SEEFOR SOUTH-EAST EUROPEAN FORESTRY

OPEN ACCESS
ISSN 1847-6481
eISSN 1849-0891

ORIGINAL SCIENTIFIC PAPER

DOI: https://doi.org/10.15177/seefor.23-07

Logging Residue Assessment in Salvage Logging Areas: a Case Study in the North-Eastern Italian Alps

Alberto Udali[1,*], Lorenzo Garollo[1], Emanuele Lingua[1], Raffaele Cavalli[1], Stefano Grigolato[1]

(1) University of Padua, Department of Land, Environment, Agriculture and Forestry, Viale dell'Università 16, I-35020 Legnaro (PD), Italy

*** Correspondence:** e-mail: alberto.udali@unipd.it

Citation: Udali A, Garollo L, Lingua E, Cavalli R, Grigolato S, 2023. Logging Residue Assessment in Salvage Logging Areas: a Case Study in the North-Eastern Italian Alps. *South-east Eur for* 14(1): 69-81. https://doi.org/10.15177/seefor.23-07.

Received: 6 Feb 2023; **Revised:** 10 May 2023; **Accepted:** 11 May 2023; **Published online:** 8 June 2023

ABSTRACT

Salvage logging operations often occur after large disturbances and usually leave behind a substantial quantity of residues, which is fundamental for maintaining soil fertility and facilitating ecosystem dynamics. This study aims to estimate the amount of logging residues following salvage operations categorized by two wood harvesting systems: Cut-To-Length (CTL) and Full-Tree System (FT). Logging residues in the harvested areas were sampled using linear transects and the data collected were divided into classes based on diameter. The quantity of residues was estimated using the Brown method for Fine Wood Debris (FWD) and the Van Wagner method for Coarse Wood Debris (CWD). Furthermore, the carbon and nutrient content associated with logging residues were also determined, considering their interaction with the soil organic layer. Overall, a higher quantity of FWD was detected in the sites cleared with the FT system and a higher quantity of CWD in the sites logged with the CTL system. Differences could be observed for all three years and systems considered, but only the third year reported statistically significant results ($p<0.01$). The soil and residue chemical analysis for carbon and nutrient contents revealed a high amount of carbon stored in a potential layer of 10 cm of soil (up to 85 $Mg \cdot C \cdot ha^{-1}$), while only up to 15 $Mg \cdot C \cdot ha^{-1}$ for the woody material.

Keywords: forest mechanization; carbon cycle; impact; management; sustainability

INTRODUCTION

In the past few decades, extreme climatic events, such as wildfires and windstorms, have increased their incidence in Europe (European Environment Agency 2019, Seidl et al. 2017) with an annual average of 0.52 disturbance patches per square kilometres of forest area (Senf and Seidl 2020). This situation made European forests more vulnerable and prone to extensive damage, with fires occurring mainly in the Mediterranean region (Verkerk et al. 2018) and storms in Northern and Central-Eastern Europe (Forzieri et al. 2019). In recent years, however, storms have become a relevant issue even in Southern Europe (Cavaleri et al. 2019, Forzieri et al. 2019, Pilli et al. 2021).

Forests are characterized by high multifunctionality, delivering multiple ecosystem services (Brockerhoff et al. 2017), especially in mountain areas where they provide not only timber production but also land protection, water supply and recreation (Häyhä et al. 2015). Furthermore, forest stands can capture and store carbon, with half of the global organic carbon in terrestrial ecosystems being stored in forest soils (Mayer et al. 2020). Moreover, European forests in the last decade have sequestered each year more than 155 Mt of carbon (Forest Europe 2020). In this way, carbon gets stocked in trees and surrounding soil, where it builds up nutrients (Bauer et al. 2000). However, this important function is put at risk by climate change and the increasing incidence of extreme events (Lindner et al. 2010). To preserve this storage function and to mitigate climate change-induced events, alternative strategies are proposed and adapted to local needs and requirements (Irauschek et al. 2017, Kramer et al. 2014, Mina et al. 2017, Pilli et al. 2021, Priewasser et al. 2013, Wohlgemuth et al. 2017).

Consequently, due to the increased incidence and magnitude of extreme events, the increase of damaged forest areas leads to an increase in salvage logging operations. Salvage logging is defined as extracting damaged timber from a disturbed forest area to minimize the economic loss of forest stands (Lindenmayer 2006). These operations are complex and pose an elevated risk of accidents. When damages occur in small and easily accessible areas close to forest roads, traditional semi-mechanized configuration systems, generally based on motor-manual processing and extraction by tractor and winch or by forest skidders (Borz et al. 2013, 2014, Iranparast Bodaghi et al. 2018), represent a valid approach despite elevated risk of accidents for the operators (Sanginés de Cárcer et al. 2021). In the case of large and damaged areas, the operations are generally performed by fully or highly mechanized configurations in order to i) foster an immediate removal of damaged trees, ii) maintain high efficiency in terms of productivity and iii) reduce logging and transportation costs (Heinimann et al. 2006, Iranparast Bodaghi et al. 2018), ensuring a higher safety level at the same time (Kymäläinen et al. 2021, Sanginés de Cárcer et al. 2021).

Salvage logging operations usually have high environmental impacts in comparison to ordinary operations, threatening ecosystem biodiversity (Thorn et al. 2018), disrupting services provided by the forests (Leverkus et al. 2018), amplifying the risks of impact on damaged forest areas in terms of soil exposure and risk of erosion (Prats et al. 2021, Robichaud et al. 2020), risk of soil degradation, with the loss of nutrients and carbon and therefore loss of fertility (Valipour et al. 2021), as well the risk of biodiversity loss (Thorn et al. 2018).

Salvage logging also affects the biomass left after the operations, such as branches, tops and stumps, hereafter referred to as "residues". The quantity and quality of residues left (fine or coarse woody debris) depend on the harvesting methods adopted (Huber et al. 2017, Tamminen et al. 2012): in salvage logging operations both Cut-To-Length (CTL) and Full-Tree (FT) extraction systems can be adopted (Figure 1a and Figure 1b).

In salvage logging operations, when the terrain is gentle, CTL is often associated with fully mechanized systems, with combined use of a harvester and a forwarder. Adopting the fully mechanized CTL system increases the level of safety in salvage logging operations with consequent reduction of the risk of accidents for the operators (Cadei et al. 2020, Sanginés de Cárcer et al. 2021). In the case of fully mechanized CTL, the tree is processed at the stump site by the harvester machine and consequently most of the logging residues are left on the ground homogeneously distributed or piled in heaps (Nurminen et al. 2006).

When the terrain gets steeper, cable yarding is the preferred system, viable also considering salvage logging conditions (Spinelli et al. 2022), favouring a higher mechanization level and efficient processing of the full tree at roadside by using excavator-based processor head or by using a processor mounted on a cable tower yarder (Mologni et al. 2016). In this case, the entire tree is extracted with the branches and the top, delimbed and cut by the processor head, thus accumulating most of the logging residues at the roadside, in the same area in which the trees are processed. Therefore, the full-mechanized CTL system and the FT systems represent two opposite ways of logging in terms of residue generation and removal from the forest.

Specifically for the two machine configurations, cable yarding is considered to have smaller impact than ground-based mechanized system (Mologni et al. 2016, Stanturf 1990). In fact, cable yarding extraction has lower impact on soil compared to ground-based systems (e.g., harvester and forwarder or tractor and winch system) (Krag et al. 1986, Laffan et al. 2001, Miller and Sirois 1986) and lower costs at the same time (Heinimann et al. 2006). However, in terms of residues left in the forest (e.g., branches, top and stump), conventional FT harvesting has a greater amount of nutrients removed from harvest sites than in CTL harvesting due to the extraction of nutrient-rich branches and foliage (Huber et al. 2017).

Forest residues and deadwood are major sources of nutrients and carbon (Janowiak and Webster 2010, Palviainen

a) b)

Figure 1. Effect of the application of different harvesting systems and machine configuration for salvage logging operations in southern Alps after the Vaia storm in 2018 based on **(a) a** CTL system with fully mechanized harvesting system with the integration of harvester and forwarder machines, and **(b)** based on a FT system with semi-mechanized felling, cable yarder extraction and tree processing at roadside.

et al. 2010). Variations in quantity and quality of residues affect soil fertility (Mayer et al. 2020), putting at risk site regeneration and future growth of forests (Bače et al. 2012, Bauer et al. 2000, Motta et al. 2006, Zielonka and Niklasson 2001). Furthermore, forest biodiversity can also be affected by disturbance regimes such forest fires and bark beetle outbreaks (Carlson et al. 2017, Mattson et al. 2019, Sullivan et al. 2021). Moreover, they create uncertainty in carbon stock quantification since fine residues are usually ignored in the estimations (Maas et al. 2020). Also, there is an increasing interest in the retrieval of this material for bioenergy production (Bessaad et al. 2021).

The aim of this study is thus to verify and quantify the effect on logging residues' quantity due to the adoption of different harvesting system and configuration in salvage logging operations, and consequently estimate the difference in terms of carbon and nutrient potential of residual availability for *in situ* nutrient and carbon cycle. Moreover, we also want to investigate the timing of operations and how this affects the residues' quantity.

MATERIALS AND METHODS

Study Area

The mountain forests considered (S. Martino di Castrozza, Paneveggio e Cadino) are located in the province of Trento in north-eastern Italy and belong to the Autonomous Province of Trento (Figure 2). The forests consist of a typical spruce mountain forest, mainly composed of Norway spruce (*Picea abies* (L.) H. Karst) and larch (*Larix decidua* Mill.), with an average altitude between 1,550-1,670 m a.s.l., and an average growing stock of 425 $m^3 \cdot ha^{-1}$. These areas were all impacted by the Vaia storm at the end of October 2018.

Two sites having similar characteristics were selected from each forest stand: large and cleared forest areas, with the possibility to find forest machine tracks and comparable forest types. The sites from Cadino have east and north-west aspect, while all the other four sites face south or south-east. The sites have been all subjected to salvage logging in the period of 2019-2021 following the Vaia storm, with the use of both harvesting CTL systems, with harvester and forwarder (HF), and harvesting FT systems, using cable yarder (CY). The field sampling over the area was performed in the summer of 2021. Table 1 summarizes the main data related to the selected study sites.

The choice of the study areas is key for understanding this study approach: the similar conditions of the forests and the selected sites (i.e., in terms of forest type, growing stock, and aspect) are the main assumptions to shift the analysis from the geographical to the temporal scale. Each site will then represent the year in which it was harvested with respect to the system and configuration adopted during salvage logging operations to better evaluate the timing effect on residue quantities.

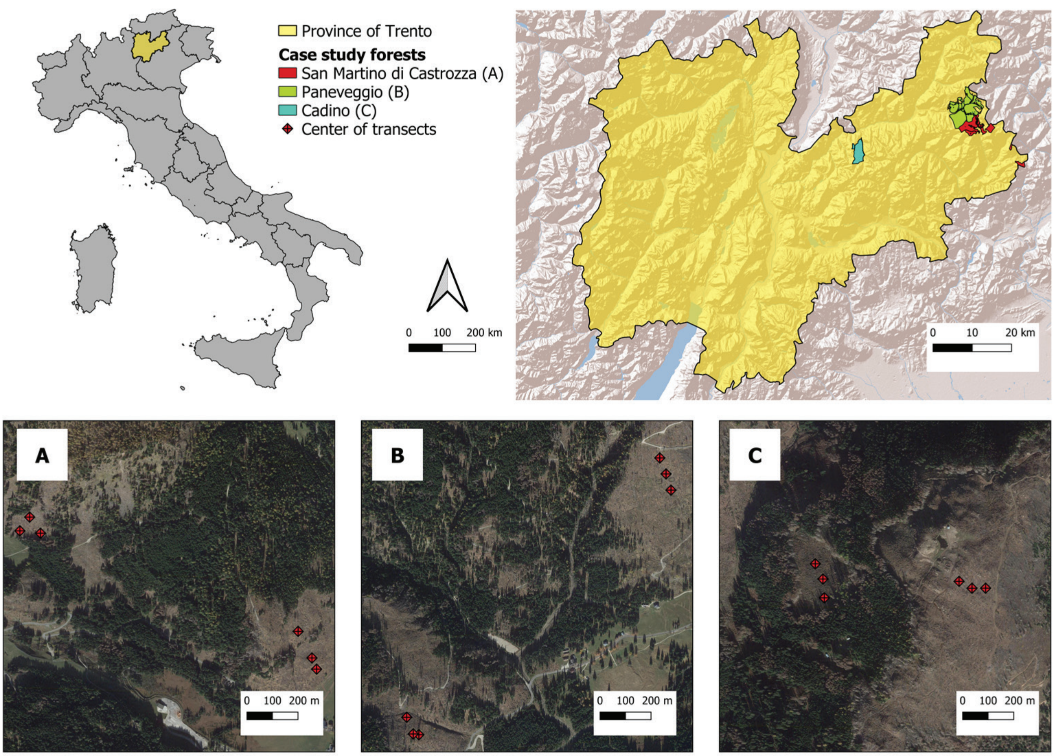

Figure 2. Study areas' locations.

Table 1. Summary of data related to the study sites selected. "Salvage logging" refers to the year of operation and the system adopted (HF - harvester-forwarder, CY - cable yarder); in brackets the years after the Vaia storm are reported.

	S. Martino di Castrozza		Paneveggio		Cadino	
Average altitude	1,570	1,670	1,650	1,550	1,660	1,640
Aspect	SE	S	S	SE	E	NW
Surface (ha)	14.48	19.92	24.28	18.38	16.88	20.12
Damaged surface (%)	92.5	27.5	69.7	63.5	96.3	19.1
Growing stock ($m^3 \cdot ha^{-1}$)	456.13	321.15	442.51	517.97	399.58	414.33
Salvage logging	CY 2019 (1)	CY 2021 (3)	HF 2019 (1)	CY 2020 (2)	HF 2020 (2)	HF 2021 (3)
Site coordinates (EPSG 32632 coordinate)	714443 E 5127902 N	715537 E 5127363 N	711231 E 5132502 N	710260 E 5131493 N	684821 E 5122355 N	684824 E 5122355 N

Field Sampling and Target Material

The selected study sites have been investigated first using aerial photos to compare the situation before and after the Vaia storm. What is more, a canopy height model (CHM) was obtained to assess the size and distribution of the trees in the sites, therefore providing an initial understanding about the potential location of residues on site (Figure 3). The tree density and growing stock were lower in HF 2020 and CY 2021 than in the other sites, whereas the tallest trees, of more than 30 m, were found in HF 2021 and CY 2020. Lower stand density, with a higher gap fraction in the canopy cover, might suggest the presence of a higher crown ratio, and therefore the presence of more branches. In contrast, the presence of tall trees might indicate the presence of thinner material on site.

Field sampling of logging residues was performed by adopting a line intersect sampling (LIS) method, which estimates weights and volumes of down woody material (Brown 1974, Woodall and Monleon 2008) over completely clear-felled areas. The main assumptions when using this sampling technique are the random orientation of the woody debris under the linear transect, lying horizontally, having a circular shape, and a normal distribution within diameter classes. For this study, the sampling method (Figure 4) was initially adapted from Rizzolo (2016) , registering the diameter of each woody debris under a 20 m line and classifying them in time lag classes (Table 2). This division refers to the time required for a fuel particle to change its moisture content accordingly to the equilibrium moisture content but can be easily adapted to other applications: material finer than 76 mm in diameter belongs to fine woody debris (FWD) and larger material to coarse woody debris (CWD). The length has also been recorded for CWD larger than 203 mm.

Each sampling is composed of three parallel transects, the central one located where the forest machines (in the case of HF) or the cable line (in the case of CY) was passing

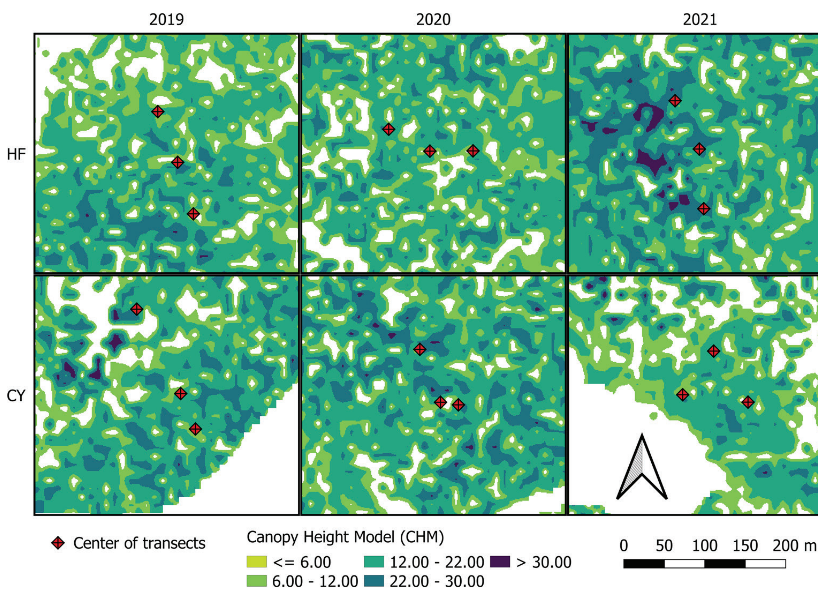

Figure 3. Canopy Height Model (CHM) of the considered sites with the centre of the transects.

and the other two on each side. The central one has been modified into a series of four sub-transects orthogonal to the extraction line to better account for the variability of residues and the harvesting system effect. The distance between the central transect and the lateral ones is 10 m for HF and 15 m for CY. Three samplings have been selected for each of the extraction lines, with a ground distance of 50 m between them, when possible. Moreover, to minimize road influence, the starting points were placed at least 20 m from the roadside for both HF and CY sites.

Residue Mass Estimation and Statistical Analysis

The residue quantity estimation (Mg·ha^{-1}) was performed for both categories of residues: for FWD classes, the Brown's formula was used (Brown 1974), described in Equation 1. For bigger elements, CWD in this case, for Class D, a simplified version of Brown's formula was applied, shown in Equation 2. For Class E elements, instead, the estimator was computed using Van Wagner formula (Van Wagner, 1968), expressed by Equation 3.

$$\hat{Y}_{FWD} = \left(\frac{1.234 \cdot n \cdot \bar{d}^2 \cdot SG \cdot c \cdot a}{\sum L}\right) \cdot k_{decay} \cdot 10{,}000 \quad (1)$$

$$\hat{Y}_{CWD} = \left(\frac{1.234 \cdot n \cdot \bar{d}^2 \cdot SG \cdot c}{\sum L}\right) \cdot k_{decay} \cdot 10{,}000 \quad (2)$$

$$\hat{Y}_{CWD(E)} = \frac{\pi^2 \sum d^2}{8L} \quad (3)$$

Where: 1.234 is a conversion constant derived from the literature; *n* is the number of elements for each class; is the average squared diameter for the class; SG is the specific gravity for the wood species considered; *c* is the corrected slope; a is the correction coefficient for the position of the elements, equal to 1.13 for FWD and equal to 1 for CWD; L is the length of the sampling line(s); *kdecay* is the decay coefficient as described by Woodall et al. (Woodall and Monleon 2008); 10,000 are the square meters in 1 ha. Due to the characteristics of the wood, as timber and debris were preserved over the previous two years by snow without major discoloration and with intact wood texture, an average SG of 0.44 was selected, with a density (ρw) of 0.44 g·cm^{-3} (oven dried). Similarly, the decay of the material was considered as class 1 (Petrillo et al. 2016). The corrected slope was calculated as described in Equation 4.

$$c = \sqrt{1 + \left(\frac{Slope_{\%}}{100}\right)^2} \quad (4)$$

Additionally, the average value of residue mass was divided to analyse the spatial distribution between the logging trails (i.e., the central transect) and the surrounding areas (i.e., the lateral transects), as shown in Figure 4.

To better analyse the results, a normality test was performed using the Shapiro-Wilk test, as well as a visual assessment of the data distribution since the number of elements for each class-harvesting system-year was small. The result of the normality assessment was a non-normal distribution. In order to validate the residue estimations resulting from the same year, but performed with a different harvesting system, a statistical analysis was performed by comparing the estimators, in order to obtain any significant differences using the two-tailed Mann-Whitney U-test (*$p<0.01$).*

Chemical Analysis of Soil and Residues

For each forest site, samples of soil and residues have also been collected for chemical analysis. Due to the large variability in forest soils, for each site, soil samples were collected randomly on eight separate locations with a total of 800 g and pooled before the analysis. Then, the soil density was derived from the total organic carbon available, as showed in Equation 5 where *ρ is the soil density* (Mg·m^{-3}) and TOC% is the concentration in the percentage of organic C (Hollis and Woods 1989), in order to compute the carbon stock (SOC), applied from Papais et al. (2014) and reported in Equation 6.

$$\rho = -0.00745 \cdot TOC\% + 0.593 \quad (5)$$

$$SOC_{soil} = \sum_{n=1}^{k} [TOC\% \cdot \rho \cdot T \cdot (1-\delta) \cdot 10] \quad (6)$$

Where: SOC is expressed in Mg·ha^{-1}; T is the height of the soil horizon; δ is the coarse fraction in the soil horizon expressed as % of material greater than 2 mm. For this study, SOC was calculated for a scenario on soil of a potential depth of 10 cm.

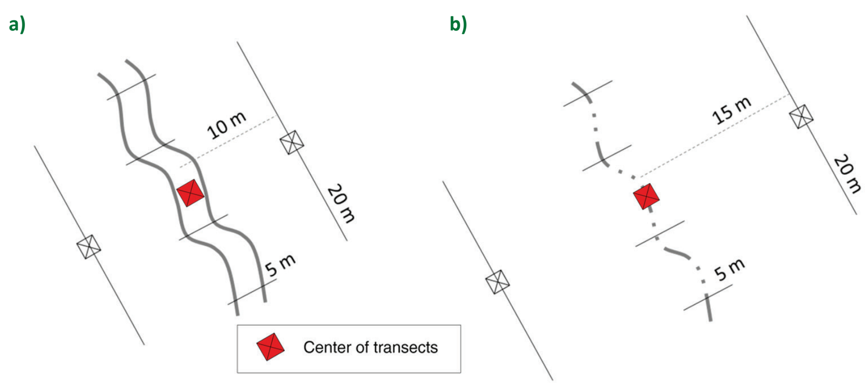

Figure 4. Transect organization and localization referred to **(a)** harvester-forwarder sites (HF) and **(b)** cable yarder sites (CY).

Table 2. Time lag class distribution, with diameter (D) thresholds, and category for forest residues (FWD - fine woody debris, CWD - coarse woody debris) (Brown 1974, Rizzolo 2016).

Class	D min (mm)	D max (mm)	Category
A	0	6	FWD
B	6	25	
C	25	76	
D	76	203	CWD
E	> 203		

For the chemical analysis of the residues, a sample for each diameter class was randomly collected on each site from the extraction lines and the areas on the side. After that, the samples from each forest and harvesting systems were regrouped, mixed and grinded, obtaining four samples, one for each diameter class. For CWD, the D and E class have been combined due to the similarity of the material. Specifically for this last sample, a quantification of the carbon stock was conducted since a lower decay rate characterizes it, therefore with potentially a higher carbon input for the soil. The adopted method was the same as by Petrillo et al. (2016), displayed in Equation 7.

$$SOC_{CWD} = \sum_i \frac{V_i \cdot TOC\%_i \cdot \rho_w}{100} \quad (7)$$

Where i refers to each decay class considered; V is the volume per hectare; and ρw is the wood density (g·cm^{-3}).

RESULTS

Residues' Quantity According to Harvesting Systems

The estimated mass per hectare for HF sites is reported in Table 3. For the time period considered it emerges that, despite class A with similar values, the tendency for the contents in the other classes is to decrease with time. The higher estimated average value remains for the residues in class C. For the coarser classes, the estimated mass showed higher values increasing throughout the years, with increasing standard deviation, and therefore variability as well. A similar trend emerges by looking at the median values (Table 4).

The mass per hectare estimation for CY sites is reported in Table 5. Compared to HF, for the cable yarder sites the emerging trend is different: for each year, the highest quantity belongs to class D, except for 2020 that is class C. Considering a broader spectrum, CWD values for CY increase through the years in the considered period. The coarser material (class E) registered the highest values of standard deviation, indicating larger variability among the sampled material. A similar trend is highlighted by the median values reported in Table 6.

The residues' spatial distribution is shown in Figure 5a and 5b, for HF sites and CY sites, respectively. For HF sites, greater variability within residues can be observed in classes with bigger dimensions. For each year and class of FWD (A, B and C), more material is found in the central transects rather than the lateral ones. The same can be said for class D, but the tendency overturns for the coarse material of class E, where there is more material on the lateral transects. For the CY sites there is much more variability in terms of estimators' values and material distribution, which generally increases through the years both for central and lateral transects.

Table 3. Average mass value (Mg·ha^{-1}) for residues (FWD - fine woody debris, CWD - coarse woody debris) in harvester-forwarder (HF) sites divided for each class. Standard deviation is also reported in brackets.

Average mass value	FWD			CWD		Sum (Mg·ha^{-1})
	A (Mg·ha^{-1})	B (Mg·ha^{-1})	C (Mg·ha^{-1})	D (Mg·ha^{-1})	E (Mg·ha^{-1})	
HF 2019	1.79 (1.25)	9.77 (4.06)	19.33 (10.80)	13.01 (9.86)	9.59 (17.84)	53.49
HF 2020	2.49 (0.94)	10.04 (4.32)	14.74 (14.97)	8.61 (10.48)	14.24 (20.20)	50.12
HF 2021	1.93 (0.98)	7.68 (3.56)	10.64 (3.26)	9.66 (6.27)	22.43 (28.99)	52.34

Table 4. Median mass values (Mg·ha^{-1}) for residues (FWD - fine woody debris, CWD - coarse woody debris) in harvester-forwarder (HF) sites divided for each class.

Median value	FWD			CWD	
	A (Mg·ha^{-1})	B (Mg·ha^{-1})	C (Mg·ha^{-1})	D (Mg·ha^{-1})	E (Mg·ha^{-1})
HF 2019	1.56	10.04	19.18	14.02	0.00
HF 2020	2.44	11.28	9.48	9.07	6.28
HF 2021	2.05	6.92	11.30	9.17	13.73

Table 5. Average mass value (Mg·ha^{-1}) for residues (FWD - fine woody debris, CWD - coarse woody debris) in cable yarder (CY) sites divided for each class. Standard deviation is also reported in brackets.

Average mass value	FWD			CWD		Sum (Mg·ha^{-1})
	A (Mg·ha^{-1})	B (Mg·ha^{-1})	C (Mg·ha^{-1})	D (Mg·ha^{-1})	E (Mg·ha^{-1})	
CY 2019	2.74 (1.21)	7.19 (2.60)	13.45 (10.45)	15.16 (7.57)	4.60 (9.57)	43.14
CY 2020	2.97 (1.38)	10.72 (5.18)	14.01 (5.39)	11.72 (9.34)	12.51 (16.14)	51.93
CY 2021	6.69 (3.55)	15.73 (7.07)	16.37 (8.43)	21.68 (13.99)	9.61 (14.04)	70.08

Table 6. Median mass value (Mg·ha^{-1}) for residues (FWD - fine woody debris, CWD - coarse woody debris) in cable yarder (CY) sites divided for each class.

Median value	FWD			CWD	
	A (Mg·ha^{-1})	B (Mg·ha^{-1})	C (Mg·ha^{-1})	D (Mg·ha^{-1})	E (Mg·ha^{-1})
CY 2019	1.94	7.06	8.09	15.95	0.00
CY 2020	2.79	8.73	14.00	9.29	0.00
CY 2021	6.04	14.85	14.05	20.01	8.98

Differences Between Residue Mass Estimators

Table 7 summarises the *p-value* computed with the test divided by year of operation and classes. Overall, for the quantities of the first and the second year (2019 and 2020, respectively), there are no significant differences that can be appreciated among the two harvesting systems. The values for the third year (2021), on the other hand, display a different outcome: the p-value computed for 3 out of 5 estimators resulted with the highest level of significance ($p<0.01$), highlighting the differences between the harvesting systems.

Chemical Analysis of Soil and Residues

The results of the chemical analysis are presented in Table 8 for both soil and residues. As for the soil, San Martino presented a higher moisture content compared to the other two. For both total nitrogen and total carbon, there is a decreasing trend with the decreasing moisture content of the sample. This is also reflected in the organic fraction and with less degree for the inorganic one.

The differences in the soil chemical composition are shown in Table 9. In particular, related to the Cadino forest, with the exception of P, all the other elements concentration are lower compared to other forests. Moreover, although the differences between Paneveggio and San Martino are not evident, and despite the closer geographic location, there is a higher concentration of Ca, Mg and Mn in the first one, and higher concentration of N, C, Fe, K and P in the second one. For the carbon stock, with a hypothetical organic horizon of 10 cm, the forests of Cadino showed the lower value (45 Mg·ha^{-1}) and San Martino the highest (85 Mg·ha^{-1}).

The same analysis was repeated on the residues and reported in Table 10. The general tendency for all the elements is to maintain a higher concentration on the finer residues, decreasing with the increasing size of material.

A potential SOC was computed for the CWD classes as aggregated information, as a possible contribution of organic carbon that can be absorbed in the soil once the material is decomposed (Table 11). The potential SOC for the 2019 and 2020 sites have similar values, with a higher value for both 2021 sites.

Table 7. A summary of the *p-values* calculated with the two-tailed Mann-Whitney U-test between cable yarder (CY) and harvester-forwarder (HF) sites for each year of operation. The time in years from the Vaia storm is reported in brackets.

	FWD			CWD	
	A	B	C	D	E
2019 (1)	0.0260	0.9213	0.9533	0.2131	0.6038
2020 (2)	0.2981	0.4648	0.1657	0.1420	0.6268
2021 (3)	0.0013*	0.0040*	0.0560	0.0067*	0.9370

Notes: '*' highlights the significant level considered. FWD -fine woody debris; CWD – coarse woody debris.

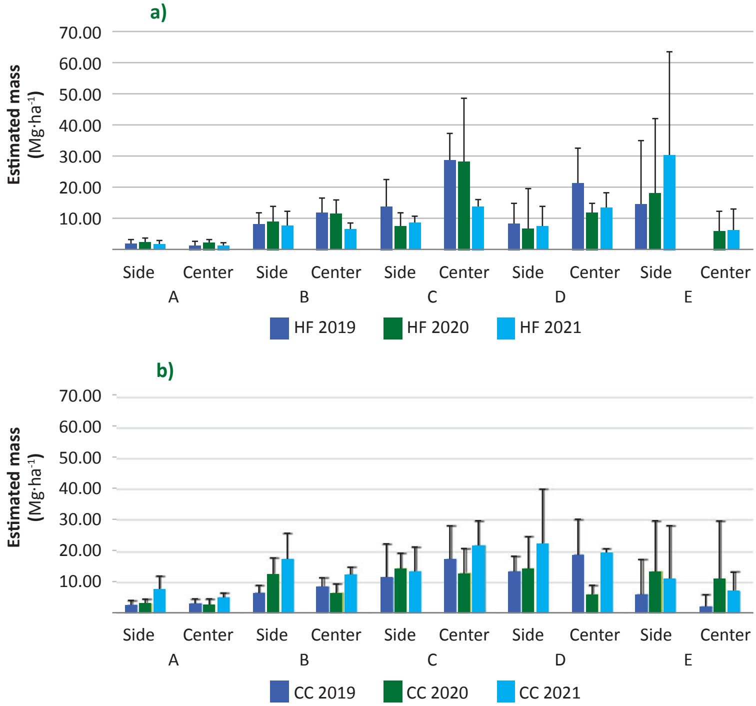

Figure 5. A comparison between average mass estimators for **a)** harvester-forwarder (HF) sites and **b)** cable yarder (CY) sites. The figure shows lateral areas (side) and extraction line (central) with the standard deviation reported in values as bars but represented only on the positive side.

Table 8. Dry matter (d.m.), nitrogen and carbon content resulted from the chemical analysis.

Analysed sample	Denomination	Total dry matter (%)	Total nitrogen (% d.m.)	Total carbon (% d.m.)	Total organic carbon (% d.m.)	Total inorganic carbon (% d.m.)
Soil	San Martino di C.	52.72	0.94	18.70	18.59	0.11
	Paneveggio	64.46	0.74	12.75	12.63	0.11
	Cadino	60.93	0.52	8.65	8.58	0.07
Residues	A	87.41	1.09	56.18	55.98	0.21
	B	84.44	0.40	53.46	53.31	0.14
	C	87.22	0.39	53.24	53.08	0.16
	D/E	88.06	0.43	51.98	51.85	0.12

Table 9. A summary of the chemical analysis for the three forests soils.

Element	Unit	San Martino di C.	Paneveggio	Cadino
N	$g \cdot kg^{-1}$ d.m.	9.41	7.35	5.20
C organic	$g \cdot kg^{-1}$ d.m.	185.86	126.34	85.80
Ca	$mg \cdot kg^{-1}$ d.m.	2,054.58	3,577.62	1,299.39
Fe	$mg \cdot kg^{-1}$ d.m.	22,152.22	20,637.05	15,272.03
K	$mg \cdot kg^{-1}$ d.m.	4,794.01	4,677.20	3,349.72
Mg	$mg \cdot kg^{-1}$ d.m.	3,821.68	4,294.74	1,991.27
Mn	$mg \cdot kg^{-1}$ d.m.	267.18	455.77	201.66
P	$mg \cdot kg^{-1}$ d.m.	576.63	395.21	384.75
Carbon stock	$Mg \cdot ha^{-1}$	85	63	45

Table 10. Average nutrient values for each residue diameter class across the three forests.

Element	Unit	A	B	C	D/E
N	g·kg^{-1} d.m.	10.86	4.05	3.92	4.30
C organic	g·kg^{-1} d.m.	559.76	533.15	530.75	518.51
Ca	mg·kg^{-1} d.m.	6,566.98	3,197.47	3,525.09	1,227.86
Fe	mg·kg^{-1} d.m.	300.73	81.71	24.21	46.23
K	mg·kg^{-1} d.m.	1,306.38	332.58	512.07	365.57
Mg	mg·kg^{-1} d.m.	616.37	325.67	207.80	123.72
Mn	mg·kg^{-1} d.m.	310.38	163.82	128.02	64.28
P	mg·kg^{-1} d.m.	666.34	108.56	84.60	50. 9

Table 11. Potential SOC stocked in coarse woody debris (CWD) quantity for each salvage logging site, cable yarder (CY) and harvester-forwarder (HF).

Salvage logging site	CWD (D/E) (Mg·ha^{-1})	SOC (Mg·ha^{-1})
HF 2019	23.80	11
HF 2020	22.85	10
HF 2021	32.09	15
CY 2019	21.08	10
CY 2020	24.23	11
CY 2021	31.29	14

DISCUSSION

Residues' Quantity According to Harvesting Systems

Overall, throughout the years, the amount of material for HF sites is similar, whereas for CY sites it is increasing. There is an increasing trend for the coarser material (class E) for both harvesting systems. The total quantity of residues is greater in the first year after the storm (2019) for HF sites than for CY. This information can therefore be considered similar to that from conventional clear-cuts (non-salvage logging conditions), where the CTL system releases more residues than FT (Hytönen and Moilanen 2014). In the following two years, the residue amounts computed for CY sites are greater than for HF, showing some marked differences. However, from the statistical point of view, no significant differences can be found between the first two years regarding the adopted systems. Moreover, significant differences emerged for the salvage logging operations occurring three years after the windthrow event. Based on the hypothesis stated, those difference should be reconducted to the choice of harvesting system and machine configuration. However, considering the results and site conditions, the influence of other factors, like the change in moisture content of the wood, should not be excluded, which may result in possible degradation (Petrillo et al. 2016) and increasing susceptibility to breakage, or the selection process of retrieving the material performed by the operators.

The fully mechanized machine configuration has a direct influence on the first two classes (A and B), which can be attributed to the transit of the forest machines (harvester and forwarder) when compared to the cable yarder full tree extraction. The passage over the logging residues causes mixing of the soil that eventually incorporates finer dead wood material, with subsequent compaction, preventing it from being correctly counted in the survey. Moreover, in HF sites, the material is processed in front of the vehicle, concentrating the logging residues on the trail, especially branches and tops producing a brush mat to reduce soil deformation and risk of erosion (Borchert et al. 2012). In contrast, the coarser material like stumps or bigger logs are deposited on the side of the same trails. This trend is particularly visible for classes B, C and D in Figure 5a. This distribution is due to the machine processes, as this type of material is usually found in higher concentrations in the working area of the machine, where the central transect is located. In the case of a harvester, residual material is in the front of the machine, whereas for stumps and coarser material (class D/E material) are usually left outside the working area.

For CY sites, on the other hand, the difference between side trails and the centre is not yet so marked (Figure 5b). The absence of a clear trend in terms of residue concentrations between lateral and central transects can be justified by the use of the FT system, where the entire tree is extracted from the forest and the majority of residues are then found at the roadside. However, the increase in the third year (2021) can be attributed to dragging in the phases of concentration and the removal of the material to cause the loss of branches and twigs. This is particularly visible in Tables 5 and 6 for finer material (A and B classes). Here the emerging differences can be reconducted to the change in the material moisture content, degradation and decomposition, especially the logs already in contact with the ground. The desiccation and subsequent loss of elasticity of the branches can lead to increasing biomass on the forest floor. These observations, without the possibility of adequately mapping the spatial distribution of residues, suffer from uncertainties, and a remote sensing approach could improve this information (Udali et al. 2022).

Growing stock, tree height and spatial distribution, together with the high gap fraction, might have some influence as well: the bigger quantity of CWD, for example, can be linked with the tree height present since usually the tallest trees also possess high diameter. This can be perceived, to some extent, for both HF and CY.

Other differences, for example for CWD, are presumed to be caused by the selection process in the sorting and extraction operations, and are thus related to the system-configuration choice. These operations are performed in the salvage logging site by the forwarder operators (CTL) – therefore leaving more material on the ground – and by the ground crew (FT) – when extracting the whole tree or part of it from the forest to roadside. The effects can be observed for the considered category of residues in Table 3 and Table 5 with the highest values in third year (2021) after the storm.

Chemical Analysis of Soil and Residues

In particular, the values computed for SOC align with those presented for Alpine forests by Gachhadar et al. (2022). Moreover, they also reported an average value of 94.95 Mg·ha^{-1}, which resulted in higher values than those obtained with almost 85 Mg·ha^{-1} from the forest in San Martino. Overall, this is valuable information considering that the soil depth in the Alpine forests is not remarkably high and the average altitude of the study sites (1,550-1,650 m a.s.l.). Although not easily detectable, in HF sites the mixing of soil horizons with residues might reduce nutrient losses and leaching (especially N), but also can lead to an increment in erosive processes (Merino et al. 1998). This also finds correspondence in the study by Huber et al. (2017), where FT cable yarding harvesting increased nitrogen removal compared to CTL-harvesting systems.

Considering the CWD material, the values observed are in line with the ones reported in previous studies in the European context, ranging between 50 and 120 m^3·ha^{-1} (Gutowski et al. 2005). The estimators are also comparable with the results obtained by Petrillo et al. (2016) in similar areas in the Province of Trento. First of all, the chemical analysis revealed higher concentrations for all the elements considered for the sites, including carbon. This information could be relevant considering the salvage logging operations running in the areas prior the survey versus the undisturbed conditions of the areas surveyed. Moreover, the SOC for CWD material computed by Petrillo et al. (2016) ranged between 3 and 17 Mg·ha^{-1}, with an average value of south-facing sites of 8.25 Mg·ha^{-1}, lower than the one obtained for the south-facing sites considered in this study (11 Mg·ha^{-1}).

Practical Outcomes

The effects of salvage logging operations on logging residues were assessed over a short time span (3 years) after the storm event. Combining the observations reported above and others from the literature, some practical considerations can be made.

i. *Conditions.* The scenario in which these operations have been conducted is of non-conventional conditions since high severity disturbance affected the stands. Salvage logging has taken place with the main intent to reduce the economic loss, but also to reduce the risk for the subsequent event, such as fires or bark beetle outbreak (Leverkus et al. 2021). In these areas traditional logging operations are normally performed using single tree selection or cut-block, and with less impacting systems (Lindenmayer and Noss 2006), preferring motor-manual operations and extraction using either tractor and winch or cable yarders.

ii. *Harvesting systems (1).* In more standard conditions, CTL systems should leave more residues on site than FT (Hytönen and Moilanen 2014), and this can be assessed by looking at the first year's residue quantities (2019) presented in this study. However, when it comes to salvage logging, this relation might not always be proved true. Both CTL and FT systems can be adopted through different degrees of mechanization, therefore having a variable impact.

iii. *Harvesting system (2).* The general recommendation is to adopt highly mechanized systems using CTL systems (Sanginés de Cárcer et al. 2021). This to ensure primarily the operator safety and to quickly recover the damaged timber. In this case, ground-based systems, such as the harvester-forwarder configuration, might be considered the optimum in the short term to maintain higher productivity and to reduce an economic loss (Udali et al. 2021). Also, ground-based system can mix up the residues within the soil horizons, and this can reduce nutrient loss. However, their passage and deep ruts can enhance nutrient leaching (especially N) and erosive processes (Merino et al. 1998).

iv. *Timing of operations.* The need to perform salvage logging operations immediately after the disturbance event is mainly needed to ensure the safety of infrastructure and to recover the economic value of timber. However, the planning of operations should also consider future impacts on site fertility: the extensive removal of residues, for example, affects tree growth and wood density (Roy et al. 2022). Both harvesting systems can be considered appropriate options to avoid nutrients losses, with the possibility to implement FT into a partial extraction of the full tree with the release of the treetop and the branches, leaving behind most of the needles and, potentially, the majority of nutrients. Furthermore, a lighter carriage can develop less tension on the mainline and reduce the overall forces on the system, making it safer for the operators. Adopting FT systems from the second year (i.e., after trees have lost their needles) can be considered a solution, as shown in this study, along with leaving behind a certain volume of finer residues (Nilsson et al. 2018).

v. *Effects of residues.* The release of residues should be weighted on a different number of elements, all site-specific. In the Alpine environment many ecosystem services granted by the forest do not have a direct market value (Häyhä et al. 2015). However, they can also be provided by the presence of residues. For example, logging residues can increase the presence of favourable microsites for regeneration, enhancing site characteristics by lowering high diurnal temperature and maintaining higher soil moisture (Marangon et al. 2022). Their presence, especially CWD, reduces the risk for gravitational hazards playing an active role against rockfalls (Costa et al. 2021). Moreover, the retention of residues also helps reduce the risk of erosion, especially on skid trails (Mazri et al. 2020).

CONCLUSIONS

The study aimed to verify the presence of differences in terms of logging residue type and quantity according to the harvesting system adopted in the case of a salvage logging operations. A second focus was put on assessing the effects on nutrients and possible impacts on carbon stocks for both soil and residues. Moreover, the effect of the timing of operations was also considered in relation to residue quantities. Overall, significant differences have emerged in terms of residues left on site due to the harvesting systems (cut-to-length versus full-tree systems) and the configuration adopted (ground-based versus aerial-based) in later years with respect to the storm event. However, the sole system-configuration combination was not able to explain all the variability between years and sites in the approach considered. Based on this study's outcomes, further investigations should address the residues' spatial distribution after logging operations at greater resolution considering the entire area of operations and the possible effects on nutrients and carbon distribution in the salvaged logging areas.

Author Contributions

AU, LG, EL, SG conceived and designed the research; LG carried out the field measurements; LG and AU processed the data and performed the statistical analysis; EL and RC revised and contributed to the discussion of results; AU, LG, SG wrote the manuscript.

Funding

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them and co-founded by the Department TESAF of the University of Padova in the framework of the project Vaia-FRONT (VAIA, FROm lessons learNT to future options) (CAVA_SID19_02) and the LERH PhD School of the University of Padova.

Acknowledgments

The authors acknowledge the agency APROFOD of the Trento province for the support during the field campaign and the ABC Laboratory of the TESAF Department of the University of Padova for the wood parameter characterization.

Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

Bače R, Svoboda M, Pouska V, Janda P, Červenka J, 2012. Natural Regeneration in Central-European Subalpine Spruce Forests: Which Logs are Suitable for Seedling Recruitment? *Forest Ecol Manag* 266: 254–262. https://doi.org/10.1016/j.foreco.2011.11.025.

Bauer GA, Persson H, Persson T, Mund M, Hein M, Kummetz E, Matteucci G, van Oene H, Scarascia-Mugnozza G, Schulze ED, 2000. Linking Plant Nutrition and Ecosystem Processes. In: Carbon and Nitrogen Cycling in European Forest Ecosystems. Springer, Berlin, Heidelberg, Germany, pp. 63–98. https://doi.org/10.1007/978-3-642-57219-7_4.

Bessaad A, Bilger I, Korboulewsky N, 2021. Assessing Biomass Removal and Woody Debris in Whole-Tree Harvesting System: are the Recommended Levels of Residues Ensured? *Forests* 12(6): 807. https://doi.org/10.3390/F12060807.

Bodaghi AI, Nikooy M, Naghdi R, Venanzi R, Latterini F, Tavankar F, Picchio R, 2018. Ground-Based Extraction on Salvage Logging in Two High Forests: A Productivity And Cost Analysis. *Forests* 9: 729. https://doi.org/10.3390/f9120729.

Borchert H, Huber C, Göttlein A, Kremer J, 2015. Nutrient Concentration on Skid Trails under Brush-Mats – Is a Redistribution of Nutrients Possible? *Croat J For Eng* 36: 243–252.

Borz SA, Dinulică F, Bîrda M, Ignea G, Ciobanu VD, Popa B, 2013. Time Consumption and Productivity of Skidding Silver Fir (*Abies Alba* Mill.) Round Wood in Reduced Accessibility Conditions: a Case Study in Windthrow Salvage Logging from Romanian Carpathians. *Ann For Res* 56: 363–375.

Borz SA, Ignea G, Popa B, 2014. Modelling and Comparing Timber Winching Performance in Windthrow and Uniform Selective Cuttings for Two Romanian Skidders. *J For Res-JPN* 19: 473–482. https://doi.org/10.1007/s10310-014-0439-0.

Brockerhoff EG, Barbaro L, Castagneyrol B, Forrester DI, Gardiner B, González-Olabarria JR, Lyver POB, Meurisse N, Oxbrough A, Taki H, Thompson ID, van der Plas F, Jactel H, 2017. Forest Biodiversity, Ecosystem Functioning and the Provision of Ecosystem Services. *Biodivers Conserv* 26: 3005–3035. https://doi.org/10.1007/s10531-017-1453-2.

Brown JK, 1974. Handbook for Inventorying Downed Woody Material, USDA For. Serv. Gen. Tech. Rep.

Cadei A, Mologni O, Röser D, Cavalli R, Grigolato S, 2020. Forwarder Productivity in Salvage Logging Operations in Difficult Terrain. *Forests* 11: 341. https://doi.org/10.3390/f11030341.

Carlson AR, Sibold JS, Assal TJ, Negrón JF, 2017. Evidence of Compounded Disturbance Effects on Vegetation Recovery Following High-Severity Wildfire and Spruce Beetle Outbreak. *PLoS ONE* 12: e0181778. https://doi.org/10.1371/journal.pone.0181778.

Cavaleri L, Bajo M, Barbariol F, Bastianini M, Benetazzo A, Bertotti L, Chiggiato J, Davolio S, Ferrarin C, Magnusson L, Papa A, Pezzutto P, Pomaro A, Umgiesser G, 2019. The October 29, 2018 Storm in Northern Italy – an Exceptional Event and its Modeling. *Prog Oceanogr* 178: 102178. https://doi.org/10.1016/j.pocean.2019.102178.

Costa M, Marchi N, Bettella F, Bolzon P, Berger F, Lingua E, 2021. Biological Legacies and Rockfall: the Protective Effect of a Windthrown Forest. *Forests* 12: 1141. https://doi.org/10.3390/f12091141.

European Environment Agency, 2019. Forest dynamics in Europe and their ecological consequences. European Environment Agency, Copenhagen K, Denmark. 9 p. Available online: https://data.europa.eu/doi/10.2800/905921 (15 December 2020).

FOREST EUROPE, 2020. State of Europe's Forests 2020, Ministerial Conference on the Protection of Forests in Europe, Bratislava, Slovakia. 392 p. Available online: https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf (15 January 2021).

Forzieri G, Pecchi M, Girardello M, Mauri A, Klaus M, Nikolov C, Rüetschi M, Gardiner B, Tomaštík J, Small D, Nistor C, Jonikavicius D, Spinoni J, Feyen L, Giannetti F, Comino R, Wolynski A, Pirotti F, Maistrelli F, Ionut S, Lucas-Stephanie W, Stefan K, Zieba-Kulawik K, Strejczek-Jazwinska P, Mokroš M, Stefan F, Krejci L, Haidu I, Nilsson M, Wezyk P, Chirici G, Cescatti A, Beck P, 2019. A Spatially-Explicit Database of Wind Disturbances in European Forests over the Period 2000–2018. *Earth System Science Data Discussions* 1–23. https://doi.org/10.5194/essd-2019-141.

Gachhadar P, Baniya CB, Mandal T, 2022. Soil Organic Carbon Stocks in the Forests of Different Continents. *Our Nature* 20: 57–69. https://doi.org/10.3126/on.v20i1.45219.

Gutowski JM, Bobiec A, Ciach M, Kujawa A, Zub K, Pawlaczyk P, 2005. The afterlife of a tree. WWF Poland - Foundation of Environmental and Natural Resources Economists.

Häyhä T, Franzese PP, Paletto A, Fath BD, 2015. Assessing, Valuing, and Mapping Ecosystem Services in Alpine Forests. *Ecosyst Serv* 14: 12–23. https://doi.org/10.1016/j.ecoser.2015.03.001

Heinimann HR, Stampfer K, Loschek J, Caminada L, 2001. Perspectives on Central European Cable Yarding Systems. In: *The International Mountain Logging and 11th Northwest Skyline Symposium 2001* 123: 268–279.

Hollis JM, Woods SM, 1989. The measurement and estimation of saturated soil hydraulic conductivity, Soil Survey and Land Res. Centre. Silsoe, 19p.

Huber C, Kastner M, Hochbichler E, Stampfer K, 2017. Effect of Topping Trees on Biomass and Nitrogen Removal in the Thinning of Norway Spruce Stands. *Sustainability-Basel* 9: 1–14. https://doi.org/10.3390/su9101856.

Hytönen J, Moilanen M, 2014. Effect of Harvesting Method on the Amount of Logging Residues in the Thinning of Scots Pine Stands. *Biomass Bioenerg* 67: 347–353. https://doi.org/10.1016/j.biombioe.2014.05.004.

Irauschek F, Rammer W, Lexer MJ, 2017. Can Current Management Maintain Forest Landscape Multifunctionality in the Eastern Alps in Austria under Climate Change? *Reg Environ Change* 17: 33–48. https://doi.org/10.1007/s10113-015-0908-9.

Janowiak MK, Webster CR, 2010. Promoting Ecological Sustainability in Woody Biomass Harvesting. *J Forest* 108: 16–23. https://doi.org/10.1093/jof/108.1.16.

Krag R, Higginbotham K, Rothwell R, 1986. Logging and Soil Disturbance in Southeast British Columbia. *Can J Forest Res* 16: 1345–1354. https://doi.org/10.1139/x86-238.

Kramer K, Brang P, Bachofen H, Bugmann H, Wohlgemuth T, 2014. Site Factors are More Important than Salvage Logging for Tree Regeneration after Wind Disturbance in Central European Forests. *Forest Ecol Manag* 331: 116–128. https://doi.org/10.1016/j.foreco.2014.08.002.

Kymäläinen H, Laitila J, Väätäinen K, Malinen J, 2021. Workability and Well-Being at Work Among Cut-To-Length Forest Machine Operators. *Croat J For Eng* 42: 405–417. https://doi.org/10.5552/crojfe.2021.874.

Laffan M, Jordan G, Duhig N, 2001. Impacts on Soils from Cable-Logging Steep Slopes in Northeastern Tasmania, Australia. *Forest Ecol Manag* 144: 91–99. https://doi.org/10.1016/S0378-1127(00)00360-1.

Leverkus AB, Rey Benayas JM, Castro J, Boucher D, Brewer S, Collins BM, Donato D, Fraver S, Kishchuk BE, Lee EJ, Lindenmayer DB, Lingua E, Macdonald E, Marzano R, Rhoades CC, Royo A, Thorn S, Wagenbrenner JW, Waldron K, Wohlgemuth T, Gustafsson L, 2018. Salvage Logging Effects on Regulating and Supporting Ecosystem Services — A Systematic Map. *Can J Forest Res* 48: 983–1000. https://doi.org/10.1139/cjfr-2018-0114.

Leverkus AB, Buma B, Wagenbrenner J, Burton PJ, Lingua E, Marzano R, Thorn S, 2021. Tamm Review: Does Salvage Logging Mitigate Subsequent Forest Disturbances? *Forest Ecol Manag* 481: 118721. https://doi.org/10.1016/j.foreco.2020.118721.

Lindenmayer D, 2006. Salvage harvesting - Past lessons and future issues. *Forest Chron* 82(1): 48–53. https://doi.org/10.5558/tfc82048-1.

Lindenmayer DB, Noss RF, 2006. Salvage Logging, Ecosystem Processes, and Biodiversity Conservation. *Conserv Biol* 20: 949-958. https://doi.org/10.1111/j.1523-1739.2006.00497.x.

Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer MJ, Marchetti M, 2010. Climate Change Impacts, Adaptive Capacity, and Vulnerability of European Forest Ecosystems. *Forest Ecol Manag* 259: 698–709. https://doi.org/10.1016/j.foreco.2009.09.023.

Maas GCB, Sanquetta CR, Marques R, Machado SDA, Sanquetta MNI, 2020. Quantification of Carbon in Forest Necromass: State of the Art. *Cerne* 26: 98–108. https://doi.org/10.1590/01047760202026012661.

Marangon D, Marchi N, Lingua E, 2022. Windthrown Elements: a Key Point Improving Microsite Amelioration and Browsing Protection to Transplanted Seedlings. *Forest Ecol Manag* 508: 120050. https://doi.org/10.1016/j.foreco.2022.120050.

Mattson LR, Coop JD, Battaglia MA, Cheng AS, Sibold JS, Viner S, 2019. Post-Spruce Beetle Timber Salvage Drives Short-Term Surface Fuel Increases and Understory Vegetation Shifts. *Forest Ecol Manag* 437: 348–359. https://doi.org/10.1016/j.foreco.2019.01.048.

Mayer M, Prescott CE, Abaker WEA, Augusto L, Cécillon L, Ferreira GWD, James J, Jandl R, Katzensteiner K, Laclau JP, Laganière J, Nouvellon Y, Paré D, Stanturf JA, Vanguelova EI, Vesterdal L, 2020. Influence of Forest Management Activities on Soil Organic Carbon Stocks: A Knowledge Synthesis. *Forest Ecol Manag* 466: 118127. https://doi.org/10.1016/j.foreco.2020.118127.

Mazri A, Parsakhoo A, Mostafa M, 2020. Efficiency of Some Conservation Treatments for Soil Erosion Control on Unallowable Slopes of Skid Trails. *Journal of Forest Science* 66: 368–374. https://doi.org/10.17221/61/2020-JFS.

Merino A, Edeso JM, González MJ, Marauri P, 1998. Soil Properties in a Hilly Area Following Different Harvesting Management Practices. *Forest Ecol Manag* 103: 235–246. https://doi.org/10.1016/S0378-1127(97)00229-6.

Miller JH, Sirois DL, 1986. Soil Disturbance by Skyline Yarding vs. Skidding in a Loamy Hill Forest. *Soil Sci Soc Am J* 50: 1579–1583. https://doi.org/10.2136/sssaj1986.03615995005000060039x.

Mina M, Bugmann H, Klopcic M, Cailleret M, 2017. Accurate Modeling of Harvesting is Key for Projecting Future Forest Dynamics: A Case Study in the Slovenian Mountains. *Reg Environ Change* 17: 49–64. https://doi.org/10.1007/s10113-015-0902-2.

Mologni O, Grigolato S, Cavalli R, 2016. Harvesting Systems for Steep Terrain in the Italian Alps: State of the Art and Future Prospects. *Contemporary Engineering Sciences* 9: 1229–1242. https://doi.org/10.12988/ces.2016.68137.

Motta R, Berretti R, Lingua E, Piussi P, 2006. Coarse Woody Debris, Forest Structure and Regeneration in the Valbona Forest Reserve, Paneveggio, Italian Alps. *Forest Ecol Manag* 235: 155–163. https://doi.org/10.1016/j.foreco.2006.08.007.

Nilsson D, Nilsson B, Thörnqvist T, Bergh J, 2018. Amount of Nutrients Extracted and Left Behind at a Clear-Felled Area Using the Fresh-Stacked and Dried-Stacked Methods of Logging Residue Extraction. *Scand J Forest Res* 33: 437–445. https://doi.org/10.1080/02827581.2018.1427786.

Nurminen T, Korpunen H, Uusitalo J, 2006. Time Consumption Analysis of the Mechanized Cut-To-Length Harvesting System. *Silva Fenn* 40: 335–363. https://doi.org/10.14214/sf.346.

Palviainen M, Finér L, Laiho R, Shorohova E, Kapitsa E, Vanha-Majamaa I, 2010. Carbon and Nitrogen Release from Decomposing Scots Pine, Norway Spruce and Silver Birch Stumps. *Forest Ecol Manag* 259: 390–398. https://doi.org/10.1016/j.foreco.2009.10.034.

Papais E, Gallo A, Bini C, 2015. Carbon Stock Evaluation from Topsoil of Forest Stands in Friuli V.G. (NE Italy), In: Proceedings Of The Second International Congress Of Silviculture. Florence, Italy, pp. 104–109. https://doi.org/10.4129/2cis-ep-va.

Petrillo M, Cherubini P, Sartori G, Abiven S, Ascher J, Bertoldi D, Camin F, Barbero A, Larcher R, Egli M, 2016. Decomposition of Norway Spruce and European Larch Coarse Woody Debris (CWD) in Relation to Different Elevation and Exposure in an Alpine Setting. *IForest* 9: 154–164. https://doi.org/10.3832/ifor1591-008.

Pilli R, Vizzarri M, Chirici G, 2021. Combined Effects of Natural Disturbances and Management on Forest Carbon Sequestration: the Case of Vaia Storm In Italy. *Ann For Sci* 78: 46. https://doi.org/10.1007/s13595-021-01043-6.

Prats SA, Malvar MC, Wagenbrenner JW, 2021. Compaction and Cover Effects on Runoff and Erosion in Post-Fire Salvage Logged Areas in the Valley Fire, California. *Hydrol Process* 35: e13997. https://doi.org/10.1002/hyp.13997.

Priewasser K, Brang P, Bachofen H, Bugmann H, Wohlgemuth T, 2013. Impacts of Salvage-Logging on the Status of Deadwood after Windthrow in Swiss Forests. *Eur J Forest Res* 132: 231–240. https://doi.org/10.1007/s10342-012-0670-1.

Rizzolo R, 2016. Fuel models development to support spatially-explicit forest fire modelling in Eastern Italian Alps. PhD Thesis, Università degli Studi di Padova, Department of Land, Environment, Agriculture and Forestry (TESAF), Padova, Italy, 156 p.

Robichaud PR, Lewis SA, Brown RE, Bone ED, Brooks ES, 2020. Evaluating Post-Wildfire Logging-Slash Cover Treatment to Reduce Hillslope Erosion after Salvage Logging Using Ground Measurements and Remote Sensing. *Hydrol Process* 34: 4431–4445. https://doi.org/10.1002/hyp.13882.

Roy S, Leban JM, Zeller B, van der Heijden G, Reichard A, Gehin MC, Santenoise P, Saint-Andre L, 2022. Removing Harvest Residues from Hardwood Stands Affects Tree Growth, Wood Density and Stem Wood Nutrient Concentration in European Beech (*Fagus Sylvatica*) and Oak (*Quercus* Spp.). *Forest Ecosystems* 9: 100014. https://doi.org/10.1016/j.fecs.2022.100014.

Sanginés de Cárcer P, Mederski PS, Magagnotti N, Spinelli R, Engler B, Seidl R, Eriksson A, Eggers J, Bont LG, Schweier J, 2021. The Management Response to Wind Disturbances in European Forests. *Current Forestry Reports* 7: 167–180. https://doi.org/10.1007/s40725-021-00144-9.

Seidl R, Thom D, Kautz M, Martin-Benito D, Peltoniemi M, Vacchiano G, Wild J, Ascoli D, Petr M, Honkaniemi J, Lexer MJ, Trotsiuk V, Mairota P, Svoboda M, Fabrika M, Nagel TA, Reyer CPO, 2017. Forest Disturbances Under Climate Change. *Nat Clim Change* 7(6): 395-402. https://doi.org/10.1038/nclimate3303.

Senf C, Seidl R, 2021. Mapping the Forest Disturbance Regimes of Europe. *Nature Sustainability* 4: 63–70. https://doi.org/10.1038/s41893-020-00609-y.

Spinelli R, Magagnotti N, Cosola G, Engler B, Leitner S, Vidoni R, 2022. Fuel and Time Consumption in Alpine Cable Yarder Operations. *Forests* 13(9): 1394. https://doi.org/10.3390/f13091394.

Stanturf JA, 1990. Cable Logging Impacts on Soils on the Allegheny Plateau. *Jour PA Acad Sci* 63: 127–130.

Sullivan TP, Sullivan DS, Klenner W, 2021. Fate of Postharvest Woody Debris, Mammal Habitat, and Alternative Management of Forest Residues on Clearcuts: a Synthesis. *Forests* 12(5): 551. https://doi.org/10.3390/f12050551.

Tamminen P, Saarsalmi A, Smolander A, Kukkola M, Helmisaari HS, 2012. Effects of Logging Residue Harvest in Thinnings on Amounts of Soil Carbon and Nutrients in Scots Pine and Norway Spruce Stands. *Forest Ecol Manag* 263: 31–38. https://doi.org/10.1016/j.foreco.2011.09.015.

Thorn S, Bässler C, Brandl R, Burton PJ, Cahall R, Campbell JL, Castro J, Choi CY, Cobb T, Donato DC, Durska E, Fontaine JB, Gauthier S, Hebert C, Hothorn T, Hutto RL, Lee EJ, Leverkus AB, Lindenmayer DB, Obrist MK, Rost J, Seibold S, Seidl R, Thom D, Waldron K, Wermelinger B, Winter MB, Zmihorski M, Müller J, 2018. Impacts of Salvage Logging on Biodiversity: a Meta-Analysis. *J Appl Ecol* 55(1): 279–289. https://doi.org/10.1111/1365-2664.12945.

Udali A, Andrighetto N, Grigolato S, Gatto P, 2021. Economic Impacts of Forest Storms-Taking Stock of after-Vaia Situation of Local Roundwood Markets in Northeastern Italy. *Forests* 12(4): 414. https://doi.org/10.3390/f12040414.

Udali A, Crous J, Talbot B, Lingua E, Puliti S, Grigolato S, 2022. Assessing the Potential for Forest Residue Classification and Distribution over Clear Felled Areas Using UAVs and Machine Learning: a Preliminary Case Study in South Africa. In: IEEE International Workshop on Metrology for Agriculture and Forestry, Perugia, Italy, 3-5 November 2022. University of Perugia, Italy, pp 1–4.

Valipour M, Johnson CE, Battles JJ, Campbell JL, Fahey TJ, Fakhraei H, Driscoll CT, 2021. Simulation of the Effects of Forest Harvesting under Changing Climate to Inform Long-Term Sustainable Forest Management Using a Biogeochemical Model. *Sci Total Environ* 767: 144881. https://doi.org/10.1016/j.scitotenv.2020.144881.

Van Wagner CE, 1968. The Line Intersect Method in Forest Fuel Sampling. *Forest Science* 14(1): 20–26. https://doi.org/10.1093/FORESTSCIENCE/14.1.20.

Verkerk PJ, Martinez de Arano I, Palahí M, 2018. The Bio-Economy as an Opportunity to Tackle Wildfires in Mediterranean Forest Ecosystems. *Forest Policy Econ* 86: 1-3. https://doi.org/10.1016/j.forpol.2017.10.016.

Wohlgemuth T, Schwitter R, Bebi P, Sutter F, Brang P, 2017. Post-Windthrow Management in Protection Forests of the Swiss Alps. *Eur J Forest Res* 136: 1029–1040. https://doi.org/10.1007/s10342-017-1031-x.

Woodall CW, Monleon VJ, 2008. Sampling Protocol, Estimation, and Analysis Procedures for the Down Woody Materials Indicator of the FIA Program. *Gen Tech Rep NRS-22* 68.

Zielonka T, Niklasson M, 2001. Dynamics of Dead Wood and Regeneration Pattern in Natural Spruce Forest in the Tatra Mountains. *Ecol Bull* 49: 159–163.