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Enhanced Impacts of Extreme Weather Events on Forest: The Upper Valtellina (Italy) Case Study

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Abstract: Extreme weather events are increasingly recognized as major stress factors for forest ecosystems, causing both immediate and long-term effects. This study focuses on the impacts experienced by the forests of Valdisotto, Valfurva, and Sondalo (28% of the total area is covered by forests) in Upper Valtellina (Italy) due to the Vaia storm that occurred in October 2018. To define the immediate impacts of Vaia, we assess the economic value of forest ecosystem services (ESs), particularly those provided by timber production and carbon sequestration, pre- and post-Vaia and during the emergency period. We used the market price method to assess the economic values of timber production and carbon sequestration, as these are considered to be marketable goods. Based on data processed from Sentinel-2 satellite images (with a spatial resolution of 10 m), our results show that, despite the reduction in forest area (−2.02%) and timber stock (−2.38%), the economic value of the timber production increased after Vaia due to higher timber prices (i.e., from a total of €124.97 million to €130.72 million). However, considering the whole emergency period (2019–2020), the total losses are equal to €5.10 million for Valdisotto, €0.32 million for Valfurva, and €0.43 million for Sondalo. Instead, an economic loss of 2.88% is experienced for carbon sequestration, with Valdisotto being the more affected municipality (−4.48% of the pre-Vaia economic value). In terms of long-term impacts, we discuss the enhanced impacts due to the spread of the bark beetle *Ips typopgraphus*.

Keywords: forest ecosystem services; economic value; Vaia; bark beetle; Lombardy (Italy)

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1. Introduction

Extreme weather events (e.g., storms, heavy rainfall, and heat waves) are increasingly recognized as significant stress factors on forest ecosystems around the world [1–3]. These events can cause both short- and long-term effects. Immediate damage caused by storms can be tree fall and crown breakage, while long-term impacts involve increased vulnerability to pests and diseases and alterations in forest structure [4]. The frequency and intensity of such events are expected to increase with ongoing climate change, posing greater risks to forest health [5].

In Europe, for example, extra-tropical North Atlantic cyclones can often cause high surface wind speeds [6]. Fast-moving cyclones can produce abnormal weather conditions, high winds, and storm surges that severely impact the environment and many socio-economic sectors [7]. Europe is experiencing more and more extreme wind events [8]. Rapella et al. [9] detected the presence of significant trends in the occurrence of extreme wind events during the period 1950–2020. The likelihood of such events having destructive effects in forest environments is influenced by a combination of weather conditions, site attributes, topography, and the characteristics of trees (i.e., tree vulnerability) [10,11]. However, the pivotal factor remains the peak wind speed: once gusts reach certain thresholds, trees become vulnerable to breakage, regardless of their individual traits. While mitigating wind damage may prove challenging in such scenarios, management strategies exist to increase the long-term resistance and resilience of [11].

This study focuses on the Vaia storm, which hit Northeastern Italy on 29 October 2018, causing widespread damage across 494 municipalities with winds exceeding 200 km/h and heavy rainfall (more than 350–400 mm) [12]. This storm was chosen as the focus of our research due to its unprecedented impact [13], destroying or severely damaging approximately 425 km^2 of forest with an estimated 8.5 million m^3 of fallen trees, resulting in a profound loss of forest-related ecosystem services [11]. In the 494 municipalities, the damage affected about 3% of the total forest area, although in some areas the damage was as high as 47% of the municipal forest area [12]. These damaged areas contained the forests with the largest timber stocks and the highest forest productivity in Italy (about two-thirds of Italy's timber comes from these forests). Lombardia was one of the regions of Northern Italy mostly affected by Vaia; more than 2200 ha of forest were completely destroyed, and over 70% of the damage involved spruce forests [14].

This paper investigates the impact of the Vaia storm on the forests of Upper Valtellina (Lombardia, Italy), as it is one of the provinces with the highest recorded damage, by assessing the lost economic value associated with forest ecosystem services (ESs). The study is particularly important as the forests of Upper Valtellina not only cover a large part of the territory but also play a crucial role in the livelihood and well-being of the local population, acting as a defense against hydrogeological instability and contributing to climate change mitigation. The Upper Valtellina, known for its important forestry sector, is also an important Italian tourist destination, with forests offering opportunities for sustainable tourism through a network of cycle paths [15] and footpaths that allow an immersive experience of nature. Given the importance of these forests, rapid assessment of storm damage using satellite data are essential to mitigate the effects of extreme events [13].

After this initial phase, it is crucial to quantify the impact not only in terms of forest area lost but also in terms of ecosystem services and associated economic value lost. Therefore, using Sentinel 2 data to identify the areas affected by storm Vaia, the economic value of certain ecosystem services provided by the forest before and after the extreme event was then calculated. Specifically, we evaluated changes in timber production and carbon sequestration before and after the storm. Contrary to other studies that assess the post-Vaia situation by focusing on one or at most two years after the extreme event (e.g., [16]), we have assessed in detail both the situation immediately after the storm (which we have called the emergency period) and after this first phase (which we have called the post-Vaia period). Moreover, we discussed the enhanced impacts of this extreme wind event due to the proliferation of the bark beetle *Ips typographus* (Coleoptera: Curculionidae, Scolytinae). Indeed, the expansion of outbreaks of bark beetles from damaged to healthy stands commonly occurs from 1 to 3 years after a storm, additionally impacting conifer forests [11].

By focusing on this specific extreme event, our study contributes to a broader understanding of how extreme weather events, exacerbated by climate change, can have compounding effects on forest ecosystems, highlighting the need for targeted management and conservation strategies.

2. Study Area

The research focused on the Alpine area of the upper sector of Valtellina (hereafter called Upper Valtellina) in Northern Italy (8.96×10^8 km^2, Figure 1). Valtellina is a typical Alpine valley, with the specificity of the valley's orientation, from west to east. Upper Valtellina includes 6 municipalities: Livigno, Valdidentro, Bormio, Valfurva, Valdisotto, and Sondalo. Moreover, it is part of the Stelvio National Park, a natural protected area of less than 600 km^2 [17] covered by extensive coniferous forests. It is crossed by the Ortles-Cevedale Mountain range, where several glaciers [18,19] contribute to the high degree of geodiversity of the territory, such as Forni Glacier [20–22].

Specifically, the research focuses on the three municipalities of Upper Valtellina most affected by the Vaia (i.e., Valdisotto, Valfurva, and Sondalo) with a total area of 3.99 × 10^2 km^2 (ranging from 940 to 3855 m a.sl. of Gran Zebrù peak), of which 1.12 × 10^2 km^2 are covered by forests (28%) (the data were obtained through the shapefiles of the Forest Action Plan, provided by the "Consorzio Forestale Alta Valtellina"—CFAV, the local forestry consortium) (Table 1).

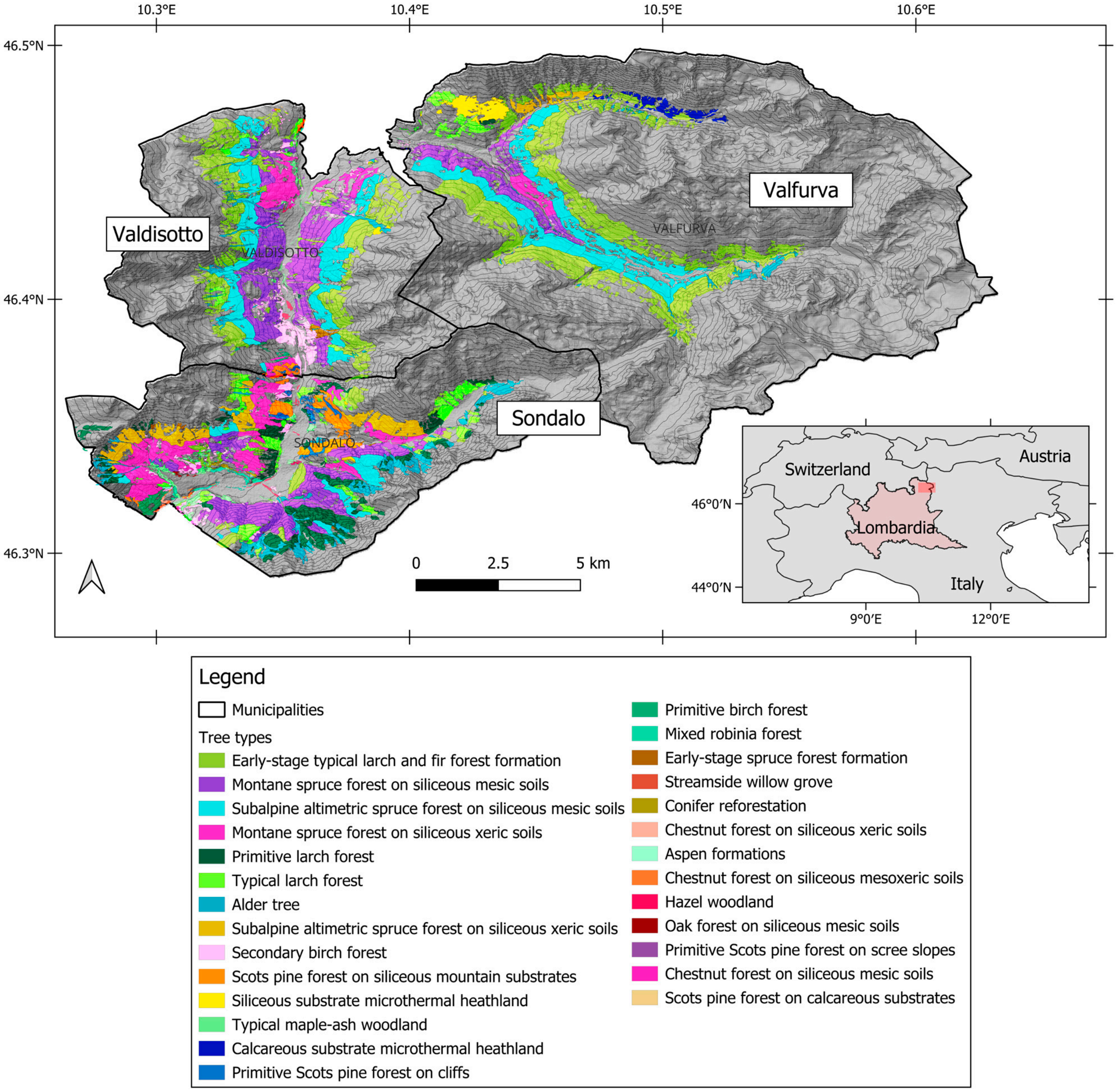

Figure 1. The study area is located in Upper Valtellina, Lombardia, Italy. The area is divided into the three municipalities impacted by the Vaia storm: Valdisotto, Valfurva, and Sondalo. The forest areas with all the tree types reported in the Forest Action Plan, provided by CFAV are also shown.

Table 1. Tree types present in the study area with their respective area in km² and percentage. All these tree types are reported in the Forest Action Plan, provided by CFAV.

Tree Types	Area (km²)	Area (%)
Early-stage typical larch and fir forest formation	31.02	27.54
Montane spruce forest on siliceous mesic soils	19.87	17.64
Subalpine altimetric spruce forest on siliceous mesic soils	18.62	16.53
Montane spruce forest on siliceous xeric soils	9.63	8.55
Primitive larch forest	6.19	5.50
Typical larch forest	5.56	4.93
Alder tree	5.32	4.73
Subalpine altimetric spruce forest on siliceous xeric soils	4.58	4.07
Secondary birch forest	3.16	2.81
Scots pine forest on siliceous mountain substrates	2.38	2.11
Siliceous substrate microthermal heathland	1.40	1.24
Typical maple-ash woodland	1.31	1.16
Calcareous substrate microthermal heathland	0.95	0.84
Primitive Scots pine forest on cliffs	0.66	0.59
Primitive birch forest	0.64	0.57
Mixed robinia forest	0.35	0.31
Early-stage spruce forest formation	0.33	0.29
Streamside willow grove	0.20	0.19
Conifer reforestation	0.13	0.11
Chestnut forest on siliceous xeric soils	0.09	0.08
Aspen formations	0.06	0.05
Chestnut forest on siliceous mesoxeric soils	0.05	0.05
Hazel woodland	0.05	0.04
Oak forest on siliceous mesic soils	0.04	0.03
Primitive Scots pine forest on scree slopes	0.04	0.03
Chestnut forest on siliceous mesic soils	0.01	0.01
Scots pine forest on calcareous substrates	<0.01	<0.01
Total	112.6466	100

3. Data

Most of the data have been provided by the local forestry consortium, CFAV. CFAV, founded in 1994 by the local authorities, has the main aim of the management of the forests and rural areas of Upper Valtellina. Its birth was due to the growth of abandoned territory and to preservation with planned interventions in the mountain environments.

The maps with the area and distribution of all the tree types are made available by CFAV through the Forest Action Plan (FAP), a tool for analyzing and guiding the management of the forest areas, for linking forest and land planning, for supporting the definition of priorities for the granting of incentives and subsidies, and for the forestry activities to be carried out (as reported by CFAV). As by analyzing in QGIS the tree types reported in the FAP are slightly different from those available in the webpage of the IIT Lombardia region (https://www.geoportale.regione.lombardia.it/, accessed on 1 October 2024) [23], we preferred to consider the FAP data because it was provided by the local consortium CFAV, which makes available further detailed data useful for our study (Figure 1).

In addition, CFAV provided Forest Management Plans (FMP), descriptive documents of the forests with technical characteristics of trees and forests in general, with a validity of about fifteen years (as reported by CFAV). The FMPs are divided into municipalities and then into parcels. For our study, we considered the FMPs of Valdisotto, Valfurva, and Sondalo (thus excluding Valdidentro, Livigno, and Bormio because they were not affected by the Vaia storm). Parcels are a subdivision of the municipalities by location made by CFAV. For each parcel, different information is available, such as the extension of the forest (km²), the tree types, the normal and total timber stock (m³), and the annual timber stock increment (m^3/year). Other information about trees is also included: age, height, number, and mean volume of trees. By comparing data relative to tree types reported in the FMPs with the ones available in the FAP, we found slight differences. Specifically in the FMPs, there are no "Calcareous substrate microthermal heathland", "Mixed robinia forest", "Streamside willow grove", "Chestnut forest on siliceous xeric soils", "Aspen formations", "Chestnut forest on siliceous mesoxeric soils", "Hazel woodland", "Oak forest on siliceous mesic soils", for a total area of 0.84 km^2, corresponding to 0.75% of the total forest area available in the FAP (Table 1).

Valdisotto's FMP was developed in 2020/2021 (i.e., post-Vaia); it is valid from 2023 to 2037, and it is formed by 63 parcels. Valfurva's FMP dates back to 2013/2014 (i.e., pre-Vaia) with validity from 2016 to 2030, and it is formed by 63 parcels. Sondalo's FMP was developed in 2015 (i.e., pre-Vaia), and its validity goes from 2018 to 2032, including 66 parcels.

Areas involved in the Vaia storm are available as shapefiles at the webpage of the IIT Lombardia region (https://www.geoportale.regione.lombardia.it/, accessed on 1 October 2024) (Figure 2). As reported on the website, the data were processed by ARPA Lombardia and ERSAF through photointerpretation of Sentinel-2 satellite images (True Color Image, with bands 2, 3, and 4 in the visible spectrum, with a spatial resolution of 10 m) from late June 2019, comparing the state of the affected areas before and after the event. In addition to Sentinel-2 images, other sources of information were used for the correct assessment of the affected areas: field surveys and aerial observations (helicopters, planes, and drones). The resulting maps show the clearly damaged parts of forests visible at this scale. Figure 3 shows an example of a comparison between the pre- (2016) and post-Vaia (2019) situation covering a portion of 2.69 km^2 of Valdisotto whose 0.76 km^2 was impacted by Vaia (the position is highlighted in Figure 2). However, the satellite could not have detected crashes in areas shaded by mountains, as well as small, diffuse crashes. The total area affected by Vaia in our study area is 1.41 km^2.

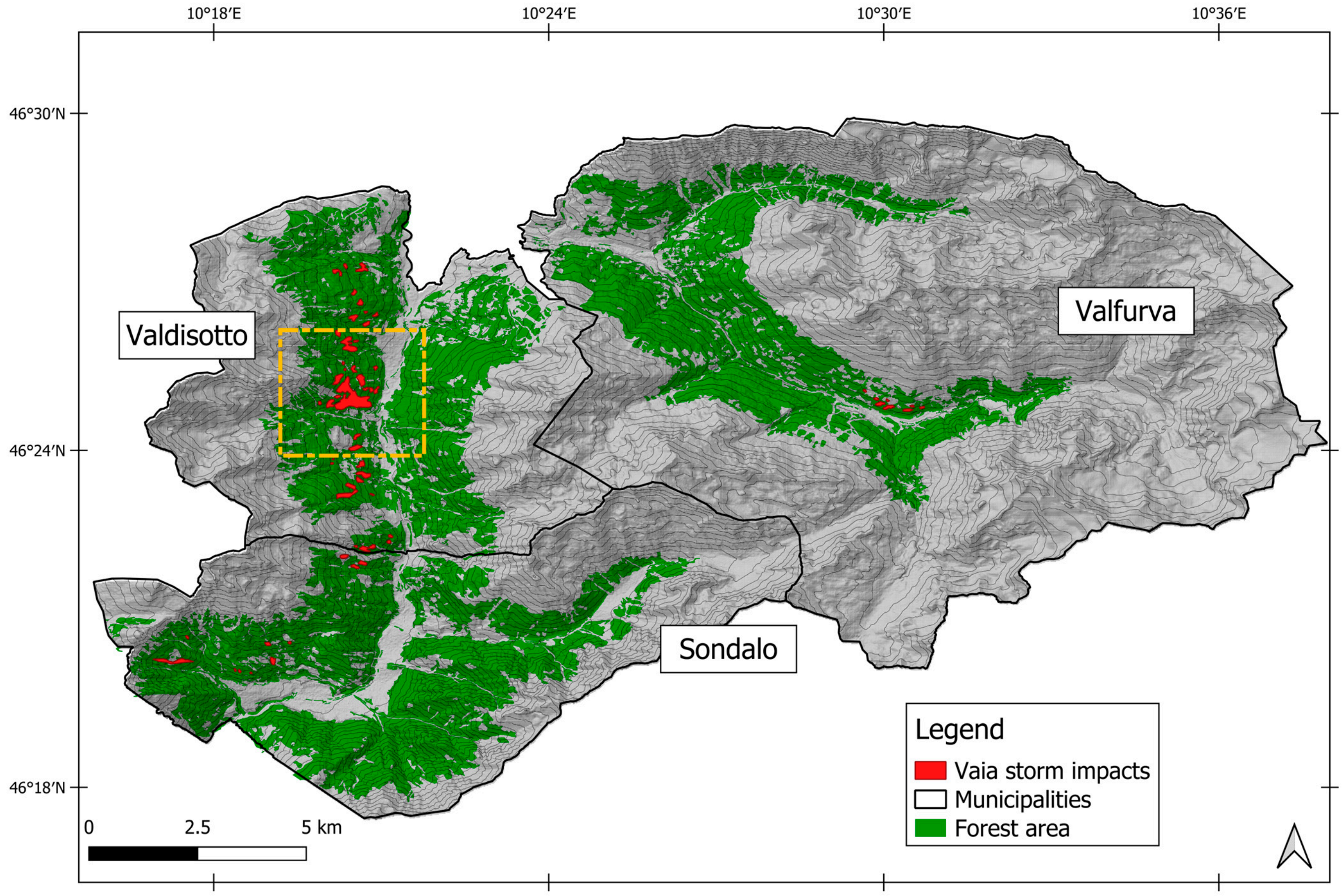

Figure 2. The areas involved in the Vaia storm are shown in red, data available at the webpage of the IIT Lombardia region (https://www.geoportale.regione.lombardia.it/, accessed on 1 October 2024) [24]. The example of photointerpretation reported in Figure 3 is highlighted by a box with a yellow line.

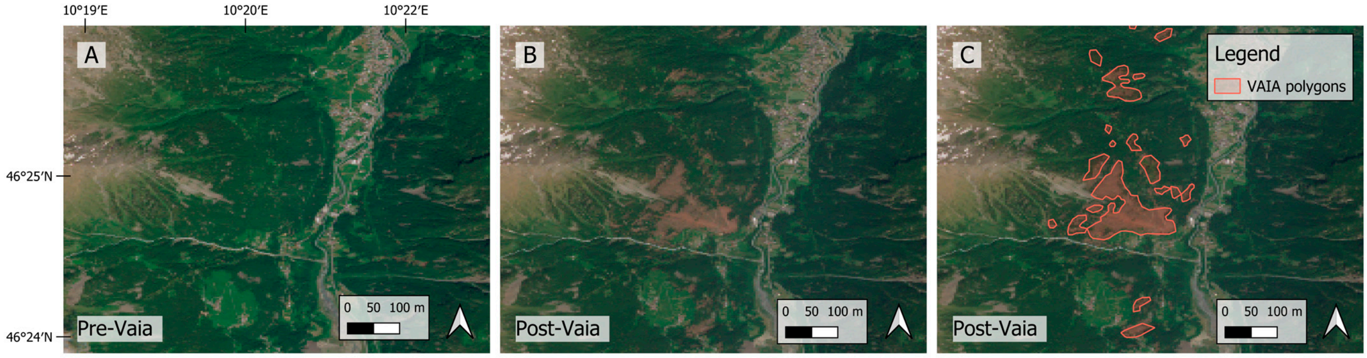

Figure 3. Example of the photointerpretation using Sentinel-2 satellite images of a portion of Valdisotto. In order: (**A**) image of the pre-Vaia storm of 2016, (**B**) image of the post-Vaia storm of 2019, (**C**) image of the post-Vaia storm of 2019 with an example of polygons (in red).

4. Methods

Ecosystems provide multiple services to human society: the well-known ecosystem services (ESs) [25]. The ESs can be divided, according to the Millenium Ecosystem Assessment [26] and then modified by Haines-Young and Potschin-Young [27], in three main categories: provisioning (i.e., products obtained from ecosystems), regulation and maintenance (i.e., provide the regulation of ecosystem processes), and cultural (i.e., nonmaterial benefits provided by the ecosystem to the people). In this study, we focused on provisioning and regulation services provided by forests, specifically on timber production and carbon sequestration.

We used the market price method to assess the economic values of timber production and carbon sequestration, as these are considered to be marketable goods. We are aware of the uncertainty associated with using the market price method, which underestimates the value of ecosystem services by excluding, for example, non-use and existence values [28]. However, we have chosen to use this downward approach to provide conservative estimates, as recommended in the literature [29].

Data processing was carried out using the R-Studio software 4.3.3 and QGIS 3.34.0.

4.1. Forest Area and Timber Stock Pre- and Post-Vaia

As CFAV reported information (i.e., shapefiles and data) for different periods, we quantified the amount of forest area and timber volume for each municipality before and after the Vaia storm. For the municipalities of Valfurva and Sondalo, for which the data were taken before the storm, the area lost was subtracted from the values provided by CFAV to calculate the area of forest post-Vaia; for Valdisotto, for which the data were taken after the storm, the area affected by Vaia was added to the post-Vaia value of forest provided by CFAV.

For the timber stock, we first calculated its average value per km^2 for each municipality. For Valfurva and Sondalo, we multiplied the mean value of the timber stock before Vaia by the post-Vaia area; for Valdisotto, the mean value of the timber stock after Vaia was multiplied by the pre-Vaia area.

4.2. Timber Production

The economic evaluation of the timber production provided by forests is based on a market price since dealing with a marketable good as wood [28]. This technique could approximate the ecosystem service value by excluding the costs associated with timber harvesting and the silvicultural treatments needed to reach the level of timber production and the non-use and existence values. However, it is recommended in the literature to make conservative estimates without introducing too many variables that increase the probability of error [30]. To estimate the timber production, the total timber stock (TTS, m^3), reported in the FMPs by CFAV, was considered. The data are available for each parcel. We quantified the total potential economic value of the timber production (V_{ptp}, €) provided by the whole forest as follows:

$$V_{ptp} = TTS \cdot p_t \quad (1)$$

where p_t represents the mean price of timber. The mean timber price was derived by "Legno Trentino" (https://www.legnotrentino.it/it/, accessed on 1 October 2024), a website managed by the Chamber of Commerce of Trento (Italy) that provides quarterly timber prices from 2006, in agreement with other studies (e.g., [16]).

To assess the economic value of timber production before and after the Vaia storm, we calculated the mean price of timber in three different periods (Figure 4). We chose to start in 2013 as it is the year when the first FMP (i.e., the one of Valfurva's municipality) was drafted, and to end in the last quarter of 2022 in order to consider a enough wide period post-Vaia. Looking at the whole dataset (2013–2022), a drastic decline is evident after Vaia (the first quarter of 2019), and a recovery occurred in early 2021. Indeed, in the fourth quarter of 2018, the timber price was 119 €/m^3, while in the consecutive quarter it was 63 €/m^3 (−47%). Therefore, to quantify the pre-Vaia economic value, we averaged the prices in the period from the first quarter of 2013 to the last one of 2018 (6 years) with a result of 90 €/m^3. During this period, prices have been almost stable, ranging from 73 to 119 €/m^3. The economic value lost due to the Vaia storm was assessed by averaging the prices in the emergency period (2019–2020, 8 quarters). The average timber price of this interval is 59 €/m^3, ranging from 56 to 63 €/m^3. The third period concerns the interval after the emergency in which the price went back to normal (8 quarters from the first quarter of 2021 to the last one of 2022). The post-Vaia average timber price is equal to 98 €/m^3, ranging from 76 to 111 €/m^3.

The choice to consider three different periods was supported by the findings by Udali et al. (2021) [16], who reported a statistically significant change in prices from September 2017–October 2018 (pre-Vaia) to November 2018–December 2019 (post-Vaia) ($p < 0.05$).

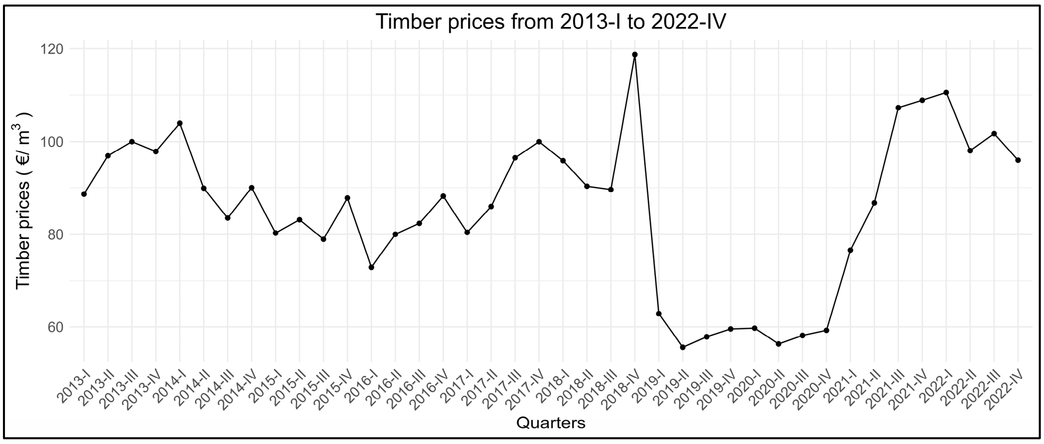

Figure 4. Timber prices (€/m^3) from 2013 to 2022 and the three averages considered to assess the economic value before and after the Vaia storm.

4.3. Carbon Sequestration

Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to, or remain, in the atmosphere [31]. Carbon dioxide (CO_2) is removed from the atmosphere either through absorption by the soil or by being transformed into biomass in the form of organic carbon [32]. This process ensures a reduction of the free component of this compound present in the atmosphere, thus preventing the enhancement of the greenhouse effect and the progress of global warming. The assessment of the economic value of the carbon sequestration was based on the formulas proposed by Grilli et al. [28]. In particular, the economic value of carbon sequestration in above- and below-ground biomass (V_{CS}, €/year) has been computed as follows:

$$V_{CS} = [(AGB + BGB) \times CC] \times P_C \tag{2}$$

where AGB is the above-ground biomass (t), BGB is the below-ground biomass (t), CC is the coefficient of carbon content (equal to 0.5 [33,34]), and Pc is the mean carbon price of the voluntary carbon market (4.59 €/t, related to 2012 [35]). We chose to use this price as in agreement with the carbon price of 5 €/t of the third trading period (2013–2020, and therefore synchronous with the data we have on forests) reported by the European Union Emissions Trading System [36]. Respectively, AGB and BGB are calculated with the following formulas:

$$AGB = I \times BEF \times WBD \tag{3}$$

$$BGB = I \times WBD \times R \tag{4}$$

where I is the annual timber stock increment (m^3/year, data from FMPs), BEF is the biomass expansion factor, WBD is the wood basal density (t/m^3), and R is the root/shoot ratio. These latter three were taken from Federici et al. [37] (Table 2); however, it was necessary to make some assumptions to be able to include each tree type present in our study area in the categories defined by Federici et al. [37] (i.e., stands, coppices, plantations, and protective). “Early-stage typical larch and fir forest formation” was included in their specific forestry type (“stands” as “larches”), as it is neo-formation with an active evolutive dynamic, which leads to the corresponding forest type [38]. “Montane spruce forest on siliceous mesic soils" was included in the "stands" category as "Norway spruce", as their dominant vegetation form is stands, and this type of vegetation is mainly composed of Norway spruce [38]. The same approach was applied to "Subalpine altimetric spruce forest on siliceous mesic soils" and "Montane spruce forest on siliceous xeric soils". "Primitive larch forest" and "Typical larch forest" were included in the specific type of forestry of "larches". "Alder tree" (*Alnus viridis*) was included in the "protective" category as "riparian forest", as it has an environmental and protective role [38]. In the Alps, it is naturally restricted to steep, north-facing subalpine slopes on well-drained soils also exhibiting highwater availability [39]. "Subalpine altimetric spruce forest on siliceous xeric soils" was included in the same category as the other montane and subalpine spruce forests according to the same argumentation. "Secondary birch forest" was included in the "stands" category as "other broadleaves" as it is typically transitional forest, whose dynamic tendency is to be gradually replaced by ecologically coherent typologies [38]. The dominant vegetation form of "Scots pine forest on siliceous mountain substrates" is stand [38]; therefore, it was included in the "stands" category as "mountain pines". "Siliceous substrate microthermal heathland" was included in the "protective" category as "shrublands", as this type of heathland includes slope formations primarily serving soil protection functions [38]. Its dominant vegetation form is shrublands [38]. The dominant vegetation form of "Typical maple-ash woodland" is coppice [38], therefore it was included in the "coppices" category. However, since there are no inside-categories regarding maple-ash woodland, it was considered as "other broadleaves". "Primitive Scots pine forest on cliffs" is stand [38], and for this reason it was counted in the "stands" category as "mountain pines". "Primitive birch forest" is a transitional forest as "secondary birch forest"; therefore, it was included in the same category, such as the "stands" category as "other broadleaves". "Early-stage spruce forest formation" was considered as spruce forestry type due to the active evolutive dynamic, typical of neo-formation, that leads to the corresponding forest type [38]. "Conifer reforestation" was included in the "stands" category as "other conifers", as its dominant vegetation form is stand [38]. "Primitive Scots pine forest on scree slopes" and "Scots pine forest on calcareous substrates" have as the dominant vegetation form stands; therefore, they were considered as such in the "mountain pines" category.

This technique to estimate the carbon sequestration value could lead to an overestimation. In fact, it does not consider eventual timber extraction for timber production. Moreover, some parts of the forest may burn during the accounting period. Then, in both these cases, carbon is released back to the atmosphere (in the long-term in the first case and in the short-term in the second one), representing this as a cost (an emission) in the economic evaluation.

We have chosen to focus on carbon sequestration because it represents the ecosystem service potentially provided by forests under stable conditions. Consequently, a disturbance, as in our case caused by the Vaia storm, changes the economic value of this service. Other models instead calculate the net budget of C, such as the Carbon Budget Model, which is an inventory-based, yield data-driven model that simulates stand and landscape level C dynamics of aboveground and belowground biomass and dead organic matter (DOM), including soil [40]. The CBM-CFS3 provides annual predictions on C stocks and fluxes, such as the annual C transfers between pools, from pools to the atmosphere and to the forest product sector, as well as ecological indicators such as the net primary production (NPP), net ecosystem production (NEP), and net biome production (NBP). However, the main limitation of the CBM model is the difficulty in simulating the impacts of environmental changes (e.g., climate) on forest growth because the model does not explicitly simulate the impacts of environmental variations on yields [41]. For these reasons, we have preferred to estimate only carbon sequestration at this phase rather than the total budget.

Table 2. Tree types present in the study area with their respective BEF, WBD (t/m^3), and R coefficients provided by Federici et al. (2008) [37].

Tree Type	Correspondence with the Categories Defined by Federici et al. (2008) [37]	BEF	WDB (t/m^3)	R
Early-stage typical larch and fir forest formation	Stands as larches	1.22	0.56	0.29
Montane spruce forest on siliceous mesic soils	Stands as Norway spruce	1.29	0.38	0.28
Subalpine altimetric spruce forest on siliceous mesic soils	Stands as Norway spruce	1.29	0.38	0.28
Montane spruce forest on siliceous xeric soils	Stands as Norway spruce	1.29	0.38	0.28
Primitive larch forest	Stands as larches	1.22	0.56	0.29
Typical larch forest	Stands as larches	1.22	0.56	0.29
Alder tree	Protective as riparian forest	1.39	0.41	0.23
Subalpine altimetric spruce forest on siliceous xeric soils	Stands as Norway spruce	1.29	0.38	0.28
Secondary birch forest	Stands as other broadleaves	1.47	0.53	0.24
Scots pine forest on siliceous mountain substrates	Stands as mountain pines	1.33	0.47	0.36
Siliceous substrate microthermal heathland	Protective as shrublands	1.49	0.63	0.62
Typical maple-ash woodland	Coppices as other broadleaves	1.53	0.53	0.24
Primitive Scots pine forest on cliffs	Stands as mountain pines	1.33	0.47	0.36
Primitive birch forest	Stands as other broadleaves	1.47	0.53	0.24
Early-stage spruce forest formation	Stands as Norway spruce	1.29	0.38	0.28
Conifer reforestation	Stands as other conifers	1.37	0.43	0.29
Primitive Scots pine forest on scree slopes	Stands as mountain pines	1.33	0.47	0.36
Scots pine forest on calcareous substrates	Stands as mountain pines	1.33	0.47	0.36

The estimated value of carbon sequestration (Vcs) refers to different time periods depending on the municipality: before Vaia storm for Valfurva and Sondalo and after Vaia for Valdisotto. In fact, AGB and BGB are calculated based on the forest type featured by each parcel and the data reported in the FMPs. Subsequently, we derived the carbon sequestration values after Vaia for Valfurva and Sondalo and before Vaia for Valdisotto as well. We averaged per km^2 ($V_{CS,i}$, where i corresponds to the ith municipality) the post-Vaia economic value of carbon sequestration of Valdisotto and pre-Vaia ones of Valfurva and Sondalo. To estimate the pre-Vaia V_{CS} for Valdisotto and post-Vaia V_{CS} for Valfurva and Sondalo ($V_{CS,new}$), we applied the following equation:

$$V_{CS,new} = \frac{V_{CS,i} \times S_{new}}{S_i} \tag{5}$$

where S_i (where i corresponds to the ith municipality) represents the total forest area obtained by the PAF's (i.e., post-Vaia area for Valdisotto and pre-Vaia area for Valfurva and Sondalo); S_{new} is the calculated pre-Vaia area for Valdisotto and calculated post-Vaia area for Valfurva and Sondalo.

5. Results

5.1. Impact of Vaia Storm on Forest Area and Timber Stock

Sondalo is covered by the widest forest area both pre- and post-Vaia: 26.51 km^2 (37.9% of the total pre-Vaia forest) and 26.33 km^2 (38.4% of the total post-Vaia forest), respectively. Although Valdisotto is not the municipality with the largest forest area (25.59 km^2, corresponding to 36.6%), it is the most affected one by the storm both in absolute terms and as a percentage (1.15 km^2 and 4.49%), followed by Sondalo (0.18 km^2 and 0.68%) and Valfurva (0.08 km^2 and 0.45%), with a total forest area impacted of 1.41 km^2 (corresponding to 2.02% of the total pre-Vaia forest area, Table 3).

Similar to the forest area, Valdisotto is the municipality with the largest total stock both pre- and post-Vaia (6.32×10^5 m^3 and 6.03×10^5 m^3, respectively) and the one that suffered the greatest loss (2.83×10^4 m^3, corresponding to 4.48% of the total pre-Vaia forest stock) compared to Valfurva (1.78×10^3 m^3, corresponding to 0.47% of the total pre-Vaia forest stock) and Sondalo (2.39×10^3 m^3, corresponding to 0.68% of the total pre-Vaia forest stock) (Table 4).

Table 3. Forest areas (km^2) per municipality before, after, and lost due to the Vaia storm.

Forest Areas	Valdisotto	Valfurva	Sondalo	Total
Pre-Vaia storm (km^2)	25.59	17.78	26.51	69.88
Post-Vaia storm (km^2)	24.45	17.70	26.33	68.48
Lost due to Vaia storm (km^2)	1.15	0.08	0.18	1.41
Lost due to Vaia storm (%)	4.49	0.45	0.68	2.02

Table 4. Timber stock values (m^3) per municipality before, after, and lost due to the Vaia storm.

Timber Stock (m^3)	Valdisotto	Valfurva	Sondalo	Total
Pre-Vaia storm	632,058	381,297	353,061	1,366,416
Post-Vaia storm	603,728	379,513	350,671	1,333,912
Lost due to Vaia storm	28,330	1784	2390	32,504
Lost due to Vaia storm (%)	4.48	0.47	0.68	2.38

5.2. Impact of the Vaia Storm on Timber Production

Although all three municipalities experienced a reduction in forest area (from −0.45% of Valfurva to −4.49% of Valdisotto) and timber stock (from −0.47% of Valfurva to −4.48% of Valdisotto) due to the Vaia storm, the economic value of the timber production increased after Vaia (Table 5). This was due to higher timber prices after the emergency period (from 90 €/m^3 pre-Vaia to 98 €/m^3 post-Vaia). The mean increase in economic value is nearly 6 million € from pre- to post-Vaia (corresponding to around 5% of the pre-Vaia value). The total value was €122.98 million before Vaia (ranging from €99.75 to €162.60 million), and it increased up to €130.72 million after Vaia (ranging from €101.38 to €148.06 million). Instead, during the Vaia emergency (2019–2020), Valdisotto lost the highest value (€1.67 million, ranging from €1.59 to €1.78 million) compared to the other municipalities (Valfurva: €0.11 million, ranging from €0.10 to €0.11 million, Sondalo: €0.14 million, ranging from €0.13 to €0.15 million). If we consider the total emergency period (2019–2020, and then 2 years) assessed focusing on the timber prices (Figure 4), the total losses are equal to €3.34 million for Valdisotto, €0.22 million for Valfurva, and €0.28 million for Sondalo. In addition, considering the pre-Vaia timber price (i.e., 90 €/m^3 instead of 59 €/m^3), the total 2-year losses are considerably greater: €5.10 million for Valdisotto, €0.32 million for Valfurva, and €0.43 million for Sondalo. Moreover, if we apply the timber price before the storm to the amount of total timber stock post-Vaia, we obtain the following economic value of timber production, as if the price was never changed: €54.34 million for Valdisotto, €34.16 million for Valfurva, and €31.56 million for Sondalo. Therefore, taking into account these economic values and the one before Vaia we obtain a total loss of €2.55 million for Valdisotto, €0.16 million for Valfurva, and €0.22 million for Sondalo.

Table 5. Timber production economic value (million €) per municipality before, after, and due to the Vaia storm. In brackets the values in percent of the lost value due to Vaia.

Time Period	Considered Prices (€/m^3)	Timber Production (million €)			Total
		Valdisotto	Valfurva	Sondalo	
Pre-Vaia storm	73	46.14	27.83	25.77	99.75
	90	56.88	34.32	31.77	122.98
	119	75.21	45.37	42.01	162.60
Post-Vaia storm	76	45.88	28.84	26.65	101.38
	98	59.16	37.19	34.37	130.72
	111	67.01	42.13	38.92	148.06
Lost due to Vaia storm	56	1.59 (3.44%)	0.10 (0.36%)	0.13 (0.52%)	1.82 (4.32%)
	59	1.67 (2.94%)	0.11 (0.31%)	0.14 (0.44%)	1.92 (1.54%)
	63	1.78	0.11	0.15	2.05

	(2.37%)	(0.25%)	(0.36%)	(2.98%)

5.3. Impact of the Vaia Storm on Carbon Sequestration

The analysis of the above- and below-ground biomass quantities shows that Valdisotto’s municipality has the highest values (AGB = 404.98 t, BGB = 90.53 t), and instead, Sondalo has the lowest ones (AGB = 132.25 t, BGB = 29.88 t) (Table 6), even if Sondalo is covered by the widest forest area. Therefore, Valdisotto features the highest economic value of carbon sequestration (from pre-Vaia 40.49 thousand €/year to post-Vaia 38.67 thousand €/year) and Sondalo the lowest ones (from pre-Vaia 11.88 thousand €/year to post-Vaia 11.80 thousand €/year). Finally, the highest loss is experienced by Valdisotto (−4.48%) and the lowest one by Valfurva (−0.47%) (Table 7).

Table 6. Above- and below-ground biomass for each municipality.

Municipality	AGB (t)	BGB (t)
Valdisotto (post-Vaia)	404.98	90.53
Valfurva (pre-Vaia)	210.79	47.94
Sondalo (pre-Vaia)	132.25	29.88

Table 7. Economic values of carbon sequestration before, after, and lost due to Vaia for the municipalities of Valdisotto, Valfurva, and Sondalo.

Municipality	$V_{cs,pre}$ (€/Year)	$V_{cs,post}$ (€/Year)	$V_{cs,lost}$ (€/Year)	$V_{cs,lost}$ (%)
Valdisotto	40,486	38,672	1815	4.48
Valfurva	16,128	16,053	75	0.47
Sondalo	11,882	11,802	80	0.68
Total	68,496	66,527	1970	2.88

6. Discussion

6.1. Areas Involved by Vaia Storm

Areas involved by the Vaia storm were derived by means of bi-temporal photointerpretation of Sentinel-2 satellite images from late June 2019. As previously reported, the use of satellite imagery may fail to detect crashes in areas shaded by mountains, as well as small, diffuse crashes. Nevertheless, Vaglio Laurin et al. (2020) [13] found that Sentinel-2 (S2) is more efficient in detecting forest damages than SAR Sentinel-1 (S1): an overall accuracy of 86% for S2 using an image acquired after 7 months from the storm and 68% for S1 using data acquired after 15–20 days after the storm. Giannetti et al. [42] tested the use of two continuous change detection algorithms, i.e., the Bayesian estimator of abrupt change, seasonal change, and trend (BEAST) and the continuous change detection and classification (CCDC), to map and estimate forest windstorm damage area using a normalized burned ration (NBR) time series calculated on three years of Sentinel-2 image collection (i.e., January 2017–October 2019). They found that close to the storm (i.e., 1 to 6 months November 2018–March 2019) it is not possible to obtain accurate results independently of the algorithm used, while accurate results were observed between 7 and 12 months from the storm (i.e., May 2019–October 2019) in terms of Standard Error (SE), percentage SE (SE%), overall accuracy (OA), producer accuracy (PA), user accuracy (UA), and an index of performance (g_{mean}) for both BEAST and CCDC (SE < 3725.3 ha, SE% < 9.69, OA > 89.7, PA and UA > 0.87, g_{mean} > 0.83).

Moreover, several authors have demonstrated that an analysis based on the multitemporal spectral signatures, derived by satellite time series (TS) imagery, can be more efficient [43,44] than a bi-temporal approach [42]. In fact, new methods based on the multitemporal spectral signatures [43,44] were developed to map forest disturbances and forest interannual changes using multispectral optical satellite TS (i.e., Landsat, MODIS, and S2 data) [43,45,46], thanks also to the development of cloud computing platforms such as Google Earth Engine (GEE).

Despite all these possible sources of errors, the estimated total area of 1.41 km^2 is in agreement with the data on timber actually reported for felling in SITaB—Forest Cutting Information System for 2019–2020–2021, which recorded the data on interventions related to this catastrophic event [47].

The areas involved in the storm all have in common the aspect and the slope (Figure 5). Most of these areas (13.6%) have exposure to East or South-East; this data could suggest that the dominant winds of the storm were coming from these directions, thus causing the most damage to the exposed areas. Moreover, most of the areas impacted by Vaia have a slope included in the range between 20 and 40 degrees (74.3%). This result could indicate a higher vulnerability of the trees to overturning and uprooting since steep slopes could have an influence on terrain stability. In terms of elevation, these areas are comprised of a maximum elevation of 1843 m a.s.l. and a minimum of 1147 m a.s., with an average of 1519 m a.s.l. (from FAP's shapefiles (CFAV), thought Tinitaly DEM-INGV).

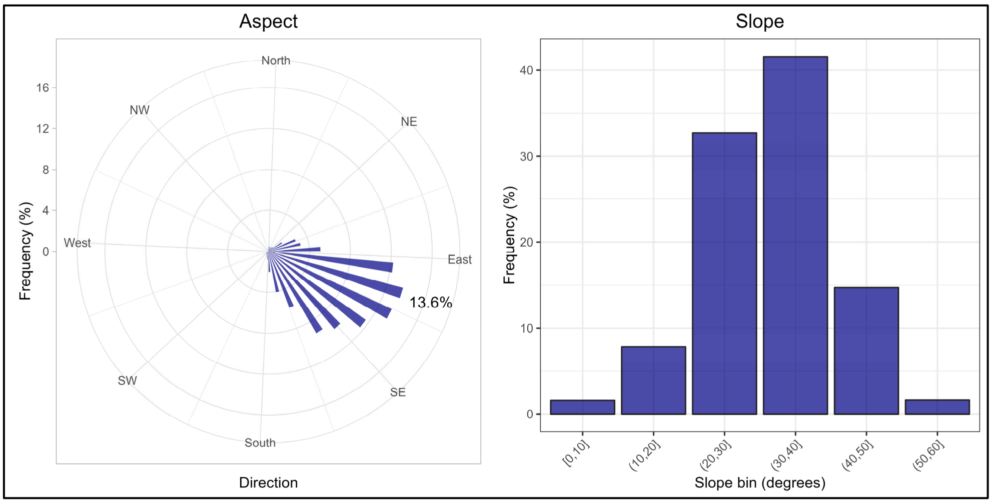

Figure 5. Aspect and slope frequency distribution of forest areas impacted by Vaia. Aspect is reported by cardinal points, with the category with the maximum frequency (13.6%) corresponding to East-SouthEast. The slope is reported in the slope bin (in degrees) with a width of 10 units. Data obtained from FAP's shapefiles (CFAV) thought Tinitaly DEM-INGV.

6.2. Timber Production

Regarding timber production, in addition to the real timber stock, we took advantage of data about the normal timber stock (NTS, in m^3, i.e., the theoretical volume considering the tree types present in the parcel) reported in the FMPs by CFAV to promote healthy forests and their renovation. Then, we evaluated the theoretical economic value of timber production (Vttp, €) provided by the whole forest, considering NTS in Equation (1) instead of TTS. The real timber production Vptp before Vaia of Valdisotto (€56.88 million) and Valfurva (€34.32 million) is greater than the normal one Vttp (€47.73 million and €30.13 million, respectively). Instead, Sondalo municipality appears to have an opposite situation, with the real timber production Vptp (€31.77 million) being less than the normal one Vttp (€36.50 million). The same situation can be found for the values of timber production post-Vaia. These results suggest that for the municipalities of Valdisotto and Valfurva, the real forests are healthier with respect to a generic one; instead, for Sondalo, the forest appears to be more tried than a standard one. However, these results do not indicate which municipality suffered more from the Vaia storm, as the forest cover differs between the municipalities. They do, however, suggest that Sondalo's forest is the weakest and therefore the most important to manage and the most challenging to make more resilient to extreme natural events.

Moreover, we compared Vptp with the values obtained considering the total annual timber stock increment (I, m^3/year) reported in the FMPs by CFAV (i.e., for Valdisotto post-Vaia and Valfurva and Sondalo pre-Vaia). Replacing TTS with I in Equation (1) allowed us to estimate the potential economic value of the annual timber production (Vitp, €/year) supplied only by the portion of forest grown every year. We obtained that Valdisotto increased per year more (8723 m^3/year) than Valfurva (4471 m^3/year) and Sondalo (3555 m^3/year). Subsequently, we computed the economic values of the annual timber production with the mean prices pre- and post-Vaia depending on the year of the FMP. The obtained values are the following: 0.85 million €/year for Valdisotto, 0.40 million €/year for Valfurva, and 0.32 million €/year for Sondalo. It is observable that Valdisotto is the municipality with a greater value. This is coherent with our results about Vptp (i.e., the economic value of timber production taking into account the total timber stock, TTS). This data allows us to say that Valdisotto, although not the most forested area (24.45 km^2 vs. 26.51 km^2 of Sondalo), is the one for which the forest area features the greatest total timber stock (603,728 m^3) and annual increment (8723 m^3/year).

The collapse of timber prices in Italy in 2019 and 2020 can be attributed to several factors related to the Vaia storm. In fact, according to Schwarzbauer and Rauch [48], the extent and direction of changes in prices after a storm depend on the combined and complex interplay of several factors and measures: Firstly, the Vaia storm felled around 8.5 million m^3 of timber, equivalent to about 7 times the amount of industrial timber that Italian sawmills can process in a year [47]. This created a sudden and massive supply of timber on the market. This oversupply far exceeded demand, leading to an inevitable price collapse. Secondly, handling such a huge amount of timber posed significant logistical and operational challenges. Local infrastructures were not prepared to manage and quickly transport these volumes, contributing to the accumulation of timber and its devaluation [16]. Thirdly, timber felled by extreme events such as Vaia tends to suffer physical damage and deterioration, reducing its quality and consequently its commercial value. In addition, felled timber that is not promptly removed increases the risk of infestation by pests such as the spruce bark beetle, further exacerbating the problem. Moreover, the large amount of timber available locally has encouraged forest owners to sell quickly to avoid further depreciation, putting pressure on local markets and encouraging downward price competition. Finally, the abundance of timber in the affected regions influenced prices nationwide, with industry operators preferring to buy timber at lower prices from the affected areas rather than from other regions unaffected by the storm. In summary, the Vaia event triggered a set of economic and operational dynamics that led to a significant collapse in timber prices in Italy from 2019 onwards. The combination of an oversupply of damaged timber, logistical difficulties, deterioration of timber quality, and pressure on local markets created an unfavorable market situation for forest owners and industry operators.

After this emergency phase, wood prices in Italy started to rise again in 2021, due to several key reasons. After absorbing much of the timber felled by the Vaia storm, the oversupply decreased significantly. The operations to collect and dispose of the damaged timber were completed, reducing the amount of timber available on the market. In addition, global demand for wood increased significantly in 2021, partly due to the economic recovery following the pandemic. Increased construction and renovation activity, stimulated by government incentives in many countries, led to higher demand for construction materials, including timber. The pandemic caused disruptions in global supply chains, including transport delays and container shortages, which increased shipping costs and reduced the availability of imported wood. These issues limited the supply of wood to the Italian market, contributing to price increases. Finally, all costs of wood production, including energy, labor, and raw materials, increased, leading to higher prices for finished products, including wood.

6.3. Carbon Sequestration

Forests, representing the most valuable carbon sinks alongside the oceans, play a critical role in mitigating climate change through carbon sequestration. However, natural disturbances, which are intensified by climate change both in strength and in frequency, significantly impact forest carbon dynamics. The study on carbon sequestration losses (Vcs values) in Valdisotto, Valfurva, and Sondalo provides a localized perspective on these broader environmental impacts. Natural disturbances, windstorms in particular, increasingly affect forest health, growth, and stability [49]. These disturbances cause relevant variations in forest carbon sinks, with windstorms alone accounting for about 10–15% of these variations at the EU level and potentially more at the Italian national scale [50]. The wind is indeed projected to damage over 40 million m^3 of growing stock annually in Europe by 2030 (by contrast, approximately 3 million m^3 are projected to be damaged by pests) in the Alpine region [51]. Climate change modifies the intensity, frequency, and geographical patterns of these disturbances. For example, in Europe, extratropical cyclones are expected to show up more often and are more capable of inflicting considerable damage [52]. This is evident from the Vaia storm in 2018, which caused damage exceeding 70% of the total roundwood removed in Italy that year, as well as the total damaged growing stock volume, which corresponded to over 0.6% of all Italian forests [53]. Comparatively, major windstorms caused even more extensive damage across Europe, highlighting the severe impact such events can have on forest carbon dynamics (Lothar & Martin, 1999; Gudrun & Erwin, 2005) [54].

Our results on carbon sequestration losses highlight significant variations across different municipalities. Valdisotto suffered the highest loss in carbon sequestration capacity, amounting to €1815/year, primarily due to a substantial timber stock loss of 28,330 m^3 (4.48%). Valfurva experienced much lower losses of 75 €/year and 1784 m^3 of timber stock (0.47%). Sondalo had a reduction in carbon sequestration capacity of 80 €/year with a timber loss of 2390 m^3 (0.68%). It is worth pointing out that these results, and in particular the proportion of carbon sequestration loss in the form of percentages, extremely resemble both the proportion of timber stock and the associated economic value. This suggests that in our case, the loss in terms of carbon sequestration is directly linked with the amount of affected area, while the other factors in the formulas have limited influence. However, this is easily explainable since the species composition of the parcels that were affected by Vaia was similar across the municipalities, thus giving us similar values of AGB and BGB.

Several factors contribute to the varying impacts observed in Valdisotto, Valfurva, and Sondalo, and among those, we focus on the tree types, as reported in Table 4. Valdisotto's significant proportion of early-stage larch and fir forests (~30%) and montane spruce forests on siliceous mesic soils (~26%) (Figure 6) made it more susceptible to windthrow and breakage during storms. Early-stage forests with younger trees and less developed root systems have weaker structural integrity. Montane spruce forests, while providing good drainage, may lack adequate root anchorage to withstand extreme wind events, leading to higher tree mortality and biomass loss. In contrast, Valfurva's forests, with ~50% early-stage larch and fir formations, showed resilience possibly due to more homogeneous and structurally stable trees. In addition, favorable soil conditions and sheltered topographical features in Valfurva contributed to their resilience. Valdisotto's montane spruce forests may lack adequate root anchorage to withstand extreme wind events, leading to higher tree mortality and biomass loss. In Sondalo, the mixed forest composition, including montane spruce (~17%) and primitive larch forests (~14%), likely exhibited varied resilience due to the different responses to stress (*Larix decidua* being an anisohydric species, while *Picea abies*, *Pinus sylvestris*, and *Abies alba* being isohydric conifer species [55].

Valdisotto's topographic features could have amplified the storm's impact, leading to concentrated damage. Protective geographical features in Valfurva and Sondalo mitigated the storm's overall impact. This highlights the need for region-specific forest management strategies to optimize resilience and carbon sequestration.

Focusing now on the consequences of these losses in terms of carbon sequestration and management actions that are conducted after a windstorm, salvage logging can reduce in situ carbon stock while increasing carbon storage in harvested wood products

[56]. The cascading effect induced by forest windstorms shifts carbon from living biomass to dead organic matter and harvested wood products, partially stabilizing the total carbon sink [53]. Additionally, biomass removed together with merchantable components is often used for energy production, further mitigating fossil fuel emissions [57].

The economic impacts of disturbances are significant, with wood prices dropping by up to 76% for felled trees in one year [58]. Strategies such as stocking and gradually allocating wood products to the market can mitigate these negative effects [59]. The magnitude of Vaia, although significant, is relatively small compared to other major European windstorms like Lothar, Martin, Gudrun, and Erwin, which damaged between 75 and 204 million m^3 of growing stock [54]. Nonetheless, in 2018, Vaia reduced the merchantable net annual increment by 36% nationally, damaging about 11 million m^3 of biomass [53].

Strategies such as increasing species richness and structural diversity improve stand resistance and resilience [60,61]. However, increased harvest rates can lead to higher emissions from litter, deadwood, and soil organic matter [61]. Furthermore, the ability of forests to act as carbon sinks or sources is influenced by the balance between carbon accumulation and losses due to removal, decomposition, and respiration [62].

Globally, forests have sequestered 35% of all greenhouse gas emissions since the Industrial Revolution [62]. Forests act as carbon sinks when the accumulation of carbon in woody biomass exceeds losses due to biomass removal and other factors [62]. Climate change impacts forest productivity and disturbance regimes, necessitating adaptive management strategies [51]. Protecting, planting, and managing forests efficiently can significantly mitigate climate change [63]. For instance, afforestation, reduction of deforestation, and improved forest management are vital strategies for enhancing carbon sequestration [64–66].

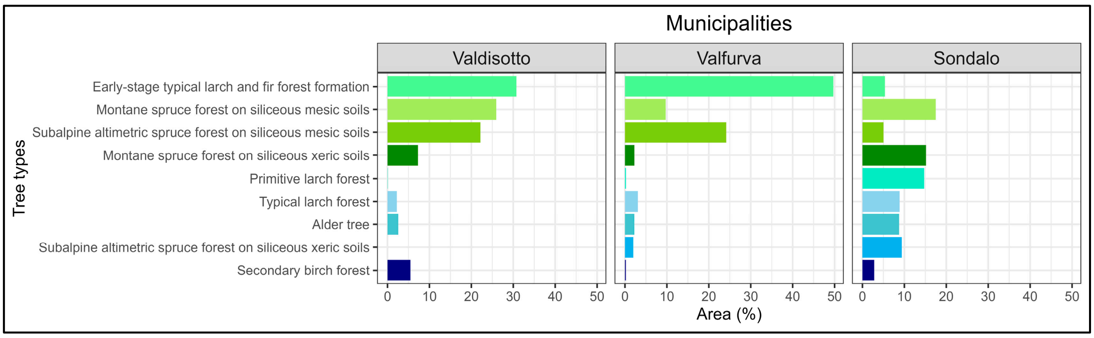

Figure 6. Area (km^2) distribution of the main tree types for each municipality. Data area from FAP (CFAV).

6.4. Enhanced Impacts

To better describe the variety of effects (both immediate and long-term) that extreme weather events have on the forests, we employ the term “enhanced impacts”, referring to the interplay of direct and indirect effects that play a role in amplifying or mitigating these consequences. Among the most influential enhanced impacts of windthrows in Alpine forests is the outbreak of bark beetle epidemics. These pests are xylophagous insects (Coleoptera, Curculionidae) that rely on dead wood to complete their life cycle. Specifically, they mate and lay eggs in the bark of trees; after hatching, the larvae spread into the wood, feeding on it and causing lethal damage to the plant [67].

In our study area, the species of bark beetle that most threatens the health of the spruce forests is *Ips typographus* (Linnaeus, 1758) [68]. This species is considered the most destructive pest of coniferous forests in the Palaearctic region, with outbreaks killing millions of Norway spruce (*Picea abies*) and causing significant ecological and economic impacts [68–70].

This beetle is distributed across the spruce woods in Europe and, due to its typical life cycle, has significant implications when evaluating the impacts of windstorms on forest ecosystems. Intense events, such as the Vaia storm, provide a quantity of weakened or dead trees that serve as ideal breeding grounds for bark beetles. This facilitates rapid population expansions due to reduced competition and minimal tree resistance [67,68,71,72]. Many studies have confirmed a highly predictable relationship between these extreme events and the outbreaks of bark beetles, resulting in large infestations within 1–3 years following the event [73]. This has led to enhanced damage to the spruce population and rising concerns regarding the eventual effects on the wood production economy. Moreover, the outbreaks have considerable consequences on diverse aspects of ecosystem services, biodiversity, and conservation, making the subject a core discussion point in management strategies [74]. It is important to evaluate the effects of bark beetles in their complexity, as there are many different implications, not all of which are negative. Understanding the role these pests play could suggest more effective forest management strategies [74].

In the context of ESs, it has been shown that the bark beetle's population growth negatively impacts all categories of ESs. In particular, timber production is affected, with linked consequences on wood harvesting and wood quality reduction caused by fungi attacking the windthrown trees. It is important to notice that this is dependent on both direct losses of the trees and the consequent actions of sanitation presumably conducted to limit the damage of the pest's spread [75]. Economically, the bark beetle has a significant negative impact, affecting both timber production and its market. In the short term, the market could be positively influenced by the beetle, as new wood from windthrown trees becomes more available for processing and export. However, this is followed by market saturation, leading to a forced decrease in wood prices, as the trees have to be removed from the woods to prevent further damage [74–76]. The reduction in the number of trees in specific areas and even the complete destruction of sections of the woods could lead to the possibility of mudslides and other natural hazards. Additionally, cultural and social ESs are affected, as bark beetle outbreaks have an indirect impact on public perception of natural environments. If this effect is prominent, it could reflect on the value of land and properties, as well as decreasing income based on tourism activities [77,78].

Large-scale bark beetle outbreaks significantly disrupt forest ecosystems' biogeochemical cycles by reducing carbon storage. This reduction occurs because tree mortality leads to a decrease in leaf area, which in turn diminishes the forest's carbon uptake [79].

There are also cases where the effects of the bark beetle population's sudden growth bring important benefits in terms of biodiversity. For example, the presence of dead wood as a microhabitat is key for the life cycle of other species, like saproxylic insects, many of which are listed in the Habitat Directive annexes and of mandatory protection in the EU. At the same time, on a landscape level, the phenomenon allows for the alteration of the forest structure [80]. This alteration, which translates into a reset of the forest succession and light diffusion in the lower vegetational layers, inevitably affects the community composition of the area [81,82]. In the long run, this could increase forest complexity [83]. As previously described, the repercussions of bark beetle outbreaks in forests managed for biodiversity are particularly complex. The conservation of biodiversity in such forests often requires allowing natural processes to occur unimpeded. Bark beetle outbreaks, while destructive, are natural disturbances that can increase structural diversity within forests and create habitats beneficial to many species [84]. Dead wood, left in the aftermath of beetle outbreaks and windthrows, plays a crucial role in sustaining biodiversity, serving as a habitat for various invertebrates, fungi, and bryophytes, which are less prevalent in managed forests. Even on a broader forest structure level, the habitat complexity that the beetle creates is beneficial to bird species [74].

The management of bark beetle outbreaks, particularly *Ips typographus*, in biodiversity-rich forests such as those in our study area poses significant ecological and economic challenges. A non-intervention approach involves maintaining natural forest dynamics, supporting the life cycle of many species dependent on decaying wood, and maintaining the heterogeneous landscapes created by disturbance. However, it also carries the risk that unchecked beetle populations could lead to widespread forest mortality, potentially undermining biodiversity conservation goals [74]. On the other hand, effective management in these areas requires targeted phytosanitary interventions to contain and prevent outbreaks, which may require the removal of dead wood from natural events or logging operations. Although these measures effectively reduce beetle populations and mitigate immediate productivity losses in production-oriented forests, they also support structural renewal and increase habitat complexity in forests prioritized for biodiversity.

However, the challenge of managing bark beetle populations is significantly exacerbated by climate change, since global warming has become a dominant force influencing beetle dynamics and forest vulnerability [85]. Rising temperatures enhance the survival and spread of beetles by reducing winter mortality, which has traditionally helped to control population sizes. Warmer winters allow beetles to survive in greater numbers and complete additional reproductive cycles within a single year, accelerating population growth. Additionally, global warming is facilitating the colonization of new habitats at higher altitudes and latitudes, where beetles were previously restricted by colder temperatures [86–88].

Moreover, climate change is increasing the frequency and intensity of extreme weather events, such as droughts and heatwaves, which weaken trees' defenses against pests such as the bark beetle. The interaction between these climatic factors and beetle life cycles suggests that disturbances from bark beetle outbreaks are likely to increase across Europe in the coming decades [89].

Regional reports from Lombardia from 2017 to 2023 illustrate the dynamic nature of *I. typographus* infestations [90–95]. Initial concerns in 2017 that the beetle was reaching altitudes of around 1500 m a.s.l. were exacerbated by the Vaia storm in 2018, which likely facilitated wider spread. In 2019, escalating infestations prompted increased research and monitoring, which revealed a severe increase in affected areas by 2020, with no effective management measures reported in certain regions. Monitoring reports from 2019 indicated an increase in infestations, prompting the launch of extensive research and planning initiatives. Despite these efforts, the beetle population expanded significantly in 2020, with more than 923 ha affected and inadequate management responses in some areas. In 2021, the situation worsened due to an intense drought, with reports of 3000 ha of damage and a targeted $3 million budget for management, although not all areas received the necessary funding [94].

In 2022 and 2023, the response to this growing threat included advanced remote sensing and GIS technologies to improve the accuracy and effectiveness of monitoring efforts. The use of Sentinel-2 satellite imagery (bands 2, 3, 4, and 8) was pivotal in this regard. These bands, with a resolution of 10 m, are crucial for assessing vegetation health through the Normalized Difference Vegetation Index (NDVI), which calculates the difference in reflectance between near-infrared and red light to measure plant vigor and potentially detect beetle-affected areas [96].

Further, the use of supervised classification on Sentinel-2 data enabled the discrimination between infested and healthy forests by training classifiers on known spectral signatures, improving detection accuracy. High-resolution aerial and drone imagery, with details finer than 50 cm per pixel, allowed for close examination of individual trees and smaller clusters of infestation. Change detection techniques, comparing imagery over time, were employed to track canopy changes, assess the progression of the infestation, and evaluate the effectiveness of management interventions [86,96].

Despite these advanced monitoring techniques, in 2023, the area under beetle damage in Upper Valtellina increased by 72.45% compared to the previous year, totaling 207.39 ha. This surge underscores the dynamic and challenging nature of managing *I. typographus* infestations, even with substantial investments in technology and management strategies totaling €231,387, with €90,000 dedicated to communication and public awareness.

As climate change continues to influence local meteorological conditions, fostering environments conducive to beetle outbreaks through droughts, high temperatures, and severe weather events, it remains imperative to sustain and adapt monitoring and management approaches to mitigate the impacts of *I. typographus* in forest ecosystems.

7. Conclusions

In this study, we evaluate both the immediate and long-term effects of the Vaia storm that occurred in 2018 on forests in Valdisotto, Valfurva, and Sondalo (Upper Valtellina, Italy). In particular, for assessing immediate effects, we price the timber production and carbon sequestration pre- and post-Vaia and during the emergency period (2019–2020). Although the reduction in forest area (−2.02%) and timber stock (−2.38%), the economic value of the timber production increased after Vaia due to higher timber prices (i.e., total from €124.97 million to €130.72 million). Nevertheless, if we consider the emergency period (2019–2020), the total losses are equal to €5.10 million for Valdisotto, €0.32 million for Valfurva, and €0.43 million for Sondalo. Regarding the evaluation of the economic value of carbon sequestration, our study suggests that Valdisotto is the municipality that experienced the greatest loss (−4.48% of the pre-Vaia economic value), and we found also a total loss for all three municipalities of −2.88% of the economic value before the storm.

To better describe the variety of effects (both immediate and long-term) that extreme weather events have on the forests, we discussed the enhanced impacts due to the outbreak of bark beetle epidemics (*Ips typographus*). On the one hand, the bark beetle has led to enhanced damage to the spruce population and negative implications on the following: (i) wood production (after a short-term positive influence), (ii) cultural and social aspects, and (iii) forest ecosystems' biogeochemical cycles (by reducing carbon storage). On the other hand, there are also cases where the effects of the bark beetle population's sudden growth bring important benefits in terms of biodiversity (e.g., invertebrates, fungi, and bryophytes). However, an alteration of the forest occurs, which translates into a reset of the forest succession and light diffusion in the lower vegetational layers, with an inevitable effect on the community composition of the area and with an increase in forest complexity.

In addition to the immediate and long-term economic impacts assessed in our study, future research should focus on several key areas to further understand and mitigate the effects of extreme weather events on forest ecosystems. Further research is needed to develop and implement adaptive management strategies that can increase the resilience of forests to extreme weather events [62,97,98]. These include the introduction of more diverse and climate-resilient tree species, improved forest management practices, and the integration of advanced monitoring technologies. In addition, the establishment of long-term monitoring programs to track the recovery of forest ecosystems following disturbance is critical to understanding the full ecological impacts of disturbance and guiding restoration efforts [62,99]. These programs should focus on both biotic and abiotic factors, such as species composition, soil health, and hydrological cycles. Beyond immediate economic losses, it is important to examine the broader socio-economic impacts of extreme weather events on local communities, including impacts on tourism, recreation, and local economies [100].

In addition, our findings on reduced carbon sequestration highlight the need for targeted climate change mitigation strategies. The potential of forest management practices to ensure healthy forest ecosystems that enhance carbon storage and reduce greenhouse gas emissions should be explored [61,101]. Finally, engaging local communities in forest management and raising awareness of climate change impacts can foster more resilient socio-ecological systems. Education programs and participatory management approaches can empower communities to contribute to forest conservation and restoration efforts.

In conclusion, while the Vaia storm has posed significant challenges, it also provides an opportunity to rethink and improve forest management practices in the context of climate change. For example, the region of Lombardia has allocated €26,987,217 for the restoration of forests affected by the Vaia storm between 2019 and 2022 (23.45 km^2) [102]. In our study area, the areas affected by these interventions amounted to 0.87 km^2 (almost 62% of the total area of forests affected by Vaia): 0.67 km^2 for Valdisotto, 0.12 km^2 for Valfurva, and 0.02 km^2 for Sondalo. As the interventions in Valfurva covered a larger area than the area affected by Vaia in 2018 (0.08 km^2), it is plausible to assume that the restoration activities also included the areas subsequently damaged by the bark beetle. By adopting adaptive strategies, improving monitoring, and fostering collaboration, forest ecosystems could be made more resilient and sustainable. Future research and policy efforts should aim to integrate these elements to effectively address the complex and dynamic nature of forest disturbances.

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