-intersect sampling (LIS) and Reference strip applied in the Test Zone and in the Pilot Stand, and results of statistical tests.

Method	**Fine Wood Volume, m^3 ha^{-1} (Mean ± SD)**	
	Test Zone	**Pilot Stand**
Reference strip	2.06 ± 0.52	
FAS	2.27 ± 0.87	5.98
LIS	1.34 ± 0.70	6.30
Statistical test	*ANOVA*	*Paired t-test*
Degree of freedom	*2*	
Statistic	*F = 1.42*	*T = 0.34*
p-value	*0.31*	*0.73*

Italic texts present the statistical results; while non-italic texts present measured figures.

3.1.2. Comparison of the Time Spent

The time spent for set-up, fieldwork and laboratory measurements on a one-person basis is presented in Table 2 for the two methods.

Table 2. Details of the time spent sampling and measuring fine woody debris (FWD) according to the fixed-area sampling (FAS) and line-intersect sampling (LIS) methods, on a one-person basis in the Pilot Stand (n = 23 plots over the area) and the Test Zone.

	Pilot Stand		**Test Zone**		
	FAS	**LIS**	**Strip**	**FAS**	**LIS**
n	23	23	3	80	150
Plot size	0.49 m^2	0.5 m	25 m^2	0.49 m^2	0.7 m
Set up, min	240	240	-	-	-
Fieldwork, min	304.8	56.4	1320	1380	132
Lab measurements, min	180	240	-	-	-
TOTAL, min	724.8	536.4			
TOTAL, hours	12.1	8.9	22	23	2.2
Time for one sample, min	32	23	440	17.3	0.9

In the Pilot Stand, total time spent for all 23 plots was 12 h for the FAS method and less than 9 h for the LIS method (Table 2). If only a volume estimate is needed, no measurements are taken in the laboratory and, in this case, the LIS method took less than 5 h (4.9 h) to complete the work (setup and fieldwork). With the FAS method, the mass estimates were directly available from the dry weight of the woody debris collected in the quadrats. If the estimated volume is needed, additional laboratory measurements are necessary to obtain woody debris density, and this would further increase the total time for FAS, which already took nine hours for the fieldwork. The time spent setting up was the same for both methods (4 h), as set-up mostly consisted in positioning each plot and walking from one plot to another. This corresponds to 44% and 81% of the total time for FAS and LIS, respectively.

The fieldwork per plot for the LIS method in the Pilot Stand took only a couple of minutes compared to the 13 min required to collect all the woody debris inside the quadrats (FAS method). In the Test Zone, there were even greater differences in time for the fieldwork: 17 min for FAS compared to only one minute for LIS, although LIS time only included tallying the wood pieces since diameter was measured at the laboratory.

3.1.3. Influence of Plot Size and Number on VFWD Estimates

Results for the Test Zone showed that doubling the sampling effort, either by increasing transect length for LIS or quadrat surface area for FAS, did not change the biomass estimates at all. Nevertheless, increasing plot surface area slightly reduced the standard deviation and, therefore, the precision of the estimates (Table 3). On the other hand, increasing the total number of plots (quadrats or transects over the whole area) dramatically reduced the coefficient of variation (CV) of the biomass estimate for the area (Figure 2). This was especially true when there were fewer than 30 plots initially. With an initial number of more than 30 plots, an increase in sampling effort did not reduce the CV very much. Similar shapes and thresholds were obtained for the Pilot Stand (Figure 3) and the Forest Stands (Figure S1). For each field site studied, around 40 transects were needed to reduce the CV to below 10% for the LIS method; 30 transects maintained the CV below 20%.

Table 3. Fine woody biomass estimated according to plot size and method: the fixed-area sampling method (FAS: simple: 0.46 and double: 0.92 m^2, n = 40) and line-intersect sampling method (LIS: simple: 0.7 m and double: 1.4 m, n = 75 in the Test Zone, and 0.5 and 1 m in the Pilot Stand, n = 15) and results of statistical tests.

Plot Size	Fine Wood Biomass, t ha^{-1} (Mean ± SD)		
	Test Zone		Pilot Stand
	FAS	LIS	LIS
Simple	2.2 ± 1.8	1.3 ± 0.6	1.8 ± 1.7
Double	2.2 ± 1.4	1.3 ± 0.6	1.5 ± 0.7
Statistical test	*Anova*	*Anova*	*Anova*
degree of freedom	*1*	*1*	*1*
Statistic F	*<0.01*	*<0.01*	*0.25*
p-value	*0.99*	*0.99*	*0.62*

Italic texts present the statistical results; while non-italic texts present measured figures.

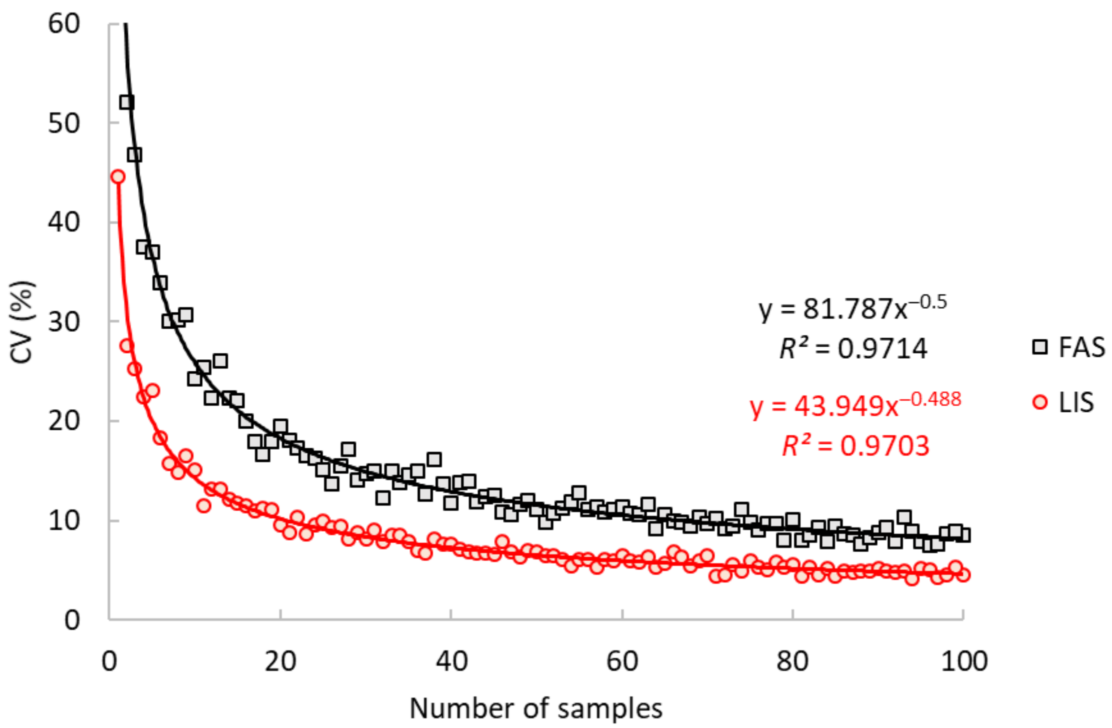

Figure 2. Sampling simulations from 1 to 100 plots for the Test Zone, and the corresponding coefficient of variation (CV) of the estimated volume for pieces from 0 to 4 cm in diameter for the fixed-area sampling methods (FAS: black squares, quadrats of 0.46 m^2) and line-intersect sampling method (LIS: red circles, 0.7 m transects). Mean of 100 simulations for each number of samples (squares and circles) and the fitted model (solid lines).

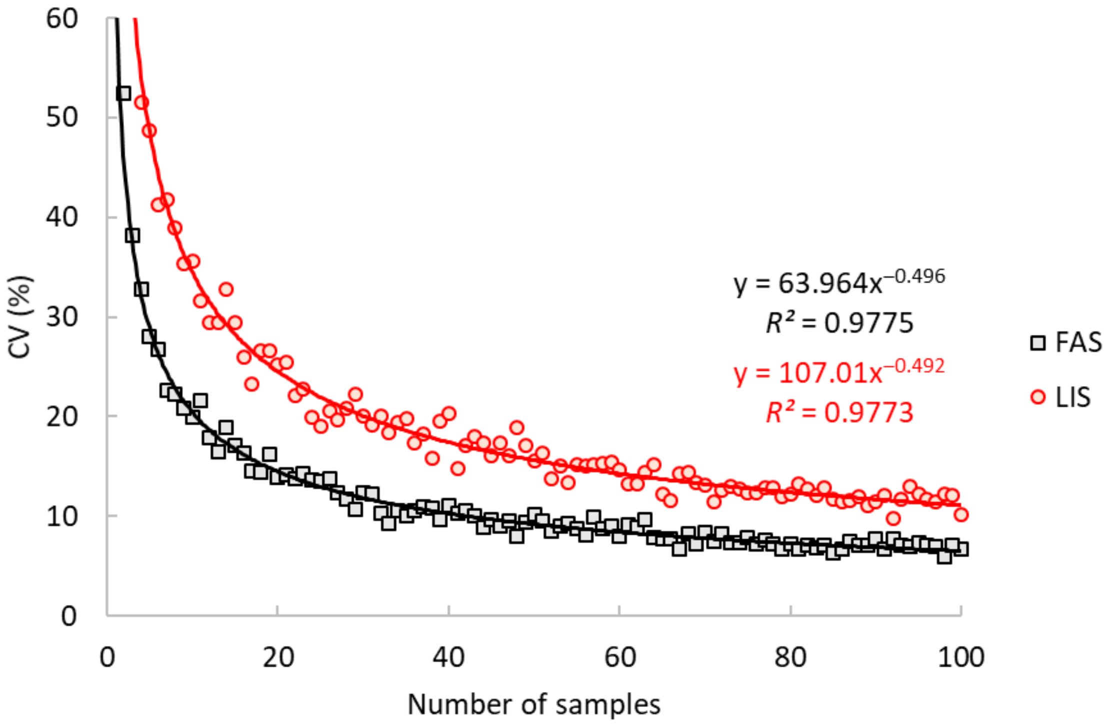

Figure 3. Sampling simulations from 1 to 100 plots for the Pilot Stand, and corresponding coefficient of variation (CV) of the estimated volume of pieces from 0 to 4 cm in diameter for the fixed-area sampling methods (FAS: black squares, quadrats of 0.46 m^2) and line-intersect sampling method (LIS: red circles, 0.7 m transects). Mean of 100 simulations for each number of samples (squares and circles) and the adjusted model (solid lines).

We also used our fitted models ($y = a.\ x^{-b}$, see Figures 3 and 4) to calculate the number of plots needed for each of the methods to reach the same level of accuracy. We found that at least 1.5 times and up to 3 times more plots were needed for LIS (transects) compared to FAS (quadrats). For example, for the Pilot Stand, 30 transects (with two sections of 0.5 m) and 10 quadrats of 0.46 m^2 are needed for LIS and FAS respectively to reach a CV of 20% (Figure 3).

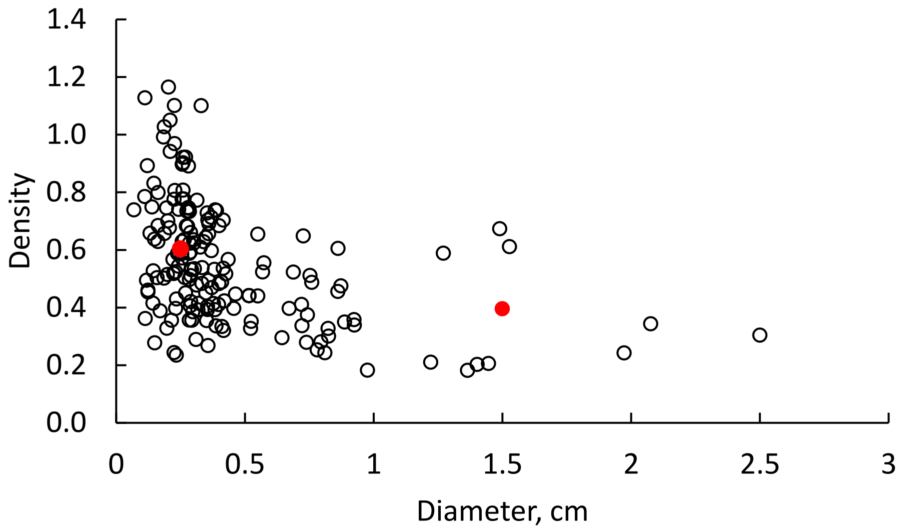

Figure 4. Density of fine woody debris (FWD) pieces in the Pilot Stand versus their measured diameter (n = 172), and mean density of the two diameter classes (red dots): 0–0.5 cm and 0.5–4 cm.

3.1.4. Influence of Debris Diameter and Density Measurements on the Estimates

For LIS, the diameter of each piece of wood must be measured to calculate volume estimates with the Huber formula. VFWD pieces can be very numerous (mean of 7.5 pieces per 0.5-m transect and high variability among transects). Therefore, we decided to check whether using only the mean or median diameter per plot, per transect and per site, and simply counting the pieces of VFWD rather than measuring the diameter of each piece, would give similar results, while reducing field time. In the case of good accuracy, the advantage would be to measure the diameter of a sample of pieces collected over the site (e.g., 100 pieces per site), and apply the mean value (or the median) to all pieces tallied.

Results from the Pilot Stand showed that using the mean diameter, per transect or per site, would lead to underestimating the stand volume by approximately 35% (Table 4). The same range of error was obtained for the biomass estimate when mean density was used (mean per transect or per site), though the direction was reversed, leading to an overestimation of from 33 to 38%.

Table 4. For the line-intersect sampling (LIS) method in the Pilot Stand, comparison of volume and biomass estimates based on the measurement (diameter or wood density) of all pieces, or based on the mean per transect (n = 23, mean ± SD, and percentage of difference compared to the measurement of all pieces) or the mean per site.

Diameter Used	Volume, m^3 ha^{-1}			Density Used	Biomass, t ha^{-1}		
Measurements for all pieces	6.0	±6.7		Measurements for all pieces	2.4	±2.4	
				Transect mean (min = 0.405, max = 0.774)	3.2	±3.5	(+33%)
				Site mean (0.552)	3.3	±3.7	(+38%)
				Site median (0.532)	3.2	±3.6	(+33%)
				Mean for smaller pieces (0.603 for pieces < 0.5 cm and measured density for the larger pieces)	2.5	±2.4	(+4%)
Transect mean (Mean min = 0.20 cm, Mean max = 1.05 cm)	3.9	±4.2	(−35%)				
Site mean (0.46 cm)	3.8	±2.1	(−37%)				
Mean for smaller pieces (0.25 cm for pieces < 0.5 cm and measurements for larger pieces)	8.3	±7.0	(+38%)				

The differences between the biomass estimates based on mean density and those based on measured density seem to be due to a few relatively large pieces with a low density (Figure 4). While the mean density value of all the pieces was 0.552, 16 pieces (mostly with a diameter > 0.5 cm) had a density value below 0.3, thus explaining the over-estimation of the biomass at the Pilot Site. Using the median of the density at the site level marginally reduced the difference. Biomass estimated based on the median density value of 0.532 was 3.18 t ha^{-1}, that is +33% compared to +38% when using the mean density for the site (Table 4).

Among the 172 pieces, three-quarters (130 pieces) were less than 0.5 cm in diameter (Figure 4). Among these smallest pieces, only five pieces (3.8%) were at densities below 0.3, while among the relatively larger pieces (diameter > 0.5 cm, 42 pieces), one forth (26%, 11 pieces) were at low densities. Then, we separated the set of pieces into two size classes and applied two different densities: we applied the mean density (0.603) for diameter class 0–0.5 cm, while we kept the measured density for diameter class 0.5–4 cm. Here, the resulting biomass estimates were similar to those based on measured diameters for each piece (2.5 t ha^{-1}, only +4%).

We further tested this size class threshold for the eight Forest Stands. Simply comparing the mean density of woody pieces in the Forest Stands provided several lessons (Figure S2). First, we saw that the 0.5 cm limit was relevant for the ten field campaigns done on the eight sites. Second, the mean debris density could be approximated to 0.61 ± 0.04

for the smaller diameter class (0–0.5 cm) and 0.42 ± 0.03 for the larger diameter class (0.5–4 cm).

3.2. Optimizing the Sampling of Woody Pieces 4–7 cm in Diameter (LFWD) with the LIS Method

3.2.1. Diameter and Density Measurements

Per site, the number of LFWD (4–7 cm) intersecting with the transects ranged from less than ten to around 50. The diameter for these larger pieces can be measured without increasing fieldwork time too much. Using mean transect or site diameter would lead to a serious mis-estimation of the volume, even more so when the number of pieces is low.

The measured LFWD diameter data from the Forest Stands (Figure S2) showed that both within-stand and inter-stand density variability was double the variability for VFWD. Therefore, the mis-estimation of LFWD biomass for calculations based on mean density would be even greater than for VFWD. In addition, it can be noted that for even larger pieces (7–22 cm and >22 cm), the variability is even higher, since the density of the woody debris for these larger diameter classes could nearly triple compared to LFWD. Consequently, it is important to measure the diameter of every piece >4 cm which intercepts the transect to avoid an error in the estimates.

3.2.2. Transect Length

We inventoried LFWD along 20 m-long transects in the Forest Stands and noted the position of each piece of woody debris on each transect to calculate debris volume. When considering the results from the first 10 m-long section of the transects, the mean volume estimate was 3.3 ± 1.0 m^3 ha^{-1}, and when we used results from the entire 20 m-long transect, the mean volume estimate was 3.0 ± 0.9 m^3 ha^{-1}. As shown in Figure 5, the CV and precision decreased with transect length: the longer the transect, the more precise the estimate (lower deviation). The slope of the curve is steep for the shorter transect length, indicating that precision increases considerably with only a slight increase in transect length. The inflection point occurred around 5 m. The slope starts to stabilize around 10 m, indicating that for longer transects an increase in precision occurs only after a greater increase in transect length. Based on 25 transects per site, the transect length needed for a deviation of around 20% of the mean estimate would be at least 7 m; at least 10 m would be required to reduce the deviation to 15%. Longer transects would increase precision by less than 1% for each extra meter of sampling and would never go below a deviation of 12.8%. When taking into account all pieces larger than 4 cm, the transect lengths needed were roughly the same (10 and 17 m-long transects for a deviation of 20% and 10%, respectively).

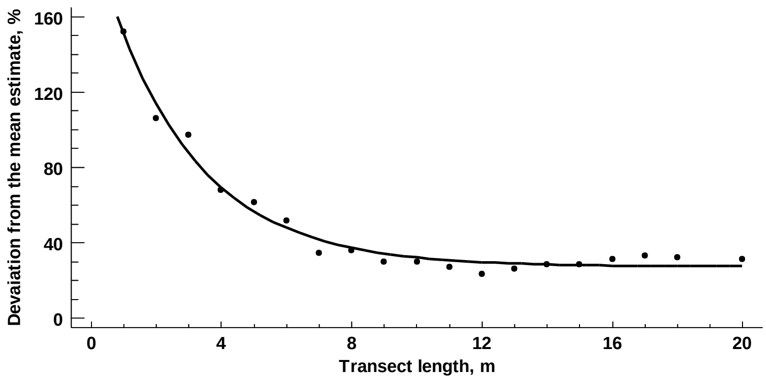

Figure 5. Improvements in precision of the mean (percentage of deviation from the mean estimate) with transect length (m) for pieces between 4 and 7 cm in diameter, based on 25 transects per site (observed data in the Forest Stands, black dots; adjusted model, black line).

3.2.3. Transect Number in Relation to Transect Length

The number of transects necessary to achieve a pre-defined precision will depend on their length (Figure 6). For the same precision, the necessary number of transects decreases as transect length increases. Based on the fitted models for three examples of transect length (2, 10 and 20 m), we determined that achieving a precision of 10% CV would require 110 transects 2 m long for a total of 220 m, 11 transects 10 m long for a total of 110 m, and 9 transects 20 m long for a total of 180 m. In other words, the most efficient transect length is 10 m. In comparison, 2 m and 20 m-long transects would respectively necessitate 2 and 1.6 times more total sampling length.

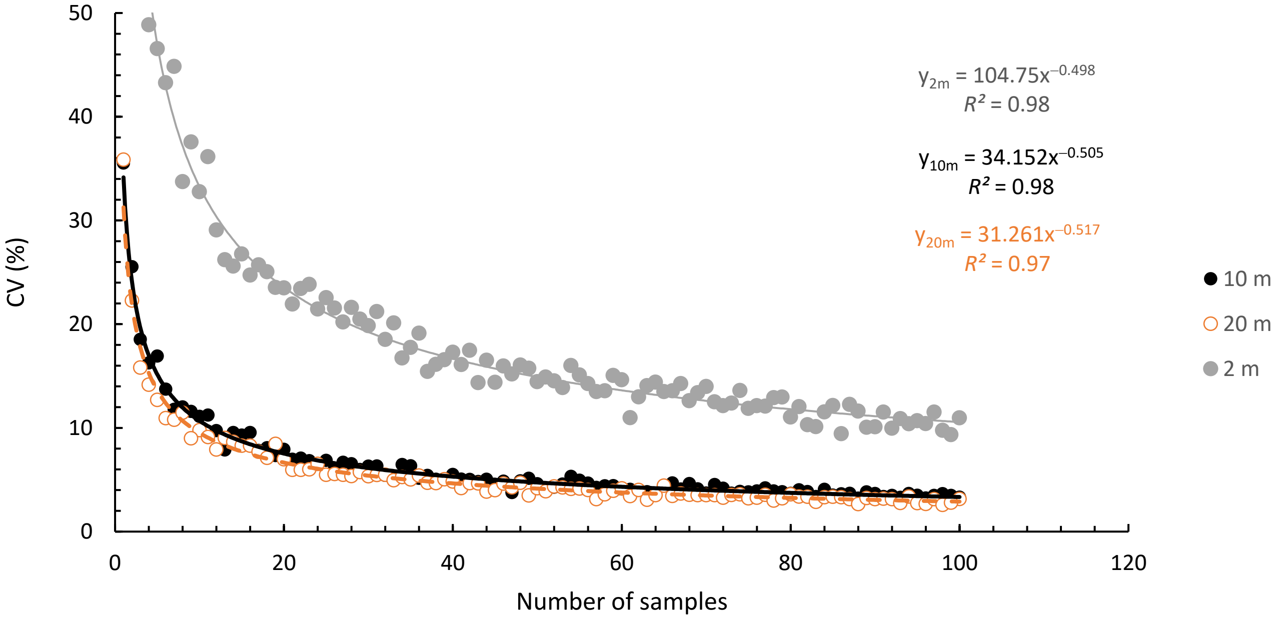

Figure 6. Improvements in precision (coefficient of variation, %) with increasing number of transects for three different transect lengths: 2, 10, and 20 m, for estimated woody debris volume of pieces from 4 to 7 cm in diameter (data from the Forest Stands where a total of 25 transects were observed). Mean of 100 simulations for each sample (dots), and the adjusted model (line).

Therefore, it is more efficient to install more, somewhat shorter transects than fewer, longer ones. Furthermore, since CV started to stabilize after 20 to 30 transects (Figure 6), the most efficient sampling design would include at least 20 transects 10 m long for a total length of 200 m. Nevertheless, to account for high variability between stands (from one to four times the volume), or sometimes within the same stand (data not shown), more transects should be included to guarantee the precision of the estimates.

4. Discussion

An accurate estimation of the characteristics of woody debris is critical for sustainable management, especially in the case of scattered, light slash such as occurs after whole tree harvesting. While LIS is adequate and widely used for CWD surveys [25,35,37], this method has not yet been assessed for FWD (pieces <7 cm in diameter). In the present study, we carried out measurements in a Test Zone, a Pilot Stand and carried out 10 extra field campaigns on various deciduous forests with different soil characteristics, understory vegetation, species and basal area as well as quantity of woody debris. We found that LIS gave unbiased estimates and was an efficient method for FWD. We also tested the influence of certain parameters on volume and biomass estimates, in order to optimize the necessary field measurements of FWD at the stand level, especially for light slash.

4.1. Trueness, Precision and Efficiency of FAS and LIS

About trueness, our results confirm that the two methods give unbiased estimates for FWD (no differences between the estimated and measured volume). To the best of our knowledge, this is the first attempt to assess the accuracy of LIS and FAS for FWD although LIS accuracy has already been proven for CWD [17,41].

Precision improved as transect length or plot number increased, following a power function [42] as $y = ax^{-b}$. Such relationships were also observed for CWD [26,42]. To maintain the CV below 20%, a number of 30 transects was necessary. We also showed that doubling the number of plots increases volume estimate precision more than doubling the plot size of each plot. Similarly, Teissier Du Cros and Lopez [17] showed that increasing the number of plots plays a greater role in decreasing standard deviation than does increasing transect length, such as found for CWD [13,26,43].

Although we showed that to obtain the same level of precision for the estimates LIS consistently required more transects than FAS did quadrats, LIS was still much faster (a couple of minute for <1 m transect compared to 13 min for 0.5-m^2 quadrat per sampling plot). Reported recording time for LIS is even faster: 40 s per meter of transect (for a minimum diameter of 0.5 cm), [17] and around 10 min per 100 m (based on two surveyors for logs $\geq$ 15 cm, [41]). Our results are consistent with previous studies which showed that a sampling method like FAS (sampling time for one large plot or cumulative time for several smaller quadrats) took much longer than sampling transects: from twice [17] to around four to five times longer [26,28,41]. Installing the plots (transect or quadrat) in the field and laboratory work (measuring volume and dry mass of the pieces to calculate debris density) were nearly equivalent in terms of time spent if both volume and mass estimates were needed. For FAS, mass was directly available, while for LIS, this was the case for volume; however, both methods require debris density values to calculate the other estimates.

Despite the evidence that the smaller the end diameter of the woody residue was taken into account, the longer it takes for inventory, for an accurate volume estimate all the woody pieces should be considered. Neglecting the smallest diameter classes in the inventories results in underestimating total woody debris volume and could be problematic because very fine debris is particularly interesting due to its high nutrient contents. Indeed, pieces less than or equal to 6 cm in diameter represent 25% of the deadwood volume [17], and if the minimum limit is 7 cm, the figure rises to 40% [17]. After whole tree harvesting in a chestnut stand, we found that VFWD represented more than 70% of the downed woody debris volume (data not shown).

The optimal total transect length or number of transects varies depending on stand type (species, management, tree health) and debris diameter; the higher the frequency of the woody pieces, the lower the CV [26]. Bate et al. [41] found that the plot size required to achieve a desired precision level was three to four times greater for harvested compared to unharvested stands. Therefore, in areas with fewer woody debris pieces, for example in whole-tree harvested stands, the spatial variability of downed woody debris is high and, therefore, the sampling effort should be higher than in unmanaged forests with numerous, large pieces.

The number of woody debris pieces increases with decreasing diameter size [17], as we observed. It follows that the appropriate sampling transect (or transect section) length can be determined according to the diameter of the woody debris, particularly when FWD is included [17,35,44]. For VFWD, shorter transects are sufficient. The procedure consists in dividing transects into sections which correspond to diameter size classes: in the first section of transect, all woody debris is measured; then for each subsequent section, the smallest diameter class is disregarded. Currently, inventories in the United States, Canada and France follow this type of procedure. In our case, the optimal transect length was around 10 m for LFWD while 0.5 m seemed adequate for VFWD. Therefore, we propose carrying out inventories on 10 m transects for larger pieces (1 plot) and on two separate sections of 0.5 m (2 plots) for smaller (0–4 cm diameter) pieces. Similar figures were proposed by Brown [30]: 0.9 to 1.8 m sections for the smallest pieces (<2.5 cm diameter), 3 to 7.6 m for medium sized pieces (2.5–7.6 cm) and 10–15 m for larger pieces (>7.6 cm).

Our results show that an optimal procedure would be to carry out 30 transects 10 m long for FWD inventory for a total of 300 m sampled including sub-transects of 0.5 m for VFWD, and a minimum of 20 transects (total of 200 m sampled) would assure a good precision. In a recent paper specifically testing the influence of transect length on LIS precision, Fraver et al. [42] recommended a total transect length of 120 m for a reasonable level of precision (18–60% CV). Other research reviewing standardized field sampling in forest multi-taxonomic biodiversity studies within the COST-Action Bottoms-up program (CA18207) tagged a total length of 150 m as the first standard (Pers. Com.). In this literature, the studied stands were not whole-tree harvested stands and they hosted more downed woody debris than did the stands in our study. As we stated earlier, the smaller the quantity of woody debris considered, the more the sampling transect length should be extended. It should be noted, however, that for large logs in harvested stands, to achieve desired precision levels, much longer transects should be used (up to 3000 to >4000 m [45]) or other protocols could be applied [24,41,46,47].

4.2. Bias in Estimates for the LIS Method

It has been reported that potential errors in estimates for the LIS method generally stem from the distribution and orientation of pieces, the use of mean diameter per class instead of the measure, and the level of decomposition and so the wood density.

First, patchiness of downed woody pieces or clustered pieces can be neutralized by extending the sampling transects over a larger area (100-m-long transects in [26]) so that they span the inherent aggregation or variability. Doing so reduces the variability among individual line transect estimates and increases the precision of the estimates at the site level [31]. In addition, and although various transect shapes—triangles, squares individual random transects, Y shaped transects (e.g., [26,32])—gave similar results, a straight line transect that samples a large area from a single given point is likely to capture more information than some other shapes (e.g., a 30 m straight line compared to a star comprising six 5 m lines or a triangle comprised of three 10 m sides) [25]. Therefore, in heterogeneous stands, long transects that cross the stand should be favored. For very large piles, some authors proceed to visual encounter census [48]. Moreover, the problem of non-random orientation can easily be solved by running sample lines in more than one direction and averaging the results [43]. Randomly choosing six directions at 30-degree intervals at each transect starting point appears to be a satisfactory approach [28,49].

Second, tallying pieces and applying the mean diameter of its class led to a mis-estimation of the stand volume, approximately 35% in our study for the class 0–4 cm. Even if the mean was only used for the smallest pieces (<0.5 cm), the error remained. Consequently, to obtain an accurate estimate, every piece must be measured. Our experiment showed that, in managed stands either before or after whole tree harvesting, this effort did not take much time (less than 2 min per 0.5 m transect) and is, therefore, quite feasible. However, in unmanaged stands, some authors proposed to tally pieces according to some diameter-class [49], and then using a representative diameter per class, such as adopted by the fire research group of the Canadian Forestry Service. The number and range of the diameter classes should depend on the purpose of the survey and the estimate accuracy desired, but the large pieces should still be measured individually [49]. On large piles, other authors proposed to take some measurements of the pile and visually estimate the packing ratio [48], but this method had not been assessed and is likely to present important operator effect. It can be noted that some authors and national surveys suggest using the FAS method for FWD, but as we have seen here, this method is less efficient. In addition, as we state above, a protocol measuring only the largest pieces would underestimate the deadwood volume, as the number of small diameter pieces may be extremely high and since FWD represents a considerable part of the total deadwood volume [17].

Third, decomposition of the downed wood itself results in very different densities and affects the biomass estimate. Calculating estimated woody debris biomass can be useful, especially when the mineralomass must be determined. For this, the nutrient concentrations in the wood (in % or mg g^{-1} of dry mass) are multiplied by the amount of woody biomass. The estimated biomass is calculated following Equation (3) and requires volume and debris density (Equations (1) and (2)). We show that using the mean diameter by class for VFWD

(<4 cm) could be an efficient way to obtain a robust estimate of the biomass while reducing laboratory working time. We further show that the lowest class (from 0 to 0.5 cm) seemed appropriate for various broadleaf stands (including birch, hornbeam, chestnut, oak and poplar). For larger pieces, differences in density values were greater among species and diameter classes so using an approximated value would increase the error on the estimate. In addition, calculations should be done per decay class for larger pieces, and when possible per species, as density varies considerably among tree species and decay stages [25,50,51]. Usually, three to four decay classes are used [17,51].

5. Conclusions

Although FWD account for a large proportion of downed woody debris, most inventory protocols are based on CWD and inventory methods have never been tested on FWD. We aimed to assess the accuracy of FAS and LIS methods to inventory FWD, based on a Test Zone, a Pilot Stand and 10 field inventories in deciduous temperate forest stands with various conditions and amounts of FWD. We showed that LIS is the most efficient method for sampling FWD (0–7 cm) in managed stands (based on trueness, precision of estimates and time spent), and can be used successfully even to estimate logging residue volumes down to VFWD. Both LIS and FAS showed good trueness and precision for volume and biomass estimates, but LIS was far more efficient. We also show that using a mean diameter, even per diameter class, would introduce errors in the estimates. However, using mean density per diameter class is acceptable and significantly reduces laboratory work. We also tested the influence of transect length and number on the estimates. By combining all of the above findings, we are able to propose an optimal protocol for FWD inventories.

6. Proposition of an Optimal Protocol for Fine Woody Debris (FWD) Inventories at Stand Level

This proposition is based on the present work, completed by a literature review about inventory of both FWD and CWD (cited in this paper), and several field studies (on 18 different stands) conducted by us or partners all over France insuring feasibility and repeatability.

The optimal number and length is 30 transects 10 m long, which should be distributed throughout the stand. Although theoretically the size of the area to be sampled is irrelevant [49]), we recommend distributing the transects over a fixed area of one hectare. Defining a fixed surface area (here 1 ha) is a precaution to avoid sampling effort effect (the precision of the estimate increases with increasing sampling effort, and the chance to detect a large, rare debris piece is higher). Another advantage is that results can be compared from one site to another without stand bias. If the stand is large or heterogeneous (>5 ha), two areas of 0.5 ha can be set up, and if the stand is very large (>10 ha), more sampling areas should be installed. As proposed by Marshall et al. [25], a systematic procedure should be used to locate the starting points of the transects to help ensure complete coverage of the area of interest and to reduce on-site travel by the field crew. An area of interest may be defined as including all the various stand structures and compositions within the boundaries of a forest stand except for such things as swamps, roads, wildlife tree patches, etc. In the case of surveys after whole tree harvesting, the wood piles on the edge of the harvested area should be avoided, but not the trails or the remaining windrows in the middle of the stand. We propose one type of design to efficiently locate transects while avoiding overlapping.

First, define the most appropriate areas where the inventory will be carried out: two 0.5 ha areas to reach 1 ha are ideal. Second, set up three straight lines per 0.5 ha, as shown in Figure 7, so that they are not oriented in the same direction as the access tracks. Each line should be spaced 20 m apart. Next, evenly distribute starting points for the transects along the lines. For a total of 30 transects, this means setting up five transects per line, each of which are 20 m apart (Figure 7). While the transect starting points should be evenly located along the line, the orientation of the transect should be chosen at random to avoid any bias caused by woody debris orientation.

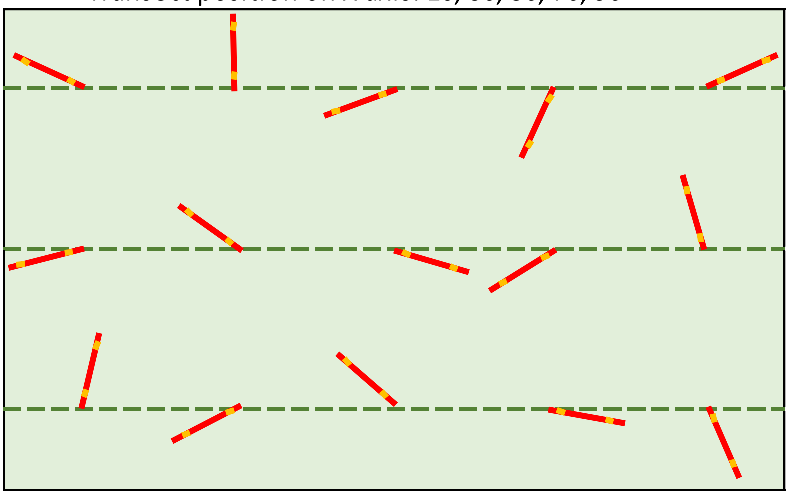

Figure 7. Example of transect layout for a forest inventory area of 0.5 ha: 50 × 100 m. The transects, 10 m long (in red), are represented in red (n = 15) and their starting points are evenly located along the X and Y axes. Woody debris pieces intersecting the transects are measured:very fine woody debris (VFWD) on two sub-sections of 0.5 m (yellow small lines within the red transects), large fine woody debris (LFWD) and coarse woody debris (CWD) along the whole transect. For CWD, extra inventory length can be added (dashed lines in green, corresponding to 300 additional meters).

Third, lay down a tape measure and take the diameter of every piece of woody debris intercepting the 10 m long transect. While LFWD (4–7 cm) are inventoried all along the transect, the smallest pieces (<4 cm), are inventoried on two sections of 0.5 m located at predetermined point along each 10 m-long transect (for example, at 1 and 6 m). Only the woody debris pieces intercepting the transect should be measured.

We recommend the following inventory procedure. CWD (>7 cm in diameter): the diameter or circumference of all the CWD pieces intercepting the 10 m transect and the 100 m line (greendashed lines in the Figure) is measured; LFWD (4–7 cm in diameter): the diameter or circumference is measured along the 10 m transects (red lines in the Figure); VFWD (≤4 cm, including the smallest pieces) is measured only along the two 0.5 m sections (yellow small lines within the red transects). For biomass estimates, wood density is needed, so the pieces should be removed and taken to the laboratory. For pieces less than 4 cm in diameter, a subsample of around 100 pieces seems reasonable. Nevertheless, the best practice is to take a small portion of every piece ≥2 cm. If possible, the decay rate should be assessed for pieces >2 cm (and when possible, species should also be recorded), and a sufficient number of samples should be collected per diameter class and decay rate [37]. Density will then be calculated per diameter class, decay rate and species. Sampling time can be reduced if data on the density of small woody pieces are available in the literature. For the broadleaf species (birch, hornbeam, chestnut, oak and poplar) studied in our stands, a density value of 0.61 and 0.42 can be used for diameter class 0–0.5 cm and 0.5–4 cm respectively. For larger pieces, samples should be taken.

In this procedure, VFWD (≤4 cm) are inventoried along 30 m/ha (15 transects ×2 ×1 m), and LFWD (4–7 cm) and CWD (>7 cm) along 300 m/ha (15 transects × 2 × 10 m). If more precision is required for CWD, a rarer type, inventory length should be increased; an easy way to do this is to measure CWD along the line with the transect starting points and/or along the edge of the inventory area. This will increase the total length of the CWD inventory to 600 or 900 m where the edges are included or not.

The above protocol was optimized for FWD (<7 cm) in managed stands, but LIS is also widely used for CWD. This protocol can be applied and is valid also for CWD since it is based on assessment results and recommendations for CWD inventory and it proposes longer total transect length, thereby leading to higher accuracy (for additional measurements for biodiversity studies for instance, see the review of Marshall 2002).

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12070881/s1, Figure S1: Sampling simulations from 1 to 100 plots, for the Forest Stands (N = 10), and the corresponding coefficient of variation (CV) of the estimated volume of pieces from 0 to 4 cm in diameter for the fixed-area sampling methods (FAS: black squares, quadrats of 0.46 m^2) and line-intersect sampling method (LIS: red circles, 0.5-m transects). Mean of 100 simulations for each number of samples (squares and circles) and the adjusted model (solid lines), Figure S2: Mean debris density at the site level (circles) for the eight Forest Stands (10 inventories) and global means (n = 10, red dash with a SD error bar) for each diameter class.

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