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Effects of Forest Management on Beetle (Coleoptera) Communities in Beech Forests (*Fagus sylvatica*) in the Apennines of Central Italy (Tuscany)

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Abstract: In European mountains most beech forest areas have been managed for timber production. This practice has reduced the availability of biomass for the whole forest-dwelling species assemblage and of deadwood for the saproxylic community. Despite most of Italy's beech stands having a long history of management, its effects on forest species remain poorly understood. To address this gap, we studied beetle abundance and diversity in five beech-dominated forests with increasing management intensity in central Italy's Apennines (Tuscany). We assessed if forests with similar management intensity exhibited comparable patterns in beetle diversity, abundance, and commonness versus rarity. Three forests were managed with even-aged shelterwood; one was managed with continuous cover forestry; and one was old-growth. We found 25 beetle families and 195 species across all sites with similar total abundance and richness. However, the representation of the most abundant families varied among sampling sites (ANOVA test: always significant for the total abundance of the most abundant families: $F \geq 2.77$, d.f. $= 4$, $p \leq 0.038$). The old-growth forest harbored more threatened species than managed sites. Saproxylic assemblages were similar between the recently cut site and the old-growth forest, and between shelterwood and continuous cover sites. While the similarity gradient among the whole species assemblages reflected geographical proximity, the similarity gradient among saproxylic assemblages reflected the successional proximity among forest management systems. Our research underscores the effects of management on beetle diversity, offering insights for sustainable forestry.

Keywords: deadwood management; forest diversity; saproxylic beetle communities; silvicultural practices; window flight traps

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1. Introduction

Europe has a global responsibility to conserve beech (*Fagus sylvatica* Linnaeus 1753) forests [1], as beech is a species endemic to Europe and one of the main tree species of this continent, covering ca. 14–15 million hectares of forest [2]. In Italy, beech forests characterize the landscape of many mountain areas, from the Alps down to the southern Apennines' regions of Campania, Basilicata, Calabria, and Sicily in the Mediterranean area [3]. According to the Italian National Forest Inventory (INFC 2015: [4]), the total area covered by beech in Italy is 1,053,183 hectares, which corresponds to 9.53% of the country's total forest area.

In European mountains, most beech forest areas that escaped clearance and cultivation have been managed for timber production [5]. Over the centuries, wood from beech forests, mainly for firewood and charcoal as well as timber for building and furniture, has been a fundamental resource for people living in mountain areas [3]. Likewise, in Italy, the intensive use of wood has significantly modified the distribution, composition, and structure of beech stands all over the country [2,3]. Economic and societal changes have brought about changes in the forestry sector in the last few decades, which, in turn, has impacted forest management, modifying forest composition and structure [3]. According to the INFC 2015 [4], 41% of beech stands have a long history of coppicing, 53% are high (i.e., mature) forests, and 6% have complex structures, mostly represented by stands in transition from coppice to high forests [4]. In Italy, beech coppices are generally clear-felled, leaving 60–80 parent trees (named "standards") per hectare. For beech coppices in conversion to high forest and beech high forests, forest management plans usually prescribe regeneration felling carried out according to the uniform shelterwood system [3], which is based on the seed cut and the removal cut. The seed cut is used to open growing space in the canopy for the establishment of regeneration; the removal cut is used to release the established seedlings. The object of the removal cut is to gradually or rapidly remove the old cohort as the newer cohort needs more growing space.

In beech coppices, clear-felling reduces the number of senescent trees and the amount of coarse woody debris (CWD), which, respectively, has a negative effect on the diversity of forest dwelling species thriving on living (epiphytic) and dead (saproxylic) wood [6]. The continuous availability of deadwood at a given site is essential for the survival of saproxylic species, which depend on deadwood for part of their life cycle [7], and most of them are represented by beetles (i.e., Coleoptera). For example, Parisi et al. [8] have observed how, even in forests where silvicultural activities affect the presence of dead wood, saproxylic beetles manage to survive in small communities by taking refuge in the stumps and branches left on the ground after harvesting.

In Europe, 4000 species of beetles are dependent on deadwood [9] and they have a pivotal ecological role in assisting fungi and bacteria in the decomposition processes of organic matter and nutrient cycles [9]. In fact, more than half of forest-dwelling beetles may be saproxylic [10]. Saproxylic beetles can be grouped as obligate or facultative saproxylic (e.g., [11]) based on their degree of dependence on wood resources, their degree of association with one or more species of host trees [12], their dependence on small- or large-diameter deadwood pieces [13], and on their preference for standing snags or lying logs [14].

Beetles, especially saproxylic species, are considered promising indicators for assessing the proximity of European forests to near-natural conditions [15]. Saproxylic beetles have been studied increasingly over the last 20 years, especially in northern and central Europe, mainly because they constitute one of the largest groups of threatened (that is, represented in the IUCN red list) species in many countries, being particularly affected by forest management. In contrast, in southern Europe, studies on the whole community of saproxylic beetles are scarce and limited to some areas of Spain and southern France [10,16]. Only two studies have been published on the communities of saproxylic beetles in Italy: one study concerned selected families in forest residues of an alluvial plain in northern Italy (Po Valley: [17]). Other studies have concerned their taxonomic and functional diversity in central ("Gran Sasso e Monti della Laga" National Park; "Parco Regionale del Matese" [18]) and southern Italy ("Cilento, Vallo di Diano e Alburni" National Park [19]; "Aspromonte" National Park [8]). Most studies involve large and threatened saproxylic species sampled in areas already subject to continuous monitoring, such as the *Cerambyx cerdo* (Linnaeus, 1758) and *Osmoderma eremita* (Scopoli, 1763) in the "Castelporziano" Presidential Estate, which is a Natura 2000 Special Area of Conservation [20], *Morimus asper* (Sulzer, 1776), *Lucanus cervus* (Linnaeus, 1758), *C. cerdo*, *Rosalia alpina* (Linnaeus, 1758), and *Osmoderma* spp. monitored in Italy through an EU Life program and a national project financed by the Ministry of the Ecological Transition [21].

While the differences between beetle assemblages in managed and old-growth forests have been well studied in Fennoscandia in spruce and pine forests [22] and the temperate deciduous forests of central Europe [23], studies for southern Europe are still rare [18]. Surveying the status of sites of potentially high conservation value relies on compiling species' lists [24]. However, the assessment of the conservation value of areas based on species richness is challenging [25], particularly for the complex species-rich communities of Mediterranean mountains.

The aim of our study was to evaluate the effects of forest management on beetle diversity. we achieved this aim through three objectives: (i) analyzing the abundance and diversity of beetle communities in five beech-dominated forests of increasing management intensity in the Apennines of central Italy (Tuscany), specifying their trophic role and risk category; (ii) analyzing relevant forest structural attributes related with the species life cycles; (iii) evaluating the effects of forest management on beetle diversity, similarity, and commonness/rarity.

2. Materials and Methods

2.1. Study Area

Saproxylic and non-saproxylic beetles were collected in five sampling sites in Tuscany (Figure 1) and characterized by different management systems (Table 1, Figure 2). Three of the five sampling sites were even-aged stands managed with the uniform shelterwood system (Casella 1, abbreviation: Ca1; Casella 2, Ca2; Pian degli Ontani, PdO), one stand was an uneven-aged stand with a continuous cover maintained via the single-tree selection system (Baldo's Forest, Bal), and one sampling site was instead an old-growth unmanaged multilayered forest (La Verna forest, LaV). The sites managed with the uniform shelterwood system represent three different developmental stages of the even-aged high forest: PdO is a beech stand of about 60 years of age, Ca2 is a stand of about 100 years where beech regeneration is taking place after the seed cut carried out in 2017, and Ca1 is a young beech stand which originated after the seed cut and the removal cut carried out in 2002 and 2018, respectively.

Table 1. Management systems and the structural and environmental parameters of the different sampling sites in the study area. The volume of living trees was calculated by double-entry volume equations, while the volume of deadwood was calculated through the cone trunk formula.

Site	Acronym	Management System	Coordinates (WGS84)	Tree Volume (m^3 ha^{-1})	Deadwood Volume (m^3 ha^{-1})	Elevation (m a.s.l.)	Exposure (°N)
Casella 1	Ca1	Even-aged stand with uniform shelterwood system.	43°39′37.34″ N, 11°55′11.7″ E	-	5.5	1125	228
Casella 2	Ca2	Even-aged stand with uniform shelterwood system	43°39′30.16″ N, 11°55′9.62″ E	204.4	14.9	1102	279
Pian degli Ontani	PdO	Even-aged stand with uniform shelterwood system	44°6′26.52″ N, 10°41′40.14″ E	528.2	6.4	1229	26
Baldo's Forest	Bal	Uneven-aged forest	44°6′33.13″N, 10°41′49.6″ E	363.4	4.4	1189	61
La Verna	LaV	Old-growth uneven-aged forest	43°42′32.48″ N, 11°55′51.67″ E	997.8	426	1165	142

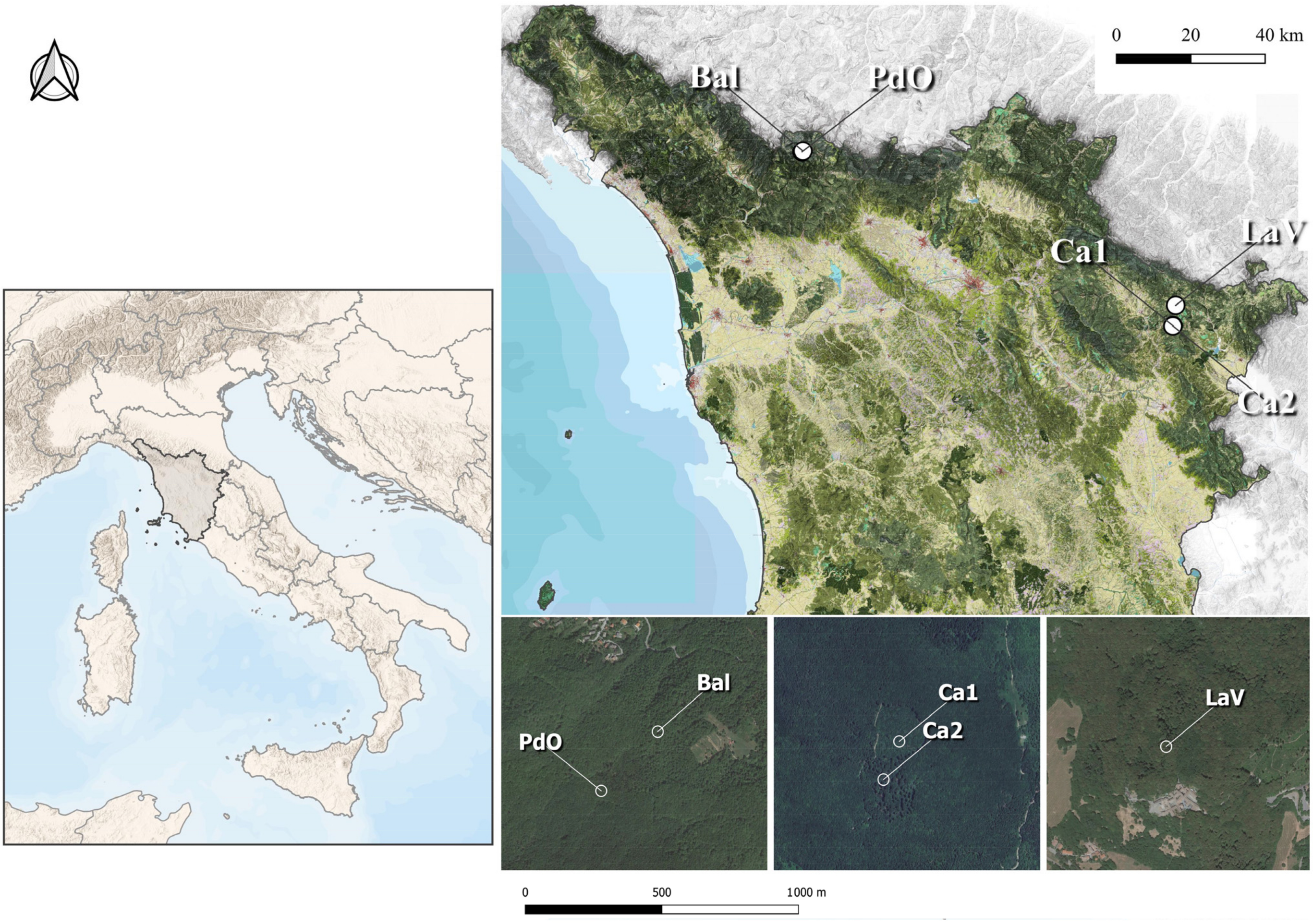


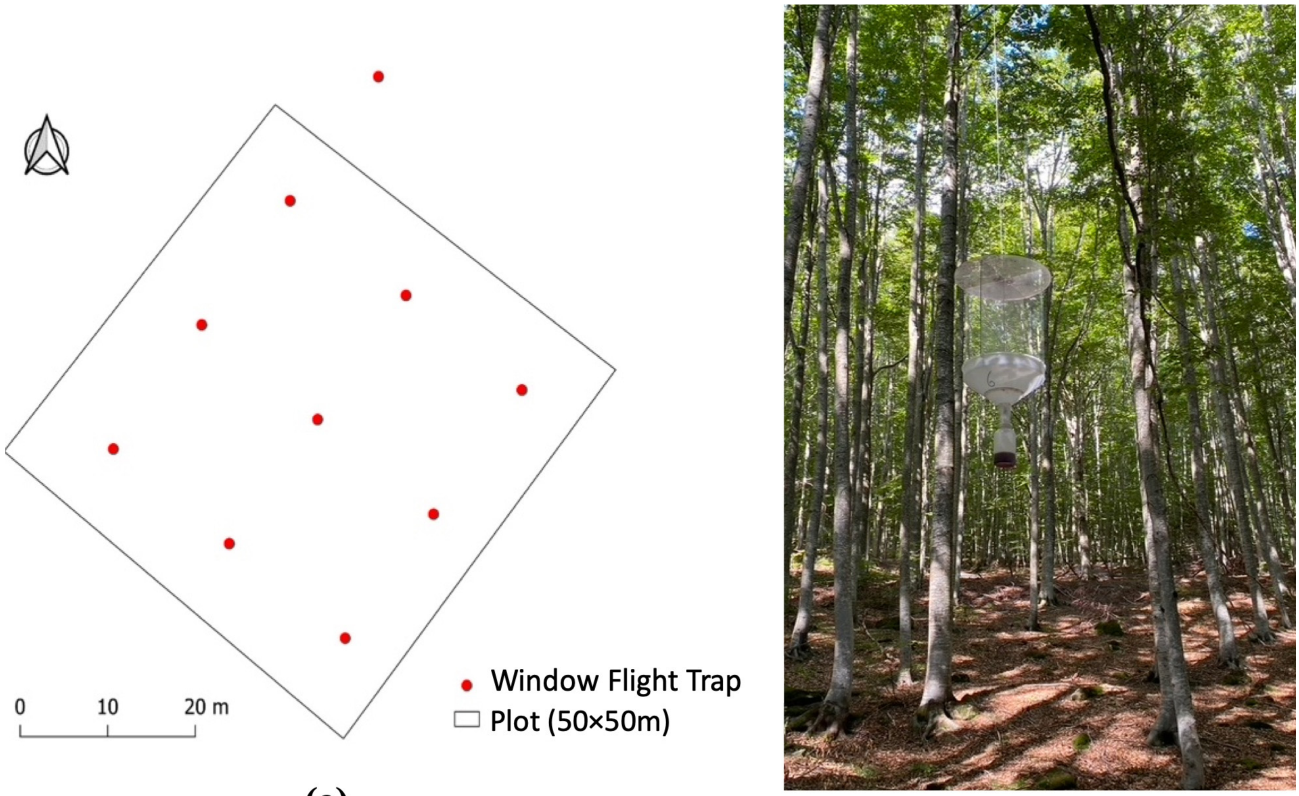
Figure 1. Location of the five sampling sites in the Tuscany Region. Legend: Ca1 = Casella 1; Ca2 = Casella 2; PdO = Pian degli Ontani; Bal = Baldo's Forest; LaV = La Verna.

Two sampling sites (PdO, Bal) are located in the Pistoia province and three (Ca1, Ca2, LaV) are in the Arezzo province. To ensure comparability, we selected all the sampling sites in a similar altitudinal range where the dominant vegetation was characterized by beech forests (*Fagus sylvatica*) located in the "Abetone" area, in the forest district "Alpe di Catenaia", and in the "Foreste Casentinesi, Monte Falterona e Campigna" National Park (central Italy). For each sampling site, we collected beetles and forest structural attributes within a squared plot of side 50 m (2500 m^2 area). Forest structural attributes, i.e., tree volume and deadwood volume, were measured in each plot taking into consideration living trees with Diameter at Brest Height (DBH) > 3 cm and deadwood components (snags and deadwood on the ground) with diameter > 5 cm (Table 1).

2.2. Beetle Sampling

From May to October 2021, we conducted beetle (Coleoptera) sampling in the five beech forest sampling sites. The collection of beetles was carried out using Window Flight Traps (WFTs) built according to Bouget's protocol [10]. The WFTs were positioned at a height of 2 m above the ground [10]. A total of 50 WFTs were placed, 10 for each sampling site, following the scheme reported in Figure 3.

Figure 2. The five sampling sites with different management systems. (**a**) Casella 1; (**b**) Casella 2; (**c**) Pian degli Ontani; (**d**) Baldo's Forest; (**e**) La Verna.



(a)

(b)

Figure 3. Sampling scheme (**a**) and Window Flight Trap (**b**) used for beetle monitoring.

Traps were checked approximately every 20 days, for a total of four surveys in 2021. All the monitoring systems were then removed after the end of the sampling period. Beetles were temporarily preserved in alcohol after capture and then preserved dry in entomological boxes. All specimens are stored in F. Parisi's private collection.

Systematics and nomenclature followed Bouchard et al. [26] and Carpaneto et al. [27]. All the taxa collected during the field activities are alphabetically listed in Table S1. Species strictly considered as saproxylic (sensu [27]) are also reported in Table S1, together with their IUCN risk category at the Italian level [27].

The species collected in the samples that were included in Carpaneto et al. [27] were considered "saproxylic" and grouped according to the prevalent trophic categories, defined as follows (Table S1): (i) xylophagus (organisms feeding exclusively or largely from wood); (ii) saproxylophagus (organisms feeding exclusively or largely from fungus-infected wood); (iii) mycophagous (organisms feeding exclusively or largely on fungi); (iv) mycetobiontic (organisms feeding on carpophores of large Polyporales and other fungi living on old trees and stumps); (v) commensal (commensals of saproxylophagus/xylophagus or of other saproxylic insects); (vi) sap-feeder (sap-feeders on trees attacked by xylophagus); (vii) predator (organisms that primarily obtain food killing and consuming other organisms); (viii) undefined (unknown or uncertain trophic category). Instead, the trophic category of the beetle species collected in the samples but not included in Carpaneto et al. [27] is currently unknown and requires further investigation; therefore, we did not specify their trophic category (Table S1).

Regarding the IUCN risk categories, the sampled saproxylic beetles follow the Italian Red List [27]: CR = Critically Endangered; Vulnerable (VU); Near Threatened (NT); Data Deficient (DD); and Least Concern (LC).

2.3. Comparison of Species Diversity, Similarity, and Commonness/Rarity Patterns

We evaluated whether forests of similar management intensity also showed similar (1) representation of family abundances, (2) beetle diversity using rarefaction curves, (3) species abundance patterns using an abundance-weighted similarity index, (4) patterns of commonness and rarity, fitting Species Abundance Distribution (SAD) models.

The representation of abundances among sampling sites was evaluated via parametric ANOVA. We tested the null hypothesis that the variance in the abundances per trap does not vary among sampling sites for each of the most abundant families, under a significance threshold $p < 0.05$. We compared the species diversity in the five sampling areas using rarefaction curves, with functions provided by Hsieh et al. [28] for the three Hill numbers (i.e., q = 0, species richness, q = 1, Shannon diversity, q = 2, Simpson diversity).

We compared the levels of similarity in the five sampling sites in the total and saproxylic species assemblages with the Morisita index for abundance data [29]. The Morisita index ranges from 0 (i.e., completely different assemblages) to 1 (the same species with the same abundance for each assemblage). Similarity dendrograms among sampling sites were drawn with the Morisita index and groups were combined based on the Unweighted Pair Group Mean Average.

We compared the patterns of species commonness and rarity in the five sampling sites by fitting SAD models [30] on rank-abundance distributions. The shape of the SAD was estimated with three parameters used to interpret changes in their shape: abundance decay rate (r), dominance (d), and relative number of rare species, that is, rarity (Fisher's α/species richness) [31]. Thus, r describes the overall steepness of the SAD curve. We estimated it with the function "rad.preempt" in R package "vegan" [32]. Dominance d, which is also known as Berger–Parker d [33], is simply $d = N1/N$, where $N1$ is the number of individuals of the most abundant species, and N is the total abundance of all species. Fisher's α is an implicit function of Fisher's log-series distribution of species abundance [34]. It describes the number of rare species in a community [35]. We estimated Fisher's α by fitting the log-series model with the function "fisherfit" in package "vegan" [32].

The statistical analyses and plots were all produced using R version 4.3.2 (https://www.R-project.org/).

3. Results

3.1. Characterization of Beetle Communities

A total of 8027 beetle specimens belonging to 25 families and 195 species were collected in the five sampling sites (Table 2). Saproxylic species represented 16.9% of the total abundance and 35.9% of the total richness (Table 2). The proportion of saproxylic species was the highest in the unmanaged La Verna site (42.1%) with respect to all the managed sites (ranging between 30.2% and 37.9%) (Table 2).

Table 2. Breakdown of the number of saproxylic and non-saproxylic individuals, species, and families for each sampling site.

Site	Individuals		Species		Families	
	Saproxylic	Total	Saproxylic	Total	Saproxylic	Total
Casella 1	133	570	28	74	12	18
Casella 2	435	1252	33	87	16	22
Pian degli Ontani	241	3457	26	86	12	16
Baldo	253	1534	21	62	12	14
La Verna	296	1214	32	76	11	17
TOTAL	1358	8027	70	195	18	25

The most abundant families were Staphylinidae (54% of the total), Curculionidae (23.4%), Elateridae (11.1%), Tenebrionidae (2.6%), Salpingidae (1.4%), and Nitidulidae (1.2%) (Figure 4). The other beetle families represented altogether less than 1% of the total abundance (Figure 4A) and less than 5% of the saproxylic abundance (Figure 4B). However, the representation of the most abundant families varied among sampling sites (ANOVA test: always significant for the total abundance of the most abundant families: $F \geq 2.77$, d.f. = 4, $p \leq 0.038$), but the representation of the most abundant saproxylic families varied only for Cerambycidae, Curculionidae, Nitidulidae, Salpingidae, and Staphylinidae (for all these saproxylic families, $F \geq 4.28$, d.f. = 4, $p \leq 0.005$), but not for Melyridae ($F = 1.46$, d.f. = 4, $p = 0.231$) and the rest of the families with abundance < 5% each ($F = 2.37$, d.f. = 4, $p = 0.067$).

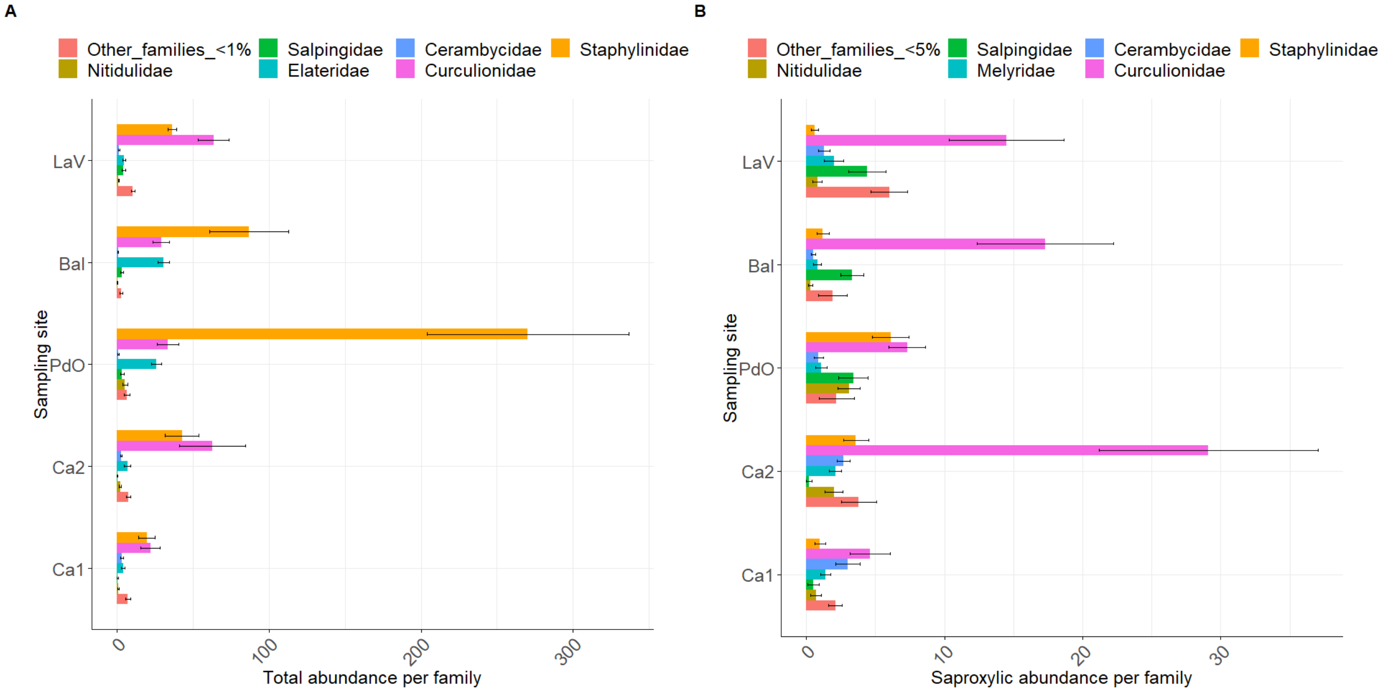


Figure 4. Abundance for each of the most represented families per sampling site (means (i.e., color bars) ± standard errors among traps (whiskers) for the total (**A**) and the saproxylic (**B**) beetle assemblages.

Concerning the representation of single species in the beetle assemblages, the most abundant species were *Eusphalerum rectangulum* (Baudi di S., 1870) (family Staphylinidae, 21.4% of the total specimens), *Orchestes fagi* (Linnaeus, 1758) (Curculionidae, 15.4%), *Aleochara sparsa* (Heer, 1839) (Staphylinidae, 14.3%), 2 *Atheta* spp. (Staphylinidae, 9.5%), *Ernoporicus fagi* (Fabricius, 1798) (Curculionidae, 8.6%) and *Athous* (*Haplathous*) *subfuscus* (O. F. Muller, 1764) (Elateridae, 5.3%), three species of *Eusphalerum* (Staphylinidae, collectively 6.3%) and *Phloeostiba plana* (Paykull, 1792) (Staphylinidae, 1.3%). The cumulative abundance of all these species represented 82.4% of the sample. Each of the remnant 185 beetle species was represented by less than 100 individuals (Table S1).

Concerning the representation of species in the IUCN red list, we found that the unmanaged forest of La Verna was the site with the highest number of species (10) belonging to a threat category (Table 3), while the managed sites similarly showed a lower number of species in threat categories, ranging from five to seven species. Five species were endangered: *Epuraea silacea* (Herbst, 1784), *Glischrochilus quadriguttatus* (Fabricius, 1776) (Nitidulidae) (Vulnerable, VU), *Calambus bipustulatus* (Linnaeus, 1767) (VU), *Stenagostus rhombeus* (Olivier, 1790) (VU), and *Brachygonus campadellii* (Platia y Gudenzi, 2000) (Critically Endangered, CR) (all Elateridae). Furthermore, one species was included in the Data

Deficient (DD) category (i.e., *Stenurella sennii* Sama, 2002, Cerambycidae). Nine species belonged to the Near Threatened (NT) category. These species belonged to the following families: Cerambycidae (one xylophagous species), Cleridae (one predatory species), Elateridae (two predatory species), Lymexylidae (two xylophagous species), Melandryidae (one mycetophagous species), and Salpingidae and Zopheridae (with one saproxylic species each).

Table 3. Breakdown of the number of saproxylic beetle species in each IUCN risk category for each sampling site. Legend: Ca1 = Casella 1; Ca2 = Casella 2; PdO = Pian degli Ontani; Bal = Baldo's Forest; LaV = La Verna.

IUCN Code	N. IUCN Species (NT + VU + CR)	Near Threatened	Vulnerable	Critically Endangered
		NT	VU	CR
Ca1	4	3 (*Tilloidea unifasciata*, *Lymexylon navale*, *Serropalpus barbatus*)	0	1 (*Brachygonus campadellii*)
Ca2	6	5 (*Leiopus femoratus*, *T. unifasciata*, *Elateroides dermestoides*, *S. barbatus*, *Synchita undata*)	0	1 (*B. campadellii*)
PdO	6	4 (*Ampedus erythrogonus*, *E. dermestoides*, *S. barbatus*, *Salpingus ruficollis*)	2 (*Epuraea silacea*, *Glischrochilus quadriguttatus*)	0
Bal	5	5 (*L. femoratus*, *Denticollis rubens*, *E. dermestoides*, *S. barbatus*, *S. ruficollis*)	0	0
LaV	9	5 (*T. unifasciata*, *A. erythrogonus*, *S. barbatus*, *S. ruficollis*, *S. undata*)	3 (*Calambus bipustulatus*, *Stenagostus rhombeus*, *G. quadriguttatus*)	1 (*B. campadellii*)

3.2. Rarefaction Curves

The comparison of the diversity curves (Figure 5) showed that the sampling site Ca1 had the highest species richness, evenness (i.e., Shannon diversity), and dominance (Simpson index) among all sites, both for the total community and for the saproxylic component. LaV instead showed higher richness and evenness values only for the saproxylic component but not for the total assemblage, where LaV showed both the lowest total evenness and dominance (Figure 5). The lowest total and saproxylic species richness was found in the Bal, which also had the lowest evenness and dominance for the saproxylic component, but intermediate and high values, respectively, for the total evenness and dominance (Figure 5). Ca2 and PdO showed, respectively, intermediate values of saproxylic and total richness, average or low values of evenness, and intermediate values of dominance (Figure 5).

3.3. Abundance-Weighted Similarity

We found that 16 species were common to all the studied sites. The similarity among sampling sites for the total species assemblage (Figure 6A) reflected the geographical distance between them, with the two sampling sites located in the Pistoia province and the three sampling sites in the Arezzo province clearly separated in two main clusters. Instead, the similarity dendrogram for the saproxylic assemblages (Figure 6B) showed a main cluster with Ca1, an even-aged stand; LaV, an unmanaged site; and a main cluster with Ca2 and Bal, both sites characterized by similar intermediate values of tree volume and amount of deadwood due to forest management characterized either by recent forest reestablishment or single tree selection (Table 1, Figure 2). Instead, the assemblage of PdO, a 60-year-old site characterized by even-aged structure, was separated from the two main clusters.

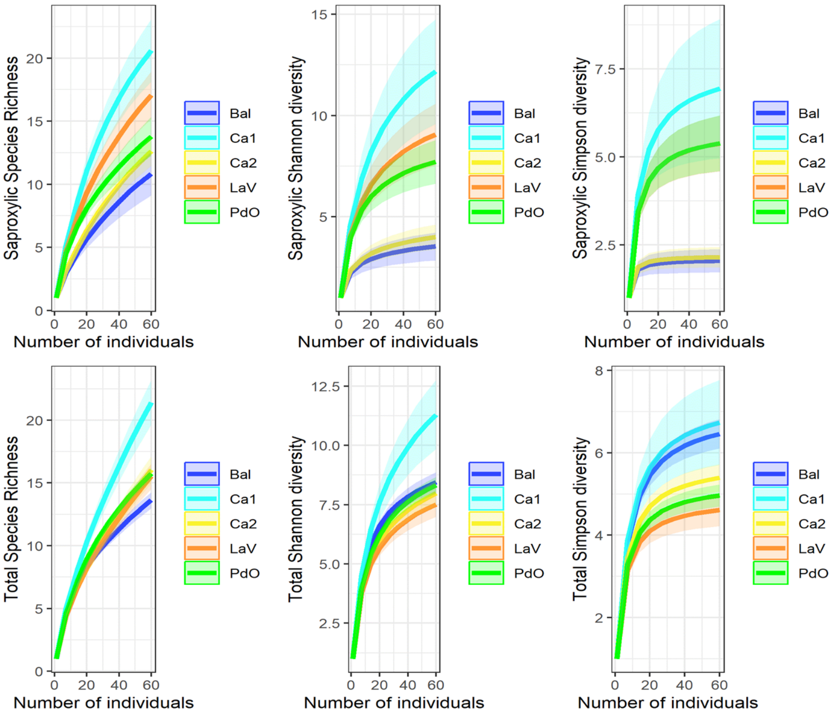


Figure 5. Rarefaction curves with 95% confidence intervals (shaded areas) for the three Hill numbers (q = 0: species richness, q = 1: Shannon diversity, q = 2: Simpson diversity), considering the whole assemblage and only the saproxylic species. Legend: Ca1 = Casella 1; Ca2 = Casella 2; PdO = Pian degli Ontani; Bal = Baldo's Forest; LaV = La Verna.

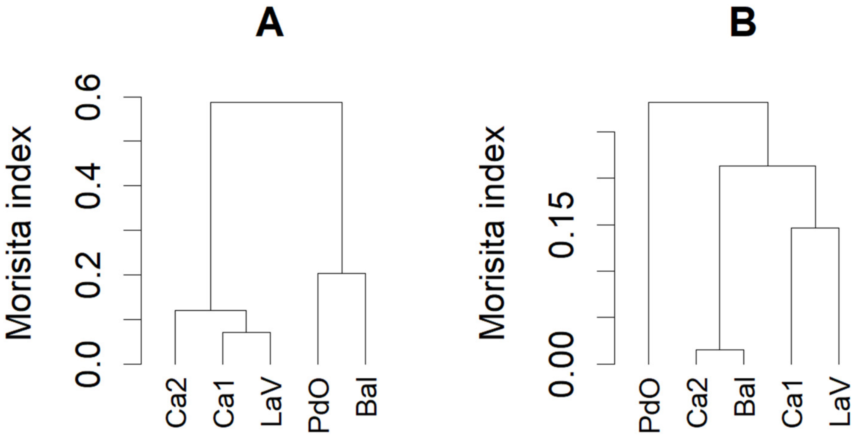


Figure 6. Similarity dendrograms among sampling sites were drawn with the Morisita index based on abundance data for (**A**) total "beetle" species and (**B**) "saproxylic" species and groups were combined based on the Unweighted Pair Group Mean Average. Legend: Ca1 = Casella 1; Ca2 = Casella 2; PdO = Pian degli Ontani; Bal = Baldo's Forest; LaV = La Verna.

3.4. Patterns of Commonness and Rarity

The shape of the SADs differed among the sampling sites (Figure 7). Shapes of the SADs were very diverse, ranging from steep distributions (high *r* values) with high dominance (high *d*) and very small numbers of rare species (low alpha) in the Bal, to shallow distributions (low *r* values) with relatively low dominance (low *d*) and a long 'tail' of singletons (high *alpha*) (LaV and Ca1). The other two sampling sites showed both intermediate steepness in the distribution (*r*), high (Ca2) or low (PdO) dominance, and an intermediate number of singletons (alpha). Finally, the relative number of rare species showed similar values for Bal, Ca2, PdO, and LaV ($0.25 \leq \alpha/S \leq 0.28$) and was instead much higher for Ca1 ($\alpha/S = 0.39$).

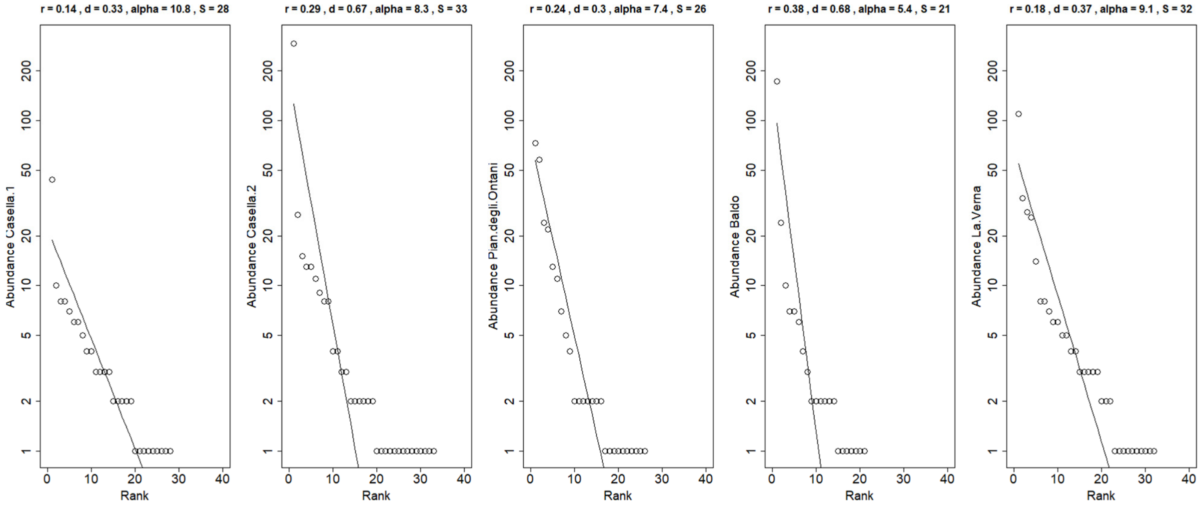


Figure 7. Rank (in *x*-axis, where the most abundant species is given rank 1)–Abundance (in *y*-axis) biplots. Fitted geometric series models (lines) and the values for the abundance decay rate (*r*), dominance (*d*), Fisher's alpha (α), and species richness (*S*) are reported for saproxylic beetle data in the five sampling sites.

4. Discussion

4.1. Characterization of Beetle Communities

Our research has deepened taxonomic and ecological knowledge on the assemblages of saproxylic and non-saproxylic beetles collected in interception traps in beech forests under different management systems in the Italian Apennines. Both in terms of abundance and diversity, a large proportion of the identified beetles were strictly saproxylic, and therefore associated with deadwood or habitat trees [7], while the remainder are considered non-wood-dependent species [36]. This proportion was larger in the unmanaged site of La Verna than in any other managed site, and this is likely related with the larger quantity of deadwood in this site. Saproxylic beetles play an essential role in the trophic chain of the forest ecosystem, particularly in the recycling of nutrients, as they depend on—or are involved in—deadwood decay processes [7]. The high number of saproxylic beetle species that we found associated with deciduous tree species highlights the importance of dead wood and tree-related microhabitats for the conservation of the entire forest beetle community. Overall, Campanaro and Parisi [18] found 918 species in a gradient of central-southern Italy in managed and unmanaged forests. However, information on the status and distribution of the populations of these species is particularly scarce in the Mediterranean area [37]. This trophic guild includes highly specialized species. Consequently, they are considered valid indicators for assessing the naturalness of forest ecosystems [27]. Our study includes several beetle species whose biology is not directly related to these habitats and can be considered incidental to deadwood. For example, research conducted in Poland [38] reveals that most of the non-wood-dependent beetles we collected are associated with accumulated organic matter, plant waste, mud and soil, various plants, mosses, birds' nests and other animals, carrion, and fungal fruiting bodies.

In the managed sites, we found a higher abundance of families requiring small amounts of deadwood to complete their life cycle, like Scolytidae and Staphylinidae, than in the unmanaged site (Table S1). In the unmanaged site, the number of species belonging to families requiring a large amount of deadwood was higher (i.e., Cerambycidae, Trogossitidae, Zopheridae) than in managed sites [18]. Forests with low canopy cover or forest gaps, like our intensively managed forests, supported a high diversity of xylophagous-thermophilus beetles (Cerambycidae and part of Buprestidae). These ecotones supply sun-exposed decaying and dead wood which supports the development of these larvae. The herbaceous layer of these open forests also supports flowering plants, representing a feeding resource for floricolous adult species [39]. The family Staphylinidae was the most abundant and diverse family in our study. Approximately half of the collected Staphylinidae species were not associated with dead wood and were characterized by relatively low abundance (Table S1). Furthermore, in our study, we observed that in the areas under regeneration covered by young beech trees associated with shrubs and ground vegetation (i.e., Ca1 and Ca2), some families related to the flowering of the herbaceous layer and decomposing litter prevail (i.e., Buprestidae, Cerambycidae, some Curculionidae, Scarabaeidae, and Staphylinidae). By contrast, in shadier areas and with a greater availability of ecological niches, species related to deadwood prevail (i.e., Elateridae, Lymexylidae, Nitidulidae, Zopheridae). The uneven-aged management of forests where shade-tolerant tree species prevail, like beech and spruce, takes place without creating canopy gaps. Instead, the reduction in tree density of these forests takes place because of occasional natural disturbances, like windthrow. Consequently, these managed forests are, alongside other managed coniferous forests at lower and mean altitudes, generally very dense and therefore do not support the majority of thermophilus and floricolous beetle species [39].

In all the sites investigated, we found 16 shared species. These mainly belonged to following the families: Cantharidae, Curculionidae, Elateridae, Melandryidae, Melyridae, Nitidulidae, Salpingidae, and Staphylinidae. Furthermore, for some species, the number of individuals in common in the different sites varied. For example, the number of specimens was constant for the Curculionidae, Elateridae, and Staphylinidae. In other families the effect of management probably caused a different relationship between individuals. For example, Cantharidae and Staphylinidae (predators) are more abundant in intensively managed sites (Ca1 and Ca2) (Table S1).

A high proportion of the beetle community can be considered rare, being collected only once during the whole sampling period. The high number of species with only one individual collected is confirmed by various studies carried out in managed beech forests [21]. It is likely that the multi-year monitoring of beetles could provide more accurate data on the diversity of forest ecosystems [10].

The saproxylic beetle species found in our study belonging to the IUCN red list represent approximately 3.5% of all red-listed saproxylic beetle species known in Italy [27]. This percentage is in line with the richness of red-listed saproxylic species found in other Italian managed beech forests [40] (3.2%), in managed chestnut forests of southern Italy [8] (4.5%), and in the Alps [41] (4.8%). The diversity of red-listed saproxylic species generally increases if research is carried out in old-growth forests. For example, De Zan et al. [42] found 13.1% of red-listed species related to dead wood in three relict beech forests of central Italy.

4.2. Effect of Management on Species Assemblages: Rarefaction Curves, Similarity, Commonness/Rarity

The comparison of the rarefaction curves showed that the early successional stage in Ca1 had the highest total and saproxylic species richness, diversity, and dominance. This is likely an indication that, in this even-aged site managed with the shelterwood system, the recent removal cut supported a diverse flying assemblage of beetle species associated both with open sunny habitats, where flowering plants likely support species associated with this microclimate, and with the local deadwood component, mostly represented by recently released stumps and small branches representing Fine Woody Debris with a diameter lower than 10 cm (FWD, Parisi, personal communication) useful for the xylophagous beetles' larvae [21]. In other words, in this recently cut area under natural regeneration, window traps sampled flying species which likely originated from surrounding forests with higher living biomass and saproxylic species associated with FWD. However, the presence of few dominant species (Simpson index) is an indication of the fact that Ca1 was highly degraded due to a recent removal cut. Instead, the fact that the LaV old-growth forest harbored only high levels of saproxylic species, due to the very high deadwood volume, but not high levels of non-saproxylic species, is an indicator of its higher level of naturalness with respect to the other managed sites. The uneven-aged Bal, which was traditionally managed with a single-tree selection system, also showed the lowest values of saproxylic richness and diversity but a high total diversity and dominance. This is also confirmed by the steep SAD curves indicating an imbalance between the high representation of common species and low representation of rare species. This is likely because, even though single-tree selection has a limited impact on the total biodiversity compared to other management alternatives, it creates an impoverished forest structure in terms of deadwood compared to an unmanaged site. The beech reestablishing process occurring in Ca2 and the uniform shelterwood system in PdO supported intermediate levels of richness and diversity and intermediate values of the steepness of the SAD curves.

The dendrograms for the whole species assemblage reflected the geographical proximity among the sites, while the similarity for the saproxylic component was more directly associated with the gradient in volumes of aboveground biomass and deadwood components and the similarity between forest successional stages. For the saproxylic assemblage, Ca1 had a higher similarity with LaV than with other managed sites. This is also confirmed by the similarity in the SAD curves' shapes (i.e., shallow distributions) and the high representation of species sampled only once (i.e., singletons). The high similarity between the Ca1 and LaV sites can be attributed to the similar number of items of deadwood present. However, while in Ca1 deadwood was mostly present as FWD (not monitored in standard monitoring), in LaV deadwood was present with quantities of CWD (diameter $\geq$ 10 cm). Therefore, even though the small volume of CWD reported for Ca1 suggests there are limited resources available for saproxylic beetle, an unmonitored high presence of FWD could explain the high similarity with the unmanaged forest. Furthermore, the open spaces in Ca1 were rich in herbaceous plants, which have attracted a high diversity of saproxylic beetles, which are floricolous as adults [39]. This can explain the substantially specific similarity of these very different forests. However, it must be noticed that the capacity of a managed system like Ca1 to support a high species diversity in the long-term is limited by its rotation system, while the unmanaged LaV forest is likely to retain a high diversity for centuries if left unmanaged.

5. Conclusions

Our study aimed to explore the patterns of diversity and similarity of saproxylic and non-saproxylic beetles in beech forests managed with different management systems in the Italian Apennines.

The response of beetle assemblages in our study sites reflected a continuum in the intensity of the management regimes applied. In the sampling sites of our study area, managed beech forests harbored a diversified beetle community which also allowed threatened species to thrive.

To guarantee the survival of these threatened species, the EU Forest Strategy for 2030 [43] has recommended the development of sustainable forest management strategies, and the improvement of monitoring activities, as conducted in our study sites.

We recommend that closer-to-nature forest management targeting deadwood retention and accumulation and increasing the occurrence of microhabitats should be practiced in our forest mosaic with different microclimatic and topographic characteristics [44]. Furthermore, the retention of large, old trees [45] (i.e., "passive" management) must be favored in different topographic contexts. These two practices will favor the saproxylic communities in two ways: locally increasing the amount and diversity of available microhabitats in living and dead wood, and reducing local tree density, which increases habitat heterogeneity [8].

Our results allow us to make some recommendations to improve the conservation value of the current sylvicultural practices in beech forests: (1) increase the volume of deadwood from the current 5–10 m^3 ha^{-1} up to >20 m^3 ha^{-1}; (2) preserve large logs

(50 cm diameter) and favor the presence of larger quantities of deadwood in an advanced decay stage; (3) designate fully protected forests, allowing for the accumulation of high deadwood volumes (>60 m^3 ha^{-1}) to preserve specialist species demanding high substrate volumes [46]. To find synergies between economic and ecological planning goals, we suggest that current sylvicultural practices balance the current recommendations for timber harvesting with quantitative recommendations concerning deadwood management.

The limited availability of standardized protocols for beetle diversity across large forest areas makes it difficult to compare our findings with inventories from other sites. Instead, most of the beetle collections represent spatially and temporally limited samplings [18]. To be cost-effective, these two activities should go together, as the capacity of closer-to-nature management interventions for restoring the habitat of threatened species can be evaluated only by implementing rigorous biodiversity assessment and ecological monitoring programs over the whole forest landscape.

However, when comparing our study with research conducted in Italy in other managed contests, we found relatively similar beetle assemblages [18]. Given the fact that the number of overlapping species is relatively small, this suggests that the number of beetle species related to beech may be much larger than it currently appears, but further research is needed to evaluate this consideration.

Beetles were collected with window traps [18]. A similar method of traps for collecting beetles has been used several times in Italy [40,45], France [14], Sweden [46], and Germany [47]. In Italy, for example, several studies in both managed and unmanaged forests have confirmed the usefulness of WFTs for monitoring beetle populations [48]. However, our study shows that WFTs may have some limitations as they only sample flying insects not necessarily associated with a particular stage of succession but which reflect the surrounding forest landscape.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15071085/s1, Table S1: List of saproxylic and non-saproxylic beetles and their abundance.

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