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Assessing Biomass Removal and Woody Debris in Whole-Tree Harvesting System: Are the Recommended Levels of Residues Ensured?

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Abstract: Forest biomass is a sustainable source of renewable energy and a valuable alternative to finite fossil fuels. However, its overharvesting may lead to soil nutrient depletion and threaten future stand productivity, as well as affect the habitat for biodiversity. This paper provides quantitative data on biomass removal, fine woody debris [d ≤ 7 cm], and coarse woody debris [d > 7 cm] left on the forest floor in whole tree harvesting systems. Using tree allometric equations and inventory field methods for woody debris estimation, we assessed biomass removal on nine fuelwood harvesting sites in Central France, as well as fine and coarse woody debris left on the sites. The aboveground biomass estimates showed a high variability between the studied sites, it varied between 118 and 519 Mg ha^{-1}. However, less variability was found among sites managed as coppice-with-standards 174 ± 56 Mg ha^{-1}. Exported biomass was 107 ± 42 Mg ha^{-1} on average, including 35 ± 9% of fine wood. The amounts of both fine and coarse woody debris left on sites were generally less than 10% of the total harvested biomass in 2/3 of the studied sites. These amounts are lower than the minimum retention levels recommended by the sustainable forest biomass harvesting guidelines. Therefore, more technical effort and additional management measures should be taken to ensure more woody debris, especially in poor forest soils and thus, to guarantee a sustainable biomass harvesting.

Keywords: whole-tree harvesting; biomass; fuelwood; fine woody debris; coarse woody debris; coppice-with-standards

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1. Introduction

The European Union is resolved to reduce greenhouse gas emissions and promoting the development of new energy policies to reverse the trend of global warming associated with climate change [1,2]. These policies aim to develop new and sustainable energy sources and contribute to a reduction in the growing dependency of EU countries on fossil fuels. Amongst renewable resources, paramount importance has been given to the bioenergy because it has low negative environmental impacts. Biomass was one of humanity's earliest sources of energy, and it remains an important resource today and for the future to enhance security energy. Today, biomass accounts more than half of all the EU's renewable energy production and 10% of all energy sources [3]. This figure is likely to rise in the future because it is considered a promising alternative to fossil energy in order to shift towards sustainability. Woody biomass accounts for more than 60% of all EU domestic biomass [4]. Indeed, fuelwood seems to be a promising option in temperate forests and developed countries [5] by providing a local supply of renewable energy and by allowing forest owners to diversify their sources of income [6]. In most European countries, woody biomass demand is rising fast with many bioenergy strategies [7,8], which have led to the adoption of new logging practices [9–11]. Different biomass harvesting methods are used in Europe; their selection depends on site conditions, silvicultural treatments, species composition, tree sizes, stand density, and the economic condition of each country. The main types of silvicultural operations, related to forest biomass extraction, are whole-tree harvesting in cleaning, thinning, and harvesting of woody debris and stumps before regeneration [12]. Nevertheless, the intensive harvesting of biomass for energy may cause additional pressure on forested ecosystems [13–19]. Recent interest in using woody debris and small-diameter material for biofuels is generating a renewed focus for studies on harvesting impacts on soils, biodiversity, and forestry practice sustainability. Indeed, this part of biomass, usually left in the forest in conventional harvesting systems, plays an essential role in nutrient cycles, maintenance of soil fertility, carbon sequestration, regeneration of communities, and biodiversity [9,10,17,20].

Forest residues, downed wood, and deadwood are different terms used to define woody debris, including all nonliving biomass. Woody debris refers to fallen dead trees and the remains of twigs, branches, and small pieces of wood left on the ground in forests. It is generally divided into two main classes: (1) Fine Woody Debris (FWD) with a diameter less than, or equal to, 10 cm, and (2) Coarse Woody Debris (CWD) greater than 10 cm in diameter [21,22]. However, as there are no clearly defined criteria to separate these two classes, the diameter limit may vary depending on the countries or research purposes. For example, the limit between the two classes is 7.6 cm (3 inches) in some studies conducted in the United States [23–25]. In addition, the number of wood diameter classes can also vary according to the objectives of the studies; three to five classes are often used to better estimate the nutrient contents of woody debris and the mineral exports associated with their removal [26–28].

Despite the relatively low proportion FWD compared to total harvested biomass, it contains a large amount of nutrients that are key elements for forest growth, and its overharvesting could compromise long-term forest site fertility [5,16,29,30]. Several studies have demonstrated that harvesting fine wood affects the soil nutrient cycling and thus future site productivity, even with high rates of fertilizer application [18,31–33]. CWD is also an important component of forest ecosystems in that it provides habitats or micro-habitats, for saproxylic species, trophic substrate, soil texturing and structuring, and temporary carbon stock [10,20].

Studies in European forests have shown that there is a significant correlation between woody debris volume, harvest methods, and such forest parameters as management, site or stand attributes [34,35]. To prevent any reduction in the woody debris left in forests and negative effects of whole-tree harvesting, many countries have established guidelines for sustainable harvesting of forest biomass in order to limit nutrient exports mainly contained in leaves and fine wood [19,28,36,37]. The guidelines are generally based on volumes or on the number of wood pieces that should be left on the forest. However, the existing recommendations for sustainable biomass harvesting may vary between countries. For instance, Nordic countries and the United Kingdom first classify sites and stands according to their sensitivity to biomass extraction (forest type, soil fertility, wood production, soil compaction, and slope), and different restrictions are then imposed for the specific site types [38,39]. For example, Finnish guidelines recommend leaving up to 30% of woody debris, or the same amount of nutrients, on the forest floor [40], using ash recycling or fertilization [12,41]. In France, the recommendations for sustainable biomass harvesting have continuously been updated since 2006 [42] through several scientific studies and increasing technical expertise [28,36,42]. The latest recommendations take into account local conditions, in particular soil sensitivity to mineral exports [28]. It is highly recommended to leave at least 10% of fine wood with a diameter of less than, or equal to, 7 cm on the forest floor for non-sensitive soils, and to increase this value to 30% on moderately sensitive soils. In the case of highly sensitive or poor soils, harvesting fine wood is not recommended; all fine wood should be left on the forest floor. Furthermore, according to USDA guidelines for the Pacific North West, at least 4%–5% of total forest biomass should be retained on the operation site to avoid soil degradation and growth decline in the next rotation [37].

Overall, the national guidelines cover the same topics and often make similar general recommendations. To protect sensitive soils, most guidelines recommend restricting biomass removal on sites identified as sensitive; site sensitivity is often based on a combination of indicators, such as slope, soil depth, and soil moisture regime, all of which may be related to susceptibility to erosion, compaction, loss of fertility, and ecosystem resilience to harvesting. To protect biodiversity, most guidelines advise for example retaining at least 10 to 30% of the slash or tops, retaining biological legacies, such as large logs, snags, or wildlife trees, and restricting biomass harvesting near critical habitats and retaining appropriate vegetation and deadwood for habitats or along rivers [37,43,44]. On top of that, it is highly recommended to harvest during the leafless period to avoid exporting leaves from forests. However, when harvesting takes place within the leafed period on evergreen species, extracting crown biomass is recommended only after pre-drying operation [12,28,42]. Pre-drying felled trees is carried out on the forest before skidding operations. This operation has two major roles: first, it may allow the weakened leaves, twigs, and fine wood to fall off during the skidding. Second, it allows maintaining a certain amount of nutrients by leaching via rainfall, depending on weather conditions.

The objective of this study was to estimate the exported biomass and to assess the amount of woody debris left in forests after whole-tree harvesting. The amounts of woody debris were also compared to the French recommended retention levels in sustainable biomass harvesting guidelines. Indeed, this research provides new quantifiable information on biomass removal through whole-tree harvesting system in Europe. A better understanding of biomass removal will enable the refinement of available forest woody debris estimates and the assessment of the potential effect of such harvesting on forest health.

2. Materials and Methods

2.1. Study Area

The study area is located in the Centre-Val de Loire region, Central France (Lat 47.705141°; Long 1.647949°). Forests are mainly private (87%), composed of broadleaves species and cover a quarter of its total area [45]. They contain an important fuelwood resource but their soils are nutrient-poor and sensitive to the loss of fertility [46]. Half of the forested area of the region has long been managed in a coppice-with-standards (CWS) regime [47]. The standard layer is mostly dominated by deciduous oaks (*Quercus robur* L., Q. *petraea* (Matt.)) Liebl. and in the coppice layer by hornbeam (*Carpinus betulus* L.), sweet chestnut (*Castanea sativa* Mill.) and other deciduous species.

Nine whole-tree harvesting sites in central France were sampled for three years 2017–2020 (Figure 1). Three sites are located in a public forest, and five are in different private forests. Some of the sites are located in protected areas of the Natura 2000 network, but none are concerned by a high-level protection measures.

All sites were harvested using a head felling shears or a feller buncher. Felled trees were cut in two or three parts and stacked in small piles on the logging area for one to three months (average 43 days). A grapple skidder was then used to extract felled trees to the roadside where they were stored in large piles of wood before chipping operation. Whole-tree harvesting was the main practice to remove the entire aboveground biomass in hardwood stands for large-scale fuelwood production, depending on stand characteristics and silvicultural objectives. Harvest treatments were either overstory removal, clearcutting, or partial improvement harvests (Table 1).

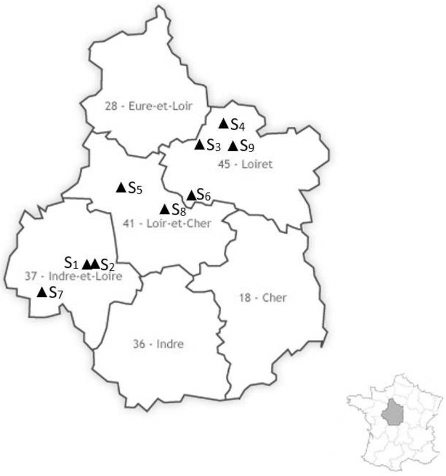

Figure 1. Location of the nine studied sites (S_1 to S_9) on the map of the Centre-Val de Loire region that comprises six departments: Cher (18), Eure-et-Loir (28), Indre (36), Indre-et-Loire (37), Loir-et-Cher (41), Loiret (45).

Table 1. Descriptive characteristics of the study sites. Presented are site number, stand type, treatment, main harvested species and basal area in m^2 ha^{-1} before the harvest.

Sites	Stand Type	Treatment	Main Harvested Species	Basal Area G (m^2 ha^{-1})
S_1	CWS	Improvement	▪ *Castanea sativa* (Mill.) ▪ *Quercus petraea (Matt.) Liebl.*	23.20
S_2	CWS	Improvement	▪ *Populus tremula* L. ▪ *Quercus petraea (Matt.) Liebl.*	32.50
S_3	High forest	Overstory removal	▪ *Carpinus betulus* L. ▪ *Populus tremula* L.	35.80
S_4	High forest	Overstory removal	▪ *Carpinus betulus* L.	45.40
S_5	CWS	Overstory removal	▪ *Castanea sativa* Mill.	33.20
S_6	Coppice	Clearcut	▪ *Castanea sativa* (Mill.)	52.20
S_7	CWS	Clearcut	▪ *Populus tremula* L. ▪ *Prunus avium* L.	28.70
S_8	CWS	Clearcut	▪ *Castanea sativa* (Mill.) ▪ *Betula pendula* Roth	32.24
S_9	High forest	Overstory removal	▪ *Carpinus betulus* L. ▪ *Betula pendula* Roth ▪ *Quercus petraea (Matt.) Liebl.*	33.30

2.2. Sampling Design and Field Measurements

2.2.1. Dendrometric Measurements

For the aboveground biomass estimates, we systematically set up one to three plots of 500 m^2 in each of the monitored sites. The number of plots by site was depending on the site area, stand heterogeneity, structure, and species composition. Every tree with a diameter greater than 1 cm was inventoried (50–70 trees per plot) including species identification and measurement of the diameter at breast height (*dbh*) at a height of 1.3 m.

Total height H_{Tot} and cutoff height H_{Cut} were measured on a representative sample of trees. H_{Cut} is defined by the French National Forest Inventory as the height of the stem measured, approximately, at the first major fork in the trunk, or, where appropriate, the height at which more than 10% decrease in diameter is reached.

After harvest, the same measurements were done for non-felled trees in case of non-clear cutting. We then used wood density for each species to convert wood volumes (m^3 ha^{-1}) to biomass (Mg ha^{-1}).

2.2.2. Woody Debris

To estimate woody debris left on each of the nine sites, we first defined two main classes according to woody debris diameter d: (i) Fine Woody Debris (FWD) [$d \leq 7$ cm] including two sub-classes [$d \leq 4$ cm], so Very Fine Woody Debris (VFWD) and [d = 4–7 cm], Large Fine Woody Debris (LFWD) (ii) Coarse Woody Debris (CWD) [$d > 7$ cm]. A variety of methods are available to assess woody debris, including fixed-area sampling (FAS) [41,42] and line-intersect sampling (LIS) [43–45]. In practice, FAS methods are based on the frequency of occurrence of individual pieces of wood in a plot of known area. Each piece that lies within the plot is tallied and parameters of interest are recorded. LIS methods are performed by establishing a sample line in the forest and tallying or recording parameters of interest for each piece wood that intersects the sample line. Both methods were used in our study, depending on diameter class.

For each site, we established a minimum of 25 sampling points and at each sampling point, we performed line-intersect sampling [48] over a 20 m-transect having a random direction. The LFWD [d = 4–7 cm] as well as CWD were tallied over the whole transect length; all pieces intersecting the 20 m-transect were measured in diameter. A sample of these pieces was brought to the laboratory where their diameter, length, and dry weight (oven-dried, 65 °C for 5 days) were measured. We then were able to calculate the wood density (Density = Mass/Volume) for each diameter class of wood and for each site.

VFWD debris [$d \leq 4$ cm] were sampled on each transect using either FAS method (two quadrats of 46 cm × 46 cm) or LIS method (two mini-transects of 50 cm). We have shown there were no differences between the two methods for FWD estimates (paired t-test, $p = 0.73$, n = 23, data not shown). All VFWD debris inside the quadrats was collected then weighed in the field (fresh weight). Sub-samples of VFWD were collected from each quadrat to form a representative sample of VFWD on each site. For the LIS method, we tallied all VFWD pieces along the mini-transects, and we measured their diameter with a sliding caliper to the nearest millimeter. We sampled VFWD pieces tallied every second mini-transect to measure their density at the laboratory.

2.3. Calculation of Biomass and Woody Debris

2.3.1. Standing Biomass

The standing volumes per hectare were estimated using tree allometric equations [49,50] as well as equations adjusted using diameter-height relation based on our field data. The distribution of aboveground biomass by tree compartments and by diameter classes (Figure 2) was calculated in three steps: (i) Estimation of total tree volume V_{Tot} (ii) Total stem, V_{Stm}, and crown volumes, V_{Crw} (iii) Volumes of the stem and crown, $V_{Stm\text{-}cut}$ and $V_{Crw\text{-}cut}$, according to the cutting levels (4 and 7 cm in diameter).

Total tree volume V_{Tot} is essential to ensure the consistency of estimates by compartments, it was calculated using Equation (1) for trees with a diameter of 4 cm or less and Equation (2) for trees with a greater diameter:

$$V_{Tot} = \mathrm{e}^{\,x + y \times ln C_{130}} \quad (1)$$

$$V_{Tot}\left(m^3\right) = \frac{H_{Tot} \times C_{130}^2}{4\pi\left(1 - \frac{1.30}{H_{Tot}}\right)^2} \times \left(a + b\,\frac{\sqrt{C_{130}}}{H_{Tot}} + c\,\frac{H_{Tot}}{C_{130}}\right) \quad (2)$$

The stem volume V_{Stm} was estimated by Equation (3) and crown volume V_{Crw} was calculated by subtracting V_{Stm} from V_{Tot}.

$$V_{Stm}\left(m^3\right) = V_{Tot}\left(d + e.ln\left(\frac{H_{Cut}}{H_{Tot} - H_{Cut}}\right) + f\,\frac{\sqrt{C_{130}}}{H_{Tot}} + \frac{g}{C_{130}}\right) \tag{3}$$

The Equations (4) and (5) allowed us to estimate volumes up to any cutting level D_{Cut} for the stem $V_{Stm\text{-}cut}$ and crown $V_{Crw\text{-}cut}$:

$$V_{Stm-Cut}\left(m^3\right) = V_{Stm} \times \left(1 - \frac{D_{Cut}{}^3}{C_{130}^3}\left(1 - \frac{1.30}{H_{Tot}}\right)^3\right) \tag{4}$$

$$V_{Crw-Cut}\left(m^3\right) = V_{Crw} \times \left(1 - \left(\frac{D_{Cut}}{C_{130}}\left(1 - \frac{1.30}{H_{Tot}}\right)\left(\frac{3-\beta}{3\alpha}\,Crown\ part\right)^{-\frac{1}{3}}\right)^{3-\beta}\right) \tag{5}$$

where: "$a, b, c, d, e, f, g, x, y, \alpha, \beta$" are parameters specific to each species and without units. C_{130} (cm) is the tree circumference at 1.30 m height and H_{Tot} (m) is total tree height. The cutoff height H_{Cut} (m) is the main parameter to distribute volumes between stem and crown, D_{Cut} (cm) is the cutting diameter. The individual tree volume was converted into biomass using density coefficients specific to each species but common to all sites, then total biomass per plot and per hectare was calculated.

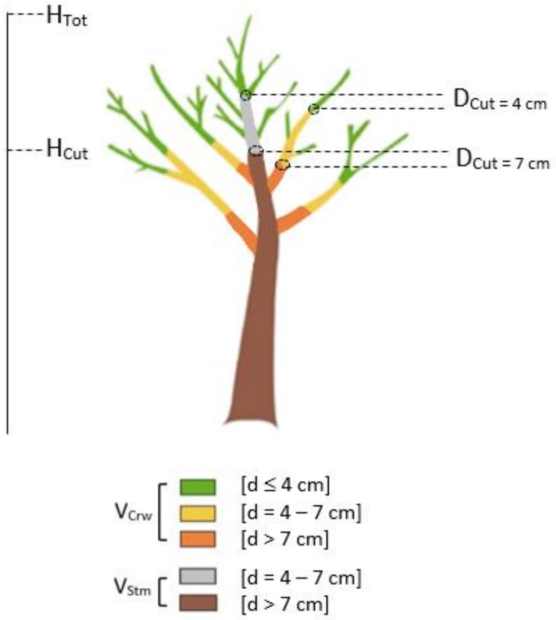

Figure 2. Distribution of tree volume by tree compartment and by diameter classes ([51], modified): H_{Tot} = total height, H_{Cut} = Cutoff height, D_{Cut} = Cutting diameter, V_{Crw} = Crown volume, V_{Stm} = Stem volume.

2.3.2. Woody Debris Volumes

First, when LIS method was performed, we calculated the volumes of woody debris using the simplified Huber's formula [48] given in Equation (6). Huber provides an estimate of the volume of a piece j on line i based on the cross-sectional area at the middle of the piece assuming that wood pieces are round or that an equivalent round diameter is recorded at the point where the piece is crossed.

$$V_i\left(m^3 \cdot ha^{-1}\right) = \frac{\pi^2}{8 \times \mathrm{L}} \times \sum_{\mathrm{j}=1}^{\mathrm{i}} \mathrm{d}_{\mathrm{ij}}^2 \tag{6}$$

where V_i is the total volume per hectare, L is the length of all transects in (m), d_{ij} is the diameter of the piece j in (cm).

The volumes of CWD and FWD were converted to biomass (Mg ha^{-1}) using wood density coefficient measured for each category of wood and for each site.

Second, when FAS method was performed for some sites for VFWD [d $\leq$ 4 cm], the estimated volume inside quadrats area was reported per hectare, then converted to biomass using wood density coefficients.

2.3.3. Total Harvested Biomass, Exported Biomass and Guidelines Comparison

Total harvested biomass corresponds to the estimated aboveground biomass, excluding non-felled trees. However, biomass, effectively exported from the forest, was calculated by subtracting volumes of FWD and CWD left on the forest after skidding operations from total harvested biomass.

Biomass harvesting guidelines include quantitative target values for post-harvest site characteristics. The guidelines refer, mainly, to the proportions of woody debris that should be left the harvest site. In this regard, the most recent recommendations [28] were used to compare our estimates to the recommended levels of woody debris. By including this aspect, we were able to take stock of the whole-tree harvesting practices within the Centre Val-de Loire region.

3. Results

3.1. Aboveground Biomass and Harvest Intensity

The studied sites correspond to different stand structures, species composition, and management systems. Aboveground biomass estimates (Figure 3) showed a high variability between sites: standing biomass varied between 118 and 519 Mg ha^{-1}. In contrast, less variability was found between sites managed as coppice and CWS (S_1, S_2, S_5, S_6, S_7, and S_8), the mean aboveground biomass was amounted to 174 $\pm$ 56 Mg ha^{-1}. High forest sites (S_3, S_4, and S_9) contain obviously more biomass 383 $\pm$ 127 Mg ha^{-1}. The proportion of wood [d > 7 cm] in total biomass was greater in high forests (83 $\pm$ 5%) than in other stands (69 $\pm$ 7%). In contrast, the percentage of wood [d $\leq$ 7 cm] was lower in high forests 17 $\pm$ 5% compared to CWS sites 31 $\pm$ 7%.

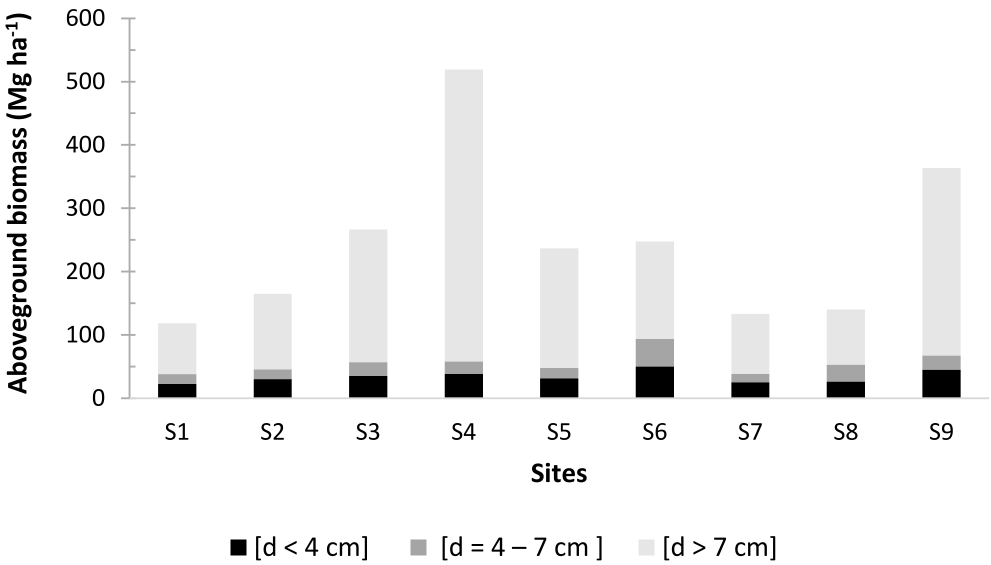

Figure 3. Estimates of standing biomass on the nine sites before harvest by diameter classes.

In general, the harvest intensity was highly variable and ranged between 13% and 100% (Table 2). On sites managed as coppice and CWS, more than 70% of aboveground biomass was harvested (S_2, S_6, S_7, and S_8), 43% for S_5 and 33% for S_1. However, the harvest intensity was lower in high forests (S_3, S_4, S_9) and ranged between 13% and 52%.

Table 2. Amounts (Mg ha^{-1}) and proportions (%) of woody debris left on sites presented for each wood diameter class.

Sites	Harvest Intensity (%)	FWD						CWD		Total Woody Debris	Total Woody Debris
		[$d \leq 4$ cm]		[d = 4–7 cm]		Total [$d \leq 7$ cm]		[$d > 7$ cm]			Harvested Biomass
		Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%
S_1	33	9.33	70	0.42	4	9.75	39	0	0	9.75	25
S_2	72	4.17	17	0.95	8	5.12	14	0.15	0	5.27	4
S_3	52	2.38	9	0.56	3	2.94	7	0.77	1	3.71	3
S_4	13	0.67	6	0.25	3	0.92	4	4.88	10	5.80	9
S_5	43	2.37	11	0	0	2.37	7	4.31	6	6.68	7
S_6	75	3.97	10	0	0	3.97	5	6.32	6	10.29	6
S_7	100	12.47	49	0.74	6	13.21	34	0	0	13.21	10
S_8	81	3.73	16	0.78	3	4.51	9	1.33	2	5.84	5
S_9	35	1.70	7	0	0	1.70	4	1.99	2	3.69	3

3.2. Woody Debris

The part of total woody debris left on the sites, compared to the total harvested biomass, was less than 10% on eight sites, and was 25% for S_1. FWD accounts for a large amount of the total woody debris and ranged from 1 to 13 Mg ha^{-1}. More precisely, the amount of VFWD [$d \leq 4$ cm] was greater than FWD [d = 4–7 cm] which was limited to a maximum of 1 Mg ha^{-1}.

In all sites, the part of FWD [$d \leq 7$ cm] left on site was less than 10% of the harvested biomass, except for S_1 and S_7 where 1/3 of total FWD was left and 14% in S_2. In high forests (S_3, S_4, S_9), an average of 5% of total FWD was left on the site. A slightly higher proportion of FWD was left in CWS sites (S_2, S_5, S_7, and S_8) from 7% to 39%.

CWD were extremely low in all sites 2.19 ± 2.38 Mg ha^{-1}, and seems to be rarely left on forest: 6% to 10% for S_4, S_5, and S_6, and less than 2% for other sites.

3.3. Woody Biomass Exports

Total biomass harvest ranged from 38 to 186 Mg ha^{-1} and was on average 114 ± 42 Mg ha^{-1} (Figure 4). However, biomass, effectively exported from the forest, do not include woody debris left on the forest. Total exported biomass ranged between 29 and 176 Mg ha^{-1}, 107 ± 42 Mg ha^{-1} on average. The part of exported fine wood [$d \leq 7$ cm] represented 35 ± 9% of the total exported biomass. More precisely, the proportion of VFWD [$d \leq 4$ cm] was 17 ± 3%, and 18 ± 9% of LFWD [d = 4–7 cm]. Larger wood [$d > 7$ cm] constitutes the largest part of the exported biomass, 65 ± 9%.

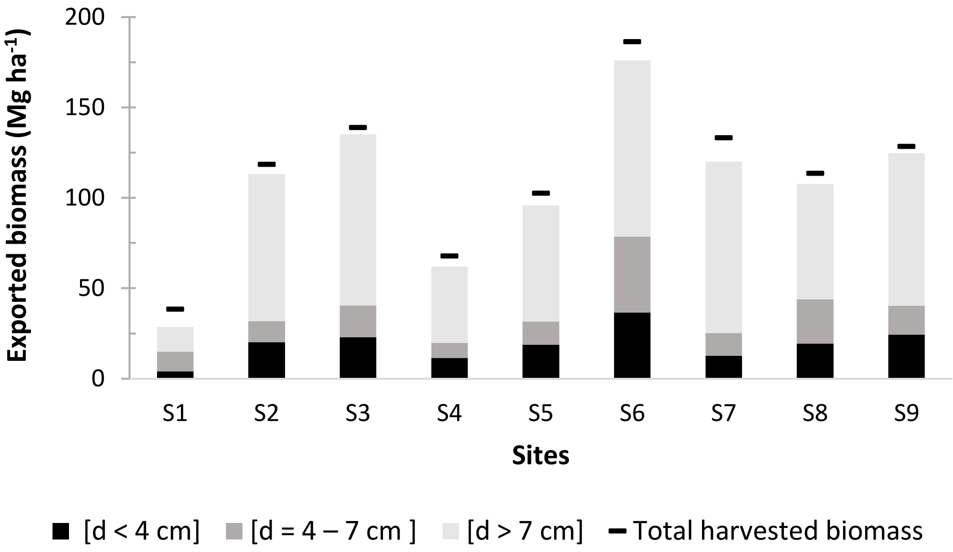

Figure 4. Representation of exported biomass by wood diameter classes and comparison to total harvested biomass.

4. Discussion

4.1. Biomass Removal and Post-Harvesting Woody Debris

In this study, biomass was extracted by whole-tree harvesting system regardless of the type of forests with a large variability of aboveground biomass. This variability could be explained by several factors: stand age, structure, basal area, management system, species composition, soil fertility, cutting methods, and silvicultural objectives. The aboveground biomass in CWS sites was 174 $\pm$ 56 Mg ha^{-1}, which is consistent with studies examining similar stands and species [27,51]. The harvest intensity was higher in CWS sites because they contain a larger proportion of small fine wood from stems and branches compared to their total aboveground biomass. In contrast, high forests contain more large wood intended for timber and the building industry and not used as a main fuelwood source. Only the crowns of larger trees are used to produce fuelwood.

The intensive removal of biomass by whole-tree harvesting has raised concern over the forest sustainability [10,17,52]. Whole-tree harvesting would decrease total ecosystem C, soil C storage, and N availability, compared with conventional harvesting [53]. It is considered to have an impact on site productivity because the nutrient-rich components, such as foliage and FWD, are removed. In this regard, several studies have shown that removing fine wood has negative effects on long-term forest yield by reducing stand productivity over time; tree growth can decrease by 3% to 20% [11,17,32,54].

The amount of total woody debris left behind in the forest after thinning or final felling in European forests ranged from 4.7 to 31.5 Mg ha^{-1} among countries and 12.3 Mg ha^{-1} on average [9]. Most woody debris is present in Central Europe, and less deadwood can be found in Northern and Mediterranean Europe. These regional differences are mainly due to differences in forest productivity and differences in management intensity across Europe. Forests in Central Europe are most productive, and forest management in Northern Europe is most intensive. In our study, the total amount of woody debris was less than 10 Mg ha^{-1}, except for one site S_7 with 13.21 Mg ha^{-1}, mostly of VFWD [d $\leq$ 4 cm]. Current levels of woody debris are generally considered low (less than 10%). These small amounts of woody debris would negatively affect soil fertility even with high rates of fertilizer application [18,33] and forest biodiversity [55–57].

CWD is also an important functional and structural component of forested ecosystems and plays an important role in creating habitat for many species of plants and animals, nutrient cycling, and long-term carbon storage [58,59]. Our findings showed that the amounts of CWD left on sites were less than 6 Mg ha^{-1}. These amounts are very low compared to similar studies related to the assessment of deadwood and post-harvesting residues. According to the French National Forest Inventory, deadwood represents an average of 23.2 m^3 ha^{-1} in the forests of metropolitan France, including 16.8 m^3 ha^{-1} of deadwood lying on the ground and 6.4 m^3 ha^{-1} of standing dead trees [60]. Moreover, CWD volume, recorded in southwestern France, was on average 35 m^3 ha^{-1} [20]. Similarly, up to 20 Mg ha^{-1} was found in the Swiss National Forest Inventory [34]. Furthermore, after whole-tree harvesting in northeastern Minnesota, 15 to 30 Mg ha^{-1} of CWD > 7.62 cm (3 inches) in diameter was left on forests [61].

The lowest amounts of CWD, less than 2 Mg ha^{-1}, could be explained by the age of the forests; younger stands would be more intensively harvested. In addition, small amounts of the pre-existing CWD could also be removed during harvesting operations [61].

On the other hand, only few studies that concerned the assessment FWD left on the forests. Most of the studies were focused on CWD because it is particularly important for biodiversity. However, FWD is as important as CWD; it mitigates erosion of exposed soil in trails and provides niches for saproxylic specialist species of fungi, beetles, and wasps [10], but most critically, it plays a role in nutrient cycling and the maintenance of soil fertility [27,30,62]. Indeed, FWD is the most nutrient-rich biomass component after leaves; it is two–three times higher in nutrient concentrations than CWD [28,63,64]. Thus, small-diameter logging debris can provide an important source of nutrients when left on harvest sites.

Studies from other regions found that FWD contributed between one-fifth and one-third of the total volume of wood, an average of 44% of the harvested FWD was left on the forest [62]. As has been found in other European managed stands, the amount of FWD was on average 11 Mg ha^{-1} [65]. Our results showed that the amount of FWD [$d \leq 7$ cm] was lower than 5 Mg ha^{-1} for six sites, and the proportion of FWD left on the sites was less than 10% (from 4% to 9%), 14% for S_2, while more than a third was left on two sites S_1 and S_7.

To summarize, the amounts of both FWD and CWD left after whole-tree harvesting were critical and, sometimes, extremely low, which would compromise forest health, ecosystems functioning, and future site productivity.

4.2. Wood Retention Levels According to Sustainable Biomass Harvesting Guidelines

Existing guidelines for biomass harvesting are addressed in varying ways, which can be broadly classified into two types: (i) those that recommend a post-harvesting fertilization or ash spreading after whole-tree harvesting [66,67], and (ii) those that prefer to maintain certain proportions of downed wood with redistribution over the whole forest [43,68–71]. For the first type of guidelines is very common in some European countries to limit, or to reduce, the negative effects of whole-tree harvesting on soil fertility [12,41]. Indeed, the use of forest biomass produces a considerable amount of ash concentrated in mineral elements, such as Ca, Mg, K, and P, which are not involved in the combustion process. In practice, several European countries allow, and encourage, the use of wood ash as an amendment in the restoration of acidified soils or as compensation method. Unlike fertilization, the objective of ash recycling is not to increase stand productivity but to support soil fertility. The idea may seem simple, but it raises many concerns, as ash also contains heavy metals from other materials burned with the forestry chips or sawmill by-products, potentially posing an environmental risk. Countries allowing ash spreading such as Germany, Austria, and Scandinavian countries are still conducting significant research on the environmental impacts as well as the social acceptability of ash spreading in forests [72–74].

In France, the development of wood burning boilers has led to a growing interest in the recycling of so-called clean ash, although it does not have yet a regulatory status (Article L 255-2 of the Rural Code). Several studies have been conducted in recent years [12,75] to better characterize ash, identify the deposits on a national scale, exploit the qualitative and quantitative data to analyze the environmental, economic and social feasibility, and finally, make the regulatory framework evolve. These studies have revealed the importance of biomass ash deposits and their expected increase. Estimates of the clean wood ash deposits, available in France, for use in forests are 107,000 tons per year according to the databases used on existing wood burning boilers [75]. Ash quality is a major criterion, and while it seems relevant to bring clean wood ash back to the forest, it is not feasible to do so for mixed wood ash, of variable composition, which sometimes exceeds thresholds in certain microelements [76]. Economically, despite higher ash input costs, it is preferable to input ash at the end of the production period, rather than at the beginning of regeneration, when other silvicultural investment costs in regeneration are already burdensome for forest managers [75]. The use of ash therefore requires a strong traceability and a follow-up of the quantities spread on the long-term in order to ensure the environmental and economic sustainability. For mineral compensation, the ADEME guide [42] recommends compensatory fertilization for any intensive biomass harvesting on moderately, or very, sensitive soils. The quantities to be brought back are specified for each silvicultural itinerary, according to the mineral exports observed on the studied sites. However, the procedures, precautions, and costs associated with the use of fertilizers were not described. In this regard, it has already been shown that compensatory fertilization and liming are more costly than the benefits derived from the additional valorization of fine wood, except when the price of fuelwood increased considerably [67].

This study focuses on the second type of biomass harvesting guidelines, which advocate leaving certain proportions of the harvested wood on the forest. Indeed, increasing the emphasis of forest management on habitat management, reducing forest fire fuel loads, or restoring ecologically degraded sites may affect how much harvest residues should be retained [37]. Biomass was extracted by whole-tree harvesting, and only small proportions of woody debris were left on the forest ground, with a median of 7%. The latest French recommendations of sustainable biomass harvesting [28] indicate to leave at least 10% of FWD whatever the conditions (stand, soil, slope, etc.) Our results showed that these thresholds were not respected in two-thirds of the sites. On top of that, most of the monitored sites had highly (S_5, S_6, and S_8) and moderate (S_1, S_2, S_4, S_7, S_9) sensitivity to intensive biomass removal according to soil sensitivity indicators based on observed soil parameters and confirmed by chemical analysis (data not shown) [46]. The recommendations take into account local conditions, in particular soil sensitivity, to mineral exports. It is highly recommended leaving at least 30% of FWD on the ground for moderately sensitive soils and to leave all the fine wood (100%) in the case of highly sensitive or poor soils. Furthermore, a recent study shows that nutrient exports by foliage are of equal importance as fine wood exports [77]. Leaving the foliage on the forest ground would significantly increase nutrient saving and will maximize nutrient returns to the soil in the case of whole-tree harvesting. However, when trees are harvested in the leafy period, the leaves cannot be easily dropped (even with 3 months of pre-drying in the forest). It is, therefore, recommended to harvest during the leafless period when possible and otherwise, letting all the leaves fall to the forest ground before skidding, not only for nutrient returns but also because easily degradable organic matter is very important for soil biological activity.

For CWD, a minimum amount of 5%–10%, in terms of the area or wood volume, has been suggested between 3 and 8 Mg ha^{-1} [78–80]. The French guidelines do not clearly specify the retention levels or volumes of CWD that should be left on the forest. The recommendations are more focused on the specific characteristics of each piece of wood (species, size, and decay class), which has a very marked influence on communities [10]. It is recommended to leave some pieces with a diameter greater than 20 cm, standing dead trees, trunks with cavities, pre-existing stumps, and isolated windfalls but also not to leave any dead trees that could contaminate other living trees [28]. In most of the studied sites, the retention levels of CWD were generally not respected, except for three sites (S_4, S_5, S_6), more than 4 Mg ha^{-1} was left on the ground. For 1/3 of the sites, the proportion of 0% suggested that a small amount of the pre-existing CWD could also be removed during harvesting operations. Therefore, more technical efforts should be made in implementing the whole-tree harvesting system to reach the recommended wood retention levels, especially in case of poor soils. In addition, there are many emerging forest policies for increasing the use of biomass, especially harvesting forest residues, tops, and branches when only timber is harvested [36,81]. Otherwise, these practices could compromise soil chemical fertility by increasing nutrient exports, modification of the biological cycles, decrease forest productivity [19,82] as well as biodiversity, and the delivery of ecosystem services [83].

5. Conclusions

This study demonstrated that only small amounts of woody debris, less than 10% of total harvested biomass, were left on whole-tree harvested sites. The amount of woody debris remaining on the studied sites were lower than in other, similar managed sites with the same harvest type. We conclude that, without additional management measures to leave more woody debris, intensification of biomass removal could negatively affect soil fertility, as well as deadwood-dependent species, which constitute an important part of biodiversity. At least, additional cutting operations should be done on the forest after felling trees, and before skidding, to ensure the recommended woody debris levels as well as a homogeneous distribution of the woody debris on the harvested area. Downed logs present before harvest and some other newly cut, and large, pieces should also be left on site to ensure a habitat for biodiversity. The most important, harvest intensity and the possibility to whole-tree harvesting should be investigated with regards to the soil sensitivity and stand characteristics (tree volumes). Further research is also needed, especially on these technical aspects: harvesting methods and residue removal to ensure necessary amounts of woody debris for ecosystem function and to guarantee a sustainable biomass harvesting.

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