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Evolution of Forest Humipedon Following a Severe Windstorm in the Italian Alps: A Focus on Organic Horizon Dynamics

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Abstract: This study investigates the effects of the 2018 Vaia windstorm on the evolution of humus profiles in forest soils of the north-eastern Italian Alps five years after the disturbance. The humipedon in five soil conditions was compared: intact forest (IF) and permanent meadow (M) for undisturbed soils, and soil under herbaceous cover (G), under dead wood (W), and bare soil (B) for windthrow-affected areas. No difference in pH and soil organic matter content (SOM) emerged within the same soil horizon between IF and windthrow-affected soils. When compared to IF, however, in G and B, a thinning of all O horizons (OL, OF, and OH) was detected, resulting in SOM loss and an increase in pH in the top 15 cm of the humipedon, conditions approaching the values found in M. Amphi was the most frequently occurring humus system in IF, with a shift towards a Mull system observed in all windthrow-affected soils—a shift more marked in G and B, approaching M conditions, but less marked in W, where the O horizon remained thicker. This study underscores the importance of considering soil heterogeneity and humus dynamics when assessing forest recovery and resilience after a severe disturbance.

Keywords: humus system; humus form; amphi; mull; windthrow; soil organic matter; Vaia storm

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1. Introduction

The influence of anthropogenic climate change on the frequency, intensity, duration, and timing of various natural disturbances has been extensively documented—events including fires, droughts, landslides, species invasions, insect and disease outbreaks, together with storms such as hurricanes, windstorms, and ice storms. Such disturbances have the potential to significantly impact forest ecosystems, affecting their composition, structure, and functionality [1–4]. The increasing frequency of catastrophic storm events is of particular concern, since these result in significant timber loss and structural damage to forest landscapes [5].

The Vaia storm, which struck the north-eastern sector of the Italian Alps in October 2018, was an event of particular significance: exceptionally strong winds (speeds up to 200 km/h) caused extensive windthrow damage, resulting in the loss of approximately 8.3 million m^3 of timber across 4500 acres of forest [6,7]. Despite the destructive nature of such events, severe storms are also a fundamental part of forest dynamics, contributing to forest regeneration and enhanced biodiversity [8,9]. Nevertheless, the extended lifespan of trees precludes their rapid adaptation to abrupt environmental shifts [2]. Consequently, the pace of forest recovery and the question of whether the increased frequency of these disturbances undermines long-term forest resilience need further investigation.

Windthrow events can severely impact topsoil. This is mainly due to tree uprooting, which leads, in turn, to the mixing of soil horizons and local changes in porosity and humidity [10–12]. Other factors to be considered are canopy loss and the subsequent increase in microbial activity due to higher solar energy input, leading to a loss of soil organic carbon

(SOC) and a reduction in C/N ratios in the topsoil [13,14]. Finally, windthrow events can result in the accumulation of potentially high amounts of coarse woody debris (CWD) on the topsoil.

While post-disturbance studies have predominantly focused on tree regeneration dynamics and changes in soil chemical properties, there is limited research specifically addressing changes in humus systems or humus forms following environmental cataclysms. Zanella et al. [15] presented a graph illustrating the integration time of fallen branches and logs into the soil after a storm, relative to humus systems. Estimated biodegradation times for whole trees range from 8 years in Mull humus systems to 56 years in Mor and Tangel systems, with longer durations observed for conifers compared to broadleaves.

Recent studies have investigated the influence of factors such as air temperature and soil moisture on litter biodegradation rates. Bayranvand [16] identified altitude and species composition as primary determinants of humus forms and their chemical characteristics. Para systems (e.g., Rhizoforms and Lignoforms) showed slower decomposition rates compared to Terrestrial systems. Elevations and the associated vegetation types (e.g., subalpine forests vs. alpine grasslands) were shown to influence humus form distribution [17].

Humus forms also vary significantly between poorly drained or waterlogged sites and well-drained areas due to the substantial effect of water on soil processes and morphology [18]. Nikpour et al. [19] demonstrated that dividing a region into altitude ranges significantly improves humus form classification accuracy; as soil moisture increases, typically facilitated by higher organic matter content in surface horizons, humus forms tend to shift toward Moder. Forest canopy composition (pure or mixed) and litterfall characteristics contribute to variations in forest-floor properties (Špulák et al.) [20].

The interplay between climate and bedrock type was shown to strongly influence litter decomposition in temperate forests. Michalet and Liancourt [21] highlighted four key patterns based on studies of Abies alba needle decomposition: (i) a marked decrease in decomposition rates from wet oceanic to dry continental sites on calcareous bedrock; (ii) no change in decomposition rates over time in siliceous sites under increasing drought conditions; (iii) an increase in decomposition rates during wet years in dry continental siliceous sites; and (iv) a stronger dependence of decomposition rates on the physical characteristics of bedrock than on climatic trends.

Organic carbon accrual in soils is primarily constrained by carbon inputs and is strongly modulated by factors such as soil texture, mineralogy, climate, and other site-specific properties [22]. Soil microbial communities also vary with forest stand age [23].

The effects of moisture and temperature on the soil's A horizon are twofold, as noted by Zhang et al. [24]: (i) soil moisture regulates the formation and thickening of the A horizon; and (ii) temperature governs solum development.

In moderate temperature regions, A horizons tend to be thicker, while higher temperatures in southern regions lead to shallower A horizons due to accelerated organic matter decomposition. Conversely, low temperatures restrict vegetation growth and organic matter input, limiting A horizon development.

Particularly intriguing are studies on the relationship between humus system dynamics and the forest's silvogenetic cycle, which may indirectly reflect responses to cataclysmic events, such as large-scale canopy openings. These studies suggest that soils evolve alongside tree age in forests, indicating a combined soil–tree cycle wherein the soil "grows with the tree above it" [25–29] (11–15). The environmental conditions of humus formation, along with the climatic influences on the organisms within the diagnostic horizons of various humus systems, were extensively detailed in three Special Issues of the Applied Soil Ecology journal titled Humusica 1, 2, and 3. In Humusica 1 [30], specific topics are addressed as follows: the seasonal and annual formation of forest horizons is discussed in Article 2 [31]; the key characteristics of each horizon are detailed in Article 4 [32]; the features of each humus system are presented in Article 5 [33]; the challenges of observing phenomena at different scales are analyzed in Article 7 [34]; and the organisms associated with each horizon are described in Article 8 [35].

The canopy openings caused by the Vaia storm, through the felling of trees, have exposed the forest floor to climatic variations—such as increased solar radiation, a rise in the water table, and elevated temperatures due to edge effects—that undoubtedly affect humus systems and forms.

With the intent of better understanding the functioning of soil as an ecosystem [36], it has recently been proposed to subdivide the entire thickness of soil into three subunits, each with distinct functional characteristics: humipedon, copedon, and lithopedon [30]. From the bottom to the top, the lithopedon comprises the rocky mineral horizons (R, C); the copedon comprises the mineral horizons of recent formation (B, E); and the humipedon consists of the organo-mineral and organic horizons, comprising the fresh litter (A, O). The humipedon is the most superficial component of the soil profile, situated in contact with the atmosphere or a water body. It is characterized by the accumulation and/or mixing of dead organic matter with the mineral component. Humipedon is dominated by bioturbation processes driven by soil biota and undergoes monthly variations, whereas the formation and alteration of the entire soil profile under normal conditions occurs over a period of centuries or even millennia.

Although humus is an essential component of forest soils, it has often been overlooked in forest studies. Its value as an ecological indicator, however, is increasingly being recognized in recent research, particularly in the European context, where it has been shown to be a good predictor of soil microbiological and chemical parameters such as SOC stock, enzyme activity, pH, and C:N ratio [37–39]. Humus analysis can, therefore, offer a valuable, cost-effective method for monitoring ecological dynamics in forest soils, also accessible to non-soil experts with appropriate training.

The highly heterogeneous environment resulting from severe storms led to the formation of diverse soil microenvironments [8,40] with the potential to act as different pedogenetic patches [40]. The evolution of microarthropod communities in windthrow sites and their relationship with soil chemical parameters, soil respiration, and humus systems have already been discussed in a previous study [41]. The objective of the present research is to examine this patchiness in greater detail, specifically in terms of humus profiles under different soil covers—an investigation focusing on the same windthrow sites as those in Visentin et al. [41]. In detail, humus dynamics is analyzed, focusing on the evolution of diagnostic horizons, particularly organic ones, expanding classification to the form level, and deepening our understanding of humipedon evolution in a severely disturbed mountain forest ecosystem.

2. Materials and Methods

2.1. Study Sites

This study was carried out in the forests of two different municipalities in the north-eastern Italian Alps that had been severely affected by the Vaia storm in 2018. Investigations took place during the summer of 2023 in San Giovanni di Fassa, located in Val di Fassa (Trentino-Alto Adige region), with a total of 60 samples (18 IF, 18 G, 12 W, 3B, 9M), and Tambre, located in Cansiglio forest (Veneto region), with a total of 27 samples (12 IF, 12 G, 3 W). The coordinates of all sampling points surveyed, as well as their altitudes, can be found in Supplementary Materials (Table S1).

In San Giovanni di Fassa, sampling was carried out at elevations between 1600 and 2000 m a.s.l. In this area, the vegetation is characterized by a managed forest primarily composed of spruce (*Picea abies* (L.) H. Karst.) and larch (*Larix decidua* Mill.), with the understory largely composed of species from the class *Polypodiopsida*, with the occasional presence of acidophilic plants from the genus *Vaccinium*. Meadows are dominated by species typical of alpine grasslands, particularly belonging to the *Poaceae* family, and are primarily used for hay production. The geological substrate mainly consists of dolomite limestone. Forest soils are found on slopes with an inclination ranging from 10% to 45% and are classified as Leptosols, with a high content of rocky debris. Occasionally, Podzol can be found, with an eluvial E horizon lying over a cambic B horizon. In contrast, the soils of permanent meadows are those typical of alpine valleys, formed by the deposition of sediment from adjacent peaks. These are characterized by gentle slopes (maximum 5%) and classified as Umbrisols.

The Cansiglio Forest is located on a karst plateau encircled by rocky peaks in the Italian Prealps. The geological substrate predominantly consists of limestone, and the plateau lies at elevations ranging from 900 to 1200 m above sea level. This topographical configuration induces thermal inversion, whereby cold air becomes trapped on the plateau. Consequently, the plateau supports a managed spruce forest, which transitions into a managed beech forest (*Fagus sylvatica* L.) at higher altitudes. The understory mainly consists of species from the *Polypodiopsida* class. A diverse soil mosaic is present, and Phaeozems and Cambisols are the most common soil types in the study areas.

Based on the Köppen–Geiger classification, both areas have a warm-summer humid continental climate (Dfb). The average annual temperature of San Giovanni di Fassa and Cansiglio is 2.4 °C and 6.1 °C, respectively, while annual precipitation is approx. 1885 mm and 2049 mm, respectively.

2.2. Experimental Design

Samplings took place in July 2023. In the two sampling areas, 20 sites were identified (12 in Val di Fassa and 8 in Cansiglio), half of which were located in windthrow-affected areas (Figure 1a,b).

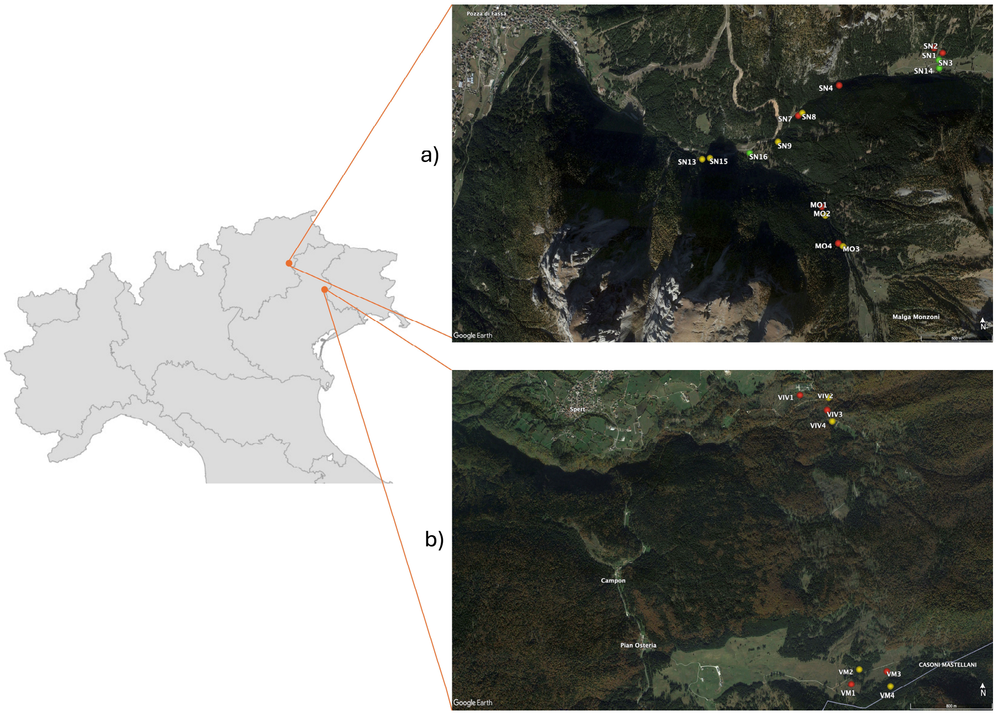


Figure 1. Location of sampling sites in (**a**) Val di Fassa and (**b**) Cansiglio. Yellow dots: intact forest; Red dots: windthrow-affected areas; Green dots: meadows. Figure from Visentin et al. [19].

Regarding windthrow-affected sites, in each site three soil coverage conditions were identified and then, when found, evaluated: patches with herbaceous vegetation cover (grass, G); patches with decaying wood on the soil (W); and patches with bare soil (B). It is important to highlight that these conditions were not uniformly present across all the selected sites. The data collected from these areas were compared with those obtained from undisturbed sites. In particular, one main undisturbed soil coverage condition was identified, i.e., intact forest (IF) adjacent to windthrow areas. In Val di Fassa, a permanent meadow condition (M) was also evaluated with 3 additional sites (Figure 1a) to test the hypothesis that humus type and soil chemical properties of G sites are shifting towards those of adjacent permanent meadows. For each condition present in all sampling sites, 3 replicate subsites were identified, at least 10 m from each other to avoid spatial autocorrelation. A total of 87 replicates were therefore sampled: 60 from Val di Fassa and 27 from Cansiglio. The number of samples for each soil coverage condition was 18 IF, 18 G, 12 W, 3 B, and 9 M for Val di Fassa, and 12 IF, 12 G, and 3 W for Cansiglio.

For each soil coverage condition, the following parameters were analyzed: (1) soil chemical features (pH, soil organic matter content); (2) humus characterization; (3) soil respiration; and (4) soil microarthropods. The classification system used to name the studied soils is the World Reference Base for Soil Resources (WRB) of the International Union of Soil Sciences. This paper focuses on humus systems and forms and how they have evolved five years after disturbance. For results on soil microarthropod communities and their relationship with soil chemical properties, soil respiration, and humus systems (see Visentin et al.) [41].

2.3. Humus Classification and Chemical Analysis

For each subsite, a soil profile was opened to classify humus forms following the methodology described by Zanella et al. [42]. After the maximum depth of the A horizon was reached, the following data were collected: thickness of all diagnostic horizons found in each profile (OL, OF, OH, A); qualitative characteristics of aggregates composing the A horizon (whether biomacro- (maA), biomeso- (meA), or biomicrostructured (miA), massive (msA), or single grained (sgA)); sharpness of the transition between O and A horizons. When occurring, para horizons (Ligno, Rhizo, or Bryo) were noted and measured. Based on these data, the humus system and form of each replicate site were classified. As some humipedon profiles, mainly in windthrow-affected areas, were disturbed and horizons not always easily discernible, the following criteria were applied: (i) when the horizon was discontinuous or <3 mm, the assigned thickness was set equal to 0; (ii) if disturbed or mixed with other horizons, the minimum undisturbed thickness of a horizon was recorded; (iii) para horizons were assigned to the O or A horizon according to the amount of organic matter present (generally "Rhizo" horizons were assigned to the A horizon, whereas "Ligno" and "Bryo" to the O horizon).

After registering the thickness of O (OL + OF + OH) and A horizons, a cylindrical soil core (approximately 100 cm^3) was collected from each horizon for chemical analysis. In the laboratory, each soil core was homogenized and sieved to 2 mm. The pH was determined using a pH meter (Xylem Analytics, Weilheim in Oberbayern, Germany) in a soil-distilled water solution with a 1:5 volume ratio [43]. SOM was assessed via loss-on-ignition, wherein 6 g of pre-dried soil (at 105 °C) was placed in a muffle furnace (Nabertherm GmbH, Lilienthal, Germany) at 160 °C for 6 h, followed by 400 °C for 4 h [44]. SOM was subsequently calculated using the following formula:

$$SOM\% = [(\text{Weight}_{160\,^\circ C} - \text{Weight}_{400\,^\circ C})/\text{Weight}_{105\,^\circ C}] * 100$$

2.4. Statistical Analysis

All statistical analyses were performed with R software v 4.2.3.

Non-parametric tests were applied after ANOVA assumptions were tested (package: stats) and not met. The Kruskal–Wallis test followed by the Mann–Whitney test with Holm correction (package: stats) was used in order to assess the differences between conditions of the following variables: pH, SOM, thickness of O horizons, and maximum depth of O horizon. Initially, the analysis was conducted separately for the two areas. However, since both areas exhibited similar variation trends, the analysis was repeated using combined data from both areas.

Subsequently, for each replicate, a single value was determined for each soil chemical parameter (pH and SOM) representing the mean for the O and A horizons within the first 15 cm of the humipedon. This value was calculated as a weighted mean, taking into account the relative thicknesses of the O (OL + OF + OH) and A horizons within the top

15 cm of the humipedon. Finally, Kruskal–Wallis and Wilcoxon tests were performed on these new variables.

3. Results

3.1. Soil Chemical Features

Soil organic matter content and pH in O and A horizons (Table 1) did not differ statistically between conditions ($p > 0.05$).

Table 1. Means and standard errors of pH and soil organic matter content (SOM) of O and A horizons in each soil coverage condition. IF = intact forest; M = permanent meadow; G = under grass in windthrow areas; W = under decaying wood in windthrow areas; B = bare soil in windthrow areas.

Condition	pHO Mean ± SE	pHA Mean ± SE	SOM O% Mean ± SE	SOM A% Mean ± SE
IF	5.01 ± 0.1	5.48 ± 0.16	56.23 ± 3.61	21.72 ± 2.08
M	5.8 ± 0.09	6.03 ± 0.1	42.63 ± 1.87	13.89 ± 1.22
G	5.39 ± 0.1	5.95 ± 0.13	43.92 ± 2.99	16.76 ± 1.07
W	5.19 ± 0.27	5.93 ± 0.22	57.98 ± 7.04	18.8 ± 3.09
B	-	5.88 ± 0.55	-	17.78 ± 10.13

In contrast, when the weighted mean of SOM and pH values of the first 15 cm of the humipedon was considered, a trend of decreasing SOM and increasing pH in G and B conditions (but not in W) in windthrow sites compared to IF emerged ($p < 0.01$ for all comparisons), with G values approaching those of M, as reported in Visentin et al. [19] (Figure 2).

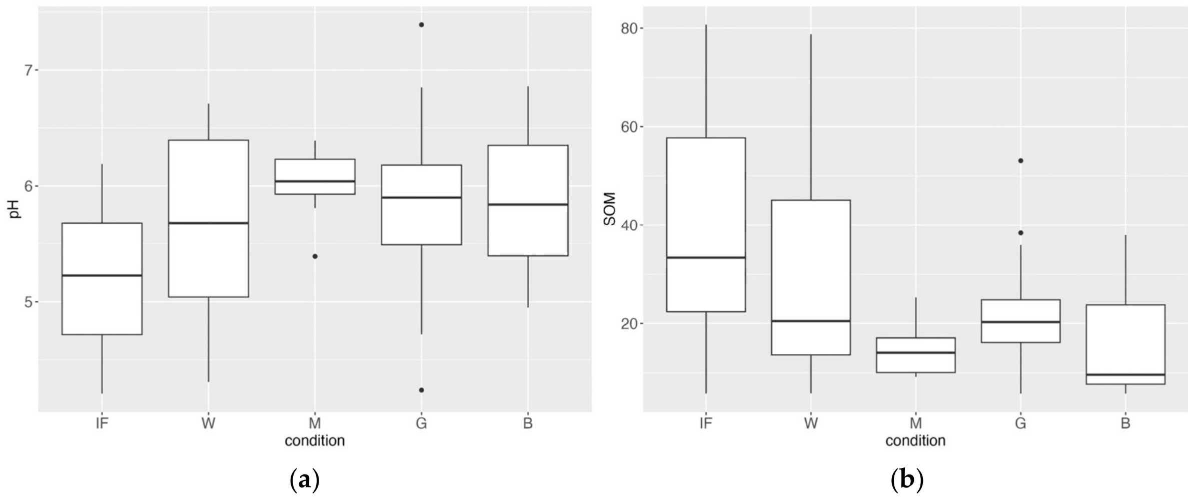
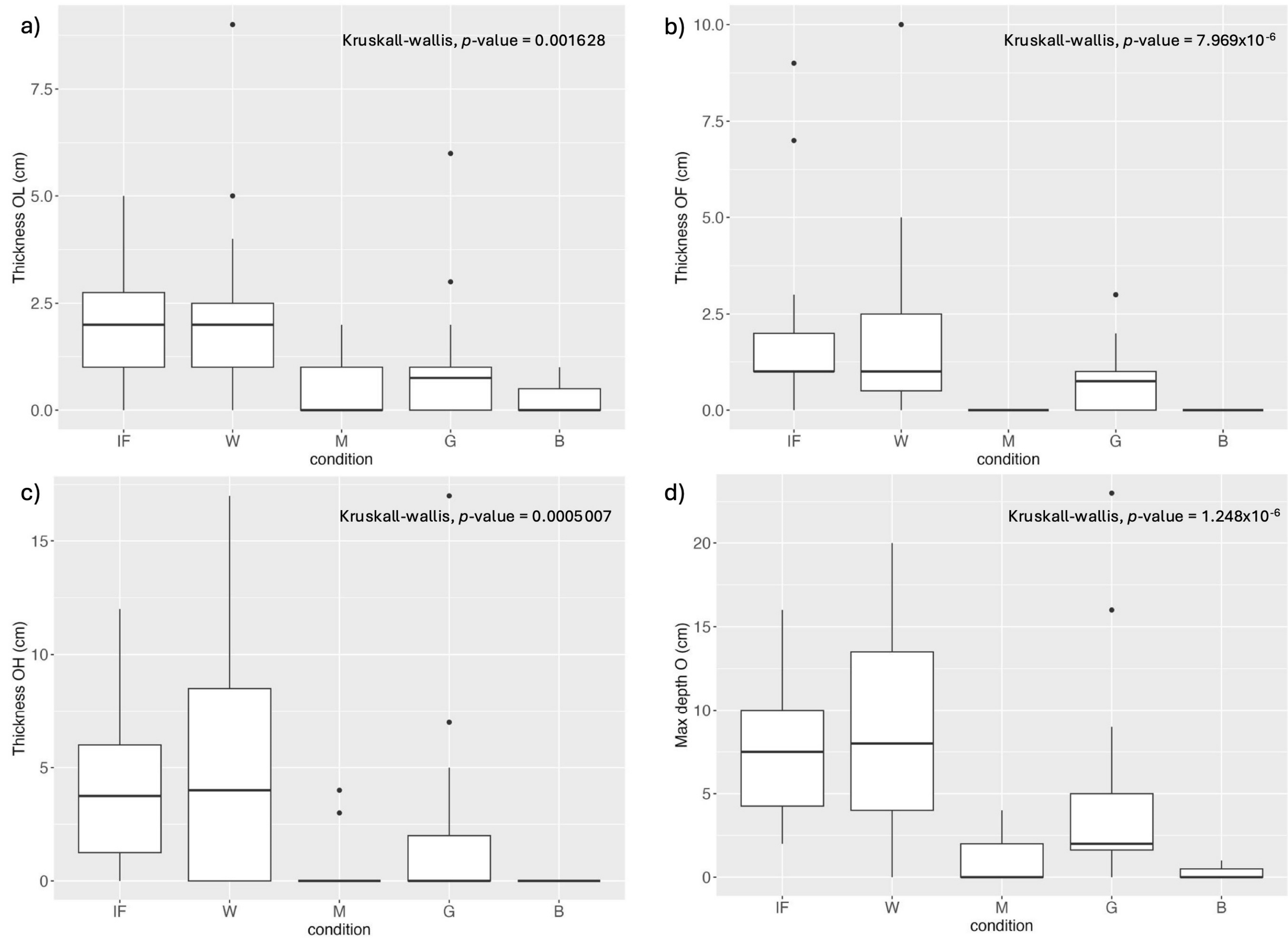


Figure 2. Boxplot of (**a**) pH and (**b**) soil organic matter content (SOM, %) in the topsoil (15 cm) of each soil coverage condition in both sampling areas: IF = intact forest; W = under decaying wood in windthrow areas; M = permanent meadow; G = under grass in windthrow areas; B = bare soil in windthrow areas.

3.2. Diagnostic Horizons

In undisturbed soils, all O diagnostic horizons were thicker in IF than in M. In windthrow-affected areas, OL, OF, and OH were thinner in G and B than in undisturbed forest, while the thickness of such horizons in W did not significantly differ from IF ($p > 0.05$). The same trend was observed when the maximum depth reached by the complete O horizon was examined (Figure 3).



	IF-W	IF-M	IF-G	IF-B	M-G	M-B	M-W	G-W	G-B	W-B
a)		*	*				*			
b)		***	**	*	*		**	*		
c)		**	**	*						
d)		***	***	*	*		**	*	*	*

Figure 3. Boxplot representing the thickness of (**a**) OL; (**b**) OF; (**c**) OH horizons; and (**d**) maximum measured depth of the entire O horizon (OL + OF + OH) in each soil coverage condition. IF = intact forest; W = under decaying wood in windthrow areas; M = permanent meadow; G = under grass in windthrow areas; B = bare soil in windthrow areas. For each boxplot, the significance of the Kruskal–Wallis test is provided. In the table, the significant couples are reported: * = $p < 0.05$, ** = $p < 0.01$, *** $p < 0.001$.

3.3. Humus Classification

Regarding undisturbed soils (Table 2 and Figure 4), Amphi humus systems accounted for 90% of the observations in IF, with only two observations of a Moder system and one of a Mull. Eleven different humus forms were observed, with the most frequent being 14 observations of Pachyamphi (Figure 5a). Para forms were also frequently present: Rhizo, Ligno, but mostly Bryo, due to the important presence of mosses in undisturbed forest soils. In permanent meadows, the Mull humus system accounted for two-thirds of the observations, with Amphi accounting for the remaining systems, all of which belonged to just one site—a permanent meadow occasionally pastured by livestock. In 83% of the cases, the Mull humus form was Eumull, with Rhizomull observed in only one case.

Table 2. Humus systems and forms, and their relative frequency, observed in the two study areas. IF = intact forest; M = permanent meadow; G = under grass in windthrow areas; W = under decaying wood in windthrow areas; B = bare soil in windthrow areas.

Condition	Humus System	Number of Observations	Humus Form	Number of Observations	%
IF	Mull	1	Dysmull	1	100
	Moder	2	Dysmoder	1	50
			Ligno Dysmoder	1	50
	Amphi	27	Pachyamphi	6	22.22
			Bryo Pachyamphi	6	22.22
			Rhizo Pachyamphi	1	3.7
			Ligno Pachiamphi	1	3.7
			Leptoamphi	3	11.11
			Eumesoamphi	3	11.11
			Bryo Eumesoamphi	6	22.22
			Eumacroamphi	1	3.7
M	Mull	6	Eumull	5	83.33
			Rhizo Mull	1	16.67
	Amphi	3	Pachyamphi	2	66.67
			Leptoamphi	1	33.33
G	Mull	14	Rhizo Mull	5	35.71
			Eumull	4	28.57
			Dysmull	4	28.57
			Ligno Rhizo Mull	1	7.14
	Amphi	16	Leptoamphi	5	31.25
			Pachyamphi	2	12.5
			Rhizo Pachyamphi	2	12.5
			Eumesoamphi	2	12.5
			Rhizo Eumesoamphi	4	25
			Bryo Eumesoamphi	1	6.25
W	Mull	7	Rhizo Mull	3	42.86
			Rhizo Ligno Mull	1	14.28
			Eumull	1	14.28
			Mesomull	1	14.29
			Dysmull	1	14.29
	Amphi	6	Leptoamphi	1	16.67
			Ligno Leptoamphi	1	16.67
			Pachyamphi	2	33.33
			Ligno Pachyamphi	1	16.67
			Rhizo Eumesoamphi	1	16.67
	Tangel	2	Eutangel	1	50
			Ligno Leptotangel	1	50
B	Mull	2	Eumull	2	100
	Amphi	1	Leptoamphi	1	100

In windthrow-affected areas (Table 2 and Figure 4), a marked tendency towards a Mull humus system was observed compared to IF (Figure 5d). Mull accounted for almost 47% of the observations in G and W, whereas it accounted for two-thirds of the observations in B. Various Mull forms were observed in G, with Rhizo being the most frequent para form (Figure 5b). One Ligno para form was detected, probably left over from the previous undisturbed forest. In G, the Amphi humus system covered the remaining observations. Leptoamphi and Eumacroaphi were the most frequent forms—a result in line with the thinning of the O horizon under this soil coverage condition. In W, on the other hand, alongside the Mull and Amphi humus systems, the Tangel system accounted for 13% of the observations and was found only under this soil coverage condition. The Rhizo paraform was observed when the soil coverage was composed of a single log surrounded by herbaceous vegetation. The presence of Ligno could mainly be attributed to the presence of an OL or OF Ligno horizon (Figure 5c). Finally, only Mull and Amphi were recorded in B.

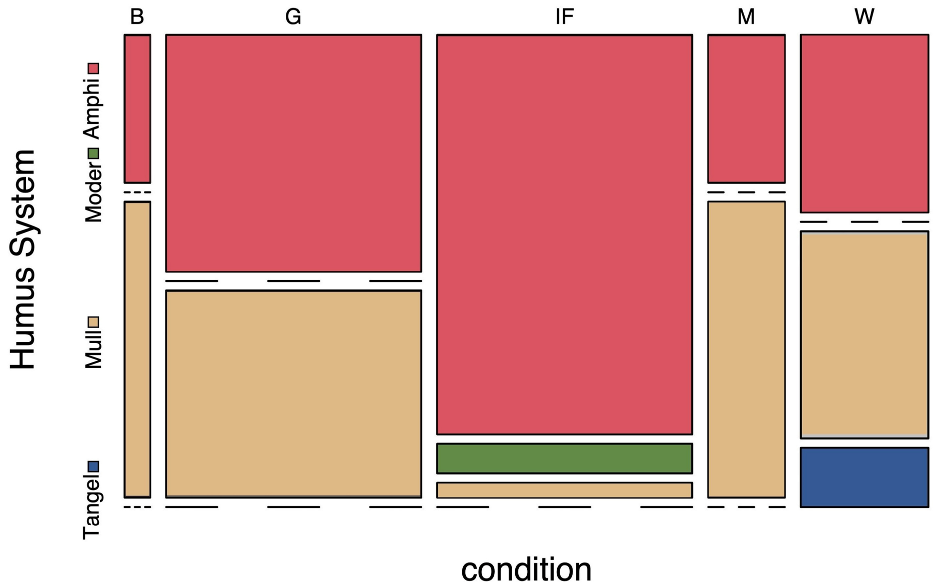


Figure 4. Mosaic plot comparing the distribution of the humus systems across the investigated soil coverage conditions: B = bare soil in windthrow areas; G = under grass in windthrow areas; IF = intact forest; M = permanent meadow; W = under decaying wood in windthrow areas.

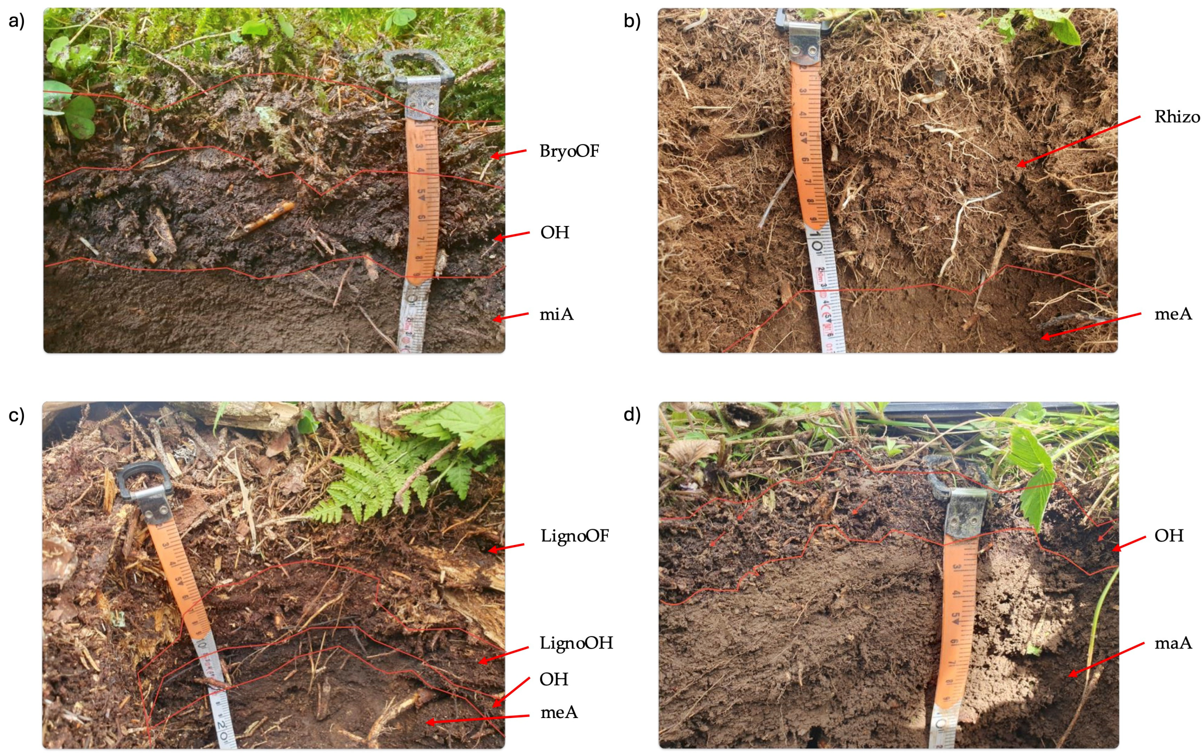


Figure 5. Examples of humus profiles from the selected study sites; red lines demarcate the diagnostic horizons: (**a**) Cansiglio, IF: Bryoeumesoamphi; (**b**) Val di Fassa, G: Rhizomull; (**c**) Val di Fassa, W: Lignoleptotangel; (**d**) Cansiglio, G: Eumesoamphi evolving towards a Mull system. Here, the O-A transition is very irregular; red arrows indicate the organo-mineral casts in the thickness of OH.

4. Discussion

This study aimed to evaluate humus dynamics, with particular attention to the evolution of the diagnostic horizons in several soil coverage conditions five years after the severe Vaia windstorm, which occurred in 2018.

Our results evidenced no significant variation either in soil organic matter (SOM) content or pH when conditions within the same horizon were compared. However, when the mean value of the top 15 cm of the humipedon—the layer in which most soil fauna typically resides, playing a crucial role in soil health and nutrient cycling—was taken as a reference, a discernible difference emerged between soil coverage conditions. This difference can be accounted for by the thinning of all O diagnostic horizons (OL, OF, and OH) in soils under herbaceous cover (G) and in bare soils (B) in windthrow-affected areas when compared with intact forest (IF). This result is in line with a study by Don et al. [45], where the soil organic carbon (SOC) stock in the Tatra mountains 3.5 years post windthrow disturbance was investigated. This study revealed a decrease in SOC stock in litter horizons in cleared areas but no similar decrease in non-cleared areas that had been left to natural regeneration; no variance in SOC stock was found in organo-mineral and mineral horizons. As demonstrated in other studies [46,47], topsoil SOC turnover rate is driven by temperature, increasing along with soil depth. Consequently, in organic (O) horizons, the mean SOM residence time is significantly shorter than in organo-mineral (A) horizons, which are more protected from solar radiation. This results in the formation of different SOM "stability pools", with the topsoil layer potentially exhibiting greater activity than deeper layers [48]. In line with these studies and with the findings of Kobler et al. [49] and Mayer et al. [50], our data suggest that in windthrow-affected areas with no soil coverage, canopy loss and the subsequent increase in solar energy may have enhanced the mineralization of the organic matter in the OL, OF, and OH horizons, which represents the less stable pool. This may have resulted in (i) the thinning of the organic horizons and the shift from an Amphi to a Mull system, and (ii) the net loss of SOM and a pH increase in the top 15 cm of the humipedon. Following this, the humipedon conditions of G and B approached those of mountain permanent meadows. A similar shift toward a Mull system was also observed following clear cuts in mature stands [51] and under mature and dying spruce trees, which, within the forest sylvogenetic cycle, favored forest regeneration [26,27,52].

On the other hand, in soils covered by dead wood (W), the changes were less pronounced than those observed in G and B. The turnover of SOM in W was slower due to the physical protection of timber, although our study revealed considerable variability. It is noteworthy that the only two observations of Tangel systems were found in the W plots. This humus system is typical of upper mountain climate with rigid ecological conditions and is characterized by slow organic matter turnover [33].

Humus forms registered in intact forest were in line with those expected in carbonate-rich alpine soil [31] and with those found in a survey of Ponge et al. [53] in forests in the Veneto region.

In windthrow-affected sites, the characterization of soil horizons was often challenging due to their irregularity and mixing. Disturbances in some OH horizons were observed, often marked by the mixing activity of earthworms, which was evidenced by organo-mineral droppings within the OH horizon and an irregular transition between the OH and A horizons. This bioturbation is expected to eventually result in the complete disappearance of the OH horizon—a process described by Zampedri et al. [28] for bipolar Amphi systems, though in our study the shift is not being driven by stand aging but by the disruption of the forest ecosystem caused by the storm. These evolving humipedons were classified as Amphi systems due to the current presence of the OH horizon, but the ongoing trend toward Mull formation was clearly evident.

Concerning Para humus forms, the most interesting were found to be the Ligno forms (Figure 5c). In IF, the registered Ligno horizons were OH horizons: residues of wood decomposition, incorporated in the humipedon profile and broken down by soil animals and microflora until it approached the amorphous state typical of OH. Tatti et al. [54] classified this advanced stage of decomposition—corresponding to the fifth stage in Maser et al. [55]—as the third stage of the decomposition process, or the "integration stage" in the soil. It is estimated that dead wood of *Picea* spp. takes from 61 to 286 years to reach this complete stage of decomposition, depending on temperature, moisture, C concentration, contact with the forest floor, and the composition of the decomposer community [56,57]. In W, on the other hand, we found dead wood in decomposition stage 1 or 2, which was mainly incorporated in the OL or OF horizons (rarely in the OH horizon) or found in the form of logs and stumps. Studies by Blønska [58,59] indicate that the maximum transfer of organic carbon into the soil occurs at the fifth stage of decomposition. This suggests that unless dead wood from the Vaia storm is left in place for several decades, it will not significantly contribute to the accumulation of soil organic carbon in these profiles. Leaving dead wood provides the additional benefit of enhancing forest regeneration, as demonstrated by Bernier et Trosset [60], who found that the growth rate of spruce and larch was higher in humus form integrated with rotten wood (third stage of decomposition, [36]) rather than in humus that did not contain any dead wood.

5. Conclusions

The question of whether soils will act as a sink or source of atmospheric carbon under climate change remains a topic of ongoing debate, highlighting the urgent need for comprehensive surveys of the relationships between humus systems and carbon storage in a wide range of both undisturbed and disturbed ecosystems. Collecting reliable data on humus systems and their carbon stock dynamics is crucial for improving global predictive models and making informed decisions about sustainable land management practices in the face of climate change.

Our study suggests that the passage of a severe storm, such as the Vaia storm, significantly increases the heterogeneity of the affected forest floor. Despite evolution dynamics still being underway, we observed a relatively rapid response to the disturbance on the part of the humipedon. The formation of Mull patches and the presence of Lignoforms are likely to promote forest regeneration. However, a critical concern emerging from our study is the loss of soil organic matter, which could have significant long-term effects on soil fertility and carbon storage. To mitigate this, we recommend leaving a portion of dead wood on-site to undergo natural decomposition, which could help preserve soil organic matter levels and enhance the resilience of forest ecosystems.

Ultimately, our study underscores the importance of understanding how disturbance events, such as severe storms, interact with humus systems and soil organic matter in forest ecosystems. Collecting detailed data on these dynamics is essential for refining global climate models and informing land management decisions. Future research should prioritize long-term monitoring of these events across diverse ecosystems to improve our ability to predict and manage the effects of climate change on soil health and forest regeneration.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15122176/s1, Table S1: The coordinates (lat, long) of all sampling points surveyed, as well as their altitudes (msl).

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