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The effects of cutting season on stump mortality and resprouting in southern European Sweet chestnut (*Castanea sativa* Mill.) coppices

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ABSTRACT

Historically, Sweet chestnut (*Castanea sativa* Mill.) has played a key role in the southern European rural economy. In the last century, due to the spread of diseases, there has been a massive shift from orchards to coppice management. Furthermore, a combination of socio-ecological factors led to chestnut cultivation decline with the withdrawal of most coppice stands from regular management. This resulted in living biomass increment, stool mortality, increased slope instability, and enhanced forest fire hazard. In most Italian regions, current forest regulations restrict coppicing to the dormant season, reflecting traditional beliefs and practices rather than scientific evidence. This restriction hinders effective management, contributing to coppice aging and abandonment. To evaluate the feasibility of extending the current cutting period, we investigated the effects of coppicing on chestnut resprouting capacity in different seasons (winter, spring, summer) by monitoring stump and shoot mortality, and shoot growth (shoot number and height) over three years in two neglected coppice stands in northwestern Italy. Results showed no significant influence of the cutting season on stump mortality, confirming the strong and lasting resprouting capacity of chestnut trees. Coppicing in spring or summer reduced shoot density and height in the following few years. However, these disparities tended to equalize rapidly over time, becoming non-significant. Additionally, no significant differences in shoot mortality were observed. Therefore, our findings suggest that chestnut coppices could endure year-round cutting in warm, temperate climates, confirming the possibilities of broader management to contrast abandonment, supporting sustainable use of this resource, and preventing natural hazards.

1. Introduction

Sweet chestnut (*Castanea sativa* Mill.) - hereafter referred to as chestnut - has been a key species for the European rural economy since its introduction and spread (Bernetti, 1995; Conedera et al., 2001). Initially cultivated as orchards for fruit production (Conedera and Krebs, 2008), its main management turned to coppice for the production of poles, fuelwood, and charcoal (Pitte, 1987; Giannini et al., 2014; Conedera et al., 2021; Clark et al., 2023). However, changes after World War II, the spread of chestnut diseases (such as the chestnut blight and the soil-borne ink disease) (Vettraino et al., 2005; Rigling and Prospero, 2018), the Asian Chestnut Gall Wasp invasion (Graziosi and Santi, 2008), and hoar-frost damage (Krebs et al., 2019; Melicharová and Kupka, 2021), led to the abandonment of coppice with major environmental and socio-economic consequences (Vogt et al., 2006; Pividori et al., 2008; Dazio et al., 2018; Marcolin et al., 2020; Conedera et al., 2021).

The main effects of forest management abandonment were the progressive aging of trees and stumps, the increase in the amount of living biomass (INFC, 2005; INFC, 2015) and in the stump density with consequent intensification of internal competition dynamics (Pezzi et al., 2011; Conedera et al., 2021). As a consequence, the natural development of this dynamic resulted in widespread stump uprooting, stool mortality and deadwood accumulation, and species replacement. In fact, aboveground biomass surpassing root system capacity has been proven to destabilize stumps and consequently trigger soil erosion,

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Abbreviations: Treatment, coppicing season either winter, spring, or summer; MMH, Mean Max Height; AMH, Absolute Max Height.

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rockfalls, or landslides (Vogt et al., 2006; Pividori et al., 2008; Dazio et al., 2018; Marcolin et al., 2020). In this context, other aspects of coppice abandonment influence the environment and landscape. For instance, the accumulation of standing and lying dead stems increases the wildfire hazard (Garfì et al., 2022) and the fallen branches and trees that accumulate in riverbeds promote flood risk by obstructing water flow (Ruiz-Villanueva et al., 2014; Panici et al., 2020). Ultimately, stump and stool mortality creates gaps, allowing the establishment of pioneers and secondary species and/or the invasion of non-native species (Manetti et al., 2001; Zlatanov et al., 2013; Marcolin et al., 2020). Therefore, neglect of active forest management has led to a deterioration in the provision of ecosystem services, and in the case of chestnut coppices, this is even more important due to their proximity to human settlements.

In recent years, the global change scenario and its predicted influences on forest ecosystems (Lee et al., 2023) have brought renewed interest in forest management. Such a consideration arises from forests' natural capacity to absorb greenhouse gases, which are considered to be one of the main drivers of climate change (Bernier and Schoene, 2009; Lucier et al., 2009; Hagerman and Pelai, 2018), and from the other ecosystem services they provide such as water regulation, protection from soil erosion, rockfall protection, and increased biodiversity (Pettenella, 2001; Vergani et al., 2017). The value of sweet chestnut stands for biodiversity has been recognised by the European Union, which declared both chestnut-dominated forests and long-established chestnut plantations with semi-natural undergrowth, relevant habitats (habitat type: Castanea sativa woods, code 9260) for biodiversity conservation (Habitat Directive 92/43/EEC) (Campagnaro et al., 2023). In this context, given chestnut coppice broad diffusion in Europe and its intrinsic relationship with urbanized areas (Conedera et al., 2004), it is being reevaluated as an opportunity. However, the aforementioned consequences of chestnut coppice abandonment and the potential interaction with climate change effects highlight the necessity of active management, with specific attention to the cascading impacts of the abandonment on natural hazard events (Vogt et al., 2006; Marcolin et al., 2020; Garfì et al., 2022). Additionally, land and forest management must cope with rising ungulate pressure promoted by climate change (Carpio et al., 2021; Champagne et al., 2021). Wild herbivores could harm young resprouts either via apical grazing, trampling, or bark stripping leading to growth delay, death, and altered competition dynamics (Motta, 1996; Bottero et al., 2022). This is mostly relevant at the end of the vegetative season and during winter when food availability decreases due to herbs withering and snow coverage (Putman and Staines, 2004; Felton et al., 2022).

Here, we sought to identify new management opportunities for chestnut coppices, aiming to counter their abandonment and mitigate the negative impacts associated with climate change dynamics. The study focuses on the Italian chestnut scenario (landscape/gamut), as Italy has one of the largest chestnut forest covers in Europe, second only to France (Conedera et al., 2016; Unrau et al., 2018). Similarly to the rest of Europe, Italian chestnut forests went from occupying a central role in rural society to the current state of decline (Conedera and Krebs, 2008; Giannini et al., 2014). Indeed, since the beginning of the XX century, the national chestnut cover decreased from around 800,000 (Giannini et al., 2014) to 778,475 ha (INFC, 2015).

In Italy, forest regulations limit the coppice cut to the period of vegetative rest (typically from mid-September to mid-April or May according to the elevation) (see RR 1/1999 for Liguria and DPGR 4/R, 2015 for Piedmont). This specific coppice regulation that roots back to old prescriptions from the second half of the XIX century was believed to have several advantages in terms of yield: the production of more stable and vigorous proventitious shoots, the conservation of stump vitality, and the prevention of mechanical damages such as bark detachment and incomplete shoots lignification before winter frost. Besides these common beliefs, the main practical reason behind this seasonal coppice management choice was the need for workers for large agricultural estates during the growing season (Piussi, 1980; Ciancio and Nocentini, 2004). This long-standing legal framework is slowly adapting to changing conditions, hindering forest adaptive management in response to societal and climate changes (Freitas et al., 2021).

In light of chestnut's remarkable ecological plasticity, high resilience, and strong, long-lasting resprouting capacity (Piccioli, 1922; Piussi, 1994; Giudici and Zingg, 2005), we hypothesize that the season of coppicing would not significantly impact resprouting capacity in terms of stump vitality, shoot growth, and mortality, making cutting season restrictions a superfluous constraint on forest management. Therefore, we hypothesized an extension of the cutting season to the whole year as an adaptive measure to increase opportunities for chestnut coppice management facing changing climate conditions. To assess how different coppicing seasons (winter, spring, and summer) affect chestnut vegetative regeneration capacity - in terms of stump mortality, shoot growth, and mortality - two study sites were established in the two Italian regions with the highest chestnut forest cover, Liguria (28 %) and Piedmont (17 %) (INFC, 2015).

2. Materials and methods

2.1. Study area

The study was conducted in two experimental chestnut aged coppices with sporadic presence of other species (*Acer campestre* L., *Acer pseudoplatanus* L., *Alnus glutinosa* (L.) Gaertn., *Carpinus betulus* L., *Fagus sylvatica* L., *Fraxinus ornus* L., *Ilex aquifolium* L., *Ostrya carpinifolia* Scop., *Pinus sylvestris* L., *Prunus avium* L., *Quercus petrea* (Matt.) Liebl., *Robinia pseudoacacia* L.). The two sites shared similar forest structures and past management. Previously managed as a coppice with standards, both sites have been neglected for 40–60 years which resulted in a dense number of stools with uniform growth and isolated standards. The first site is located in the Piedmont region, Cascina Caramagna - Voltaggio (AL), 44°37’57” N, 8°50’13” E, at an average elevation of 415 m a.s.l., with a slope ranging from 11° to 33°, and main aspect variable from south to north-east. The second site is located in the Liguria region, Camponuovo - Cairo Montenotte (SV) (hereafter Cairo), 44°23’41” N, 8°19’58” E, with an average elevation of 600 m a.s.l., a slope ranging from 2° to 23°, and main aspect variable from south-east to south-west. The two sites present a similar climate: warm temperate, with hot and dry summers, classifiable as “Csa” according to the updated Köppen-Geiger climate classification (Kottek et al., 2006; Zepner et al., 2020). Both sites have a mean annual temperature of 13°C, while yearly precipitation is 972 mm in Voltaggio, and 776 mm in Cairo.

2.2. Sampling design

At each site, three replicas per treatment (cutting season) were established, resulting in nine replicas per site and 18 total. Fig. 1 exemplifies how plots were distributed across varying elevations and aspects to sample potential micro-site diversities. Each replica was structured around a square sampling area with a surface of 900 m^2 (30 ×30 m), paying attention to avoid including any group of standards within the plot or nearby and releasing a buffer zone of at least 15 m around the plot to prevent the edge effect. Within the plots, all stems above 8 cm diameter at breast height (DBH, cm) were measured with a manual caliper, and status (dead/alive) was visually assessed. Moreover, for each stump, a sub-sample of stem heights (m), based on the diametric stand distribution and the maximum alive stem height (m), was measured using a hypsometer with ultrasound technology (Vertex 5). In each replica, 30–40 stools were permanently labeled and mapped which measured azimuth (°) and distance (m) from a fixed point of known coordinates.

In 2021 (t0), following the experimental design, both sites were coppiced restoring stand management. Unlike past management and contrary to the common coppicing practice in Liguria, standards were

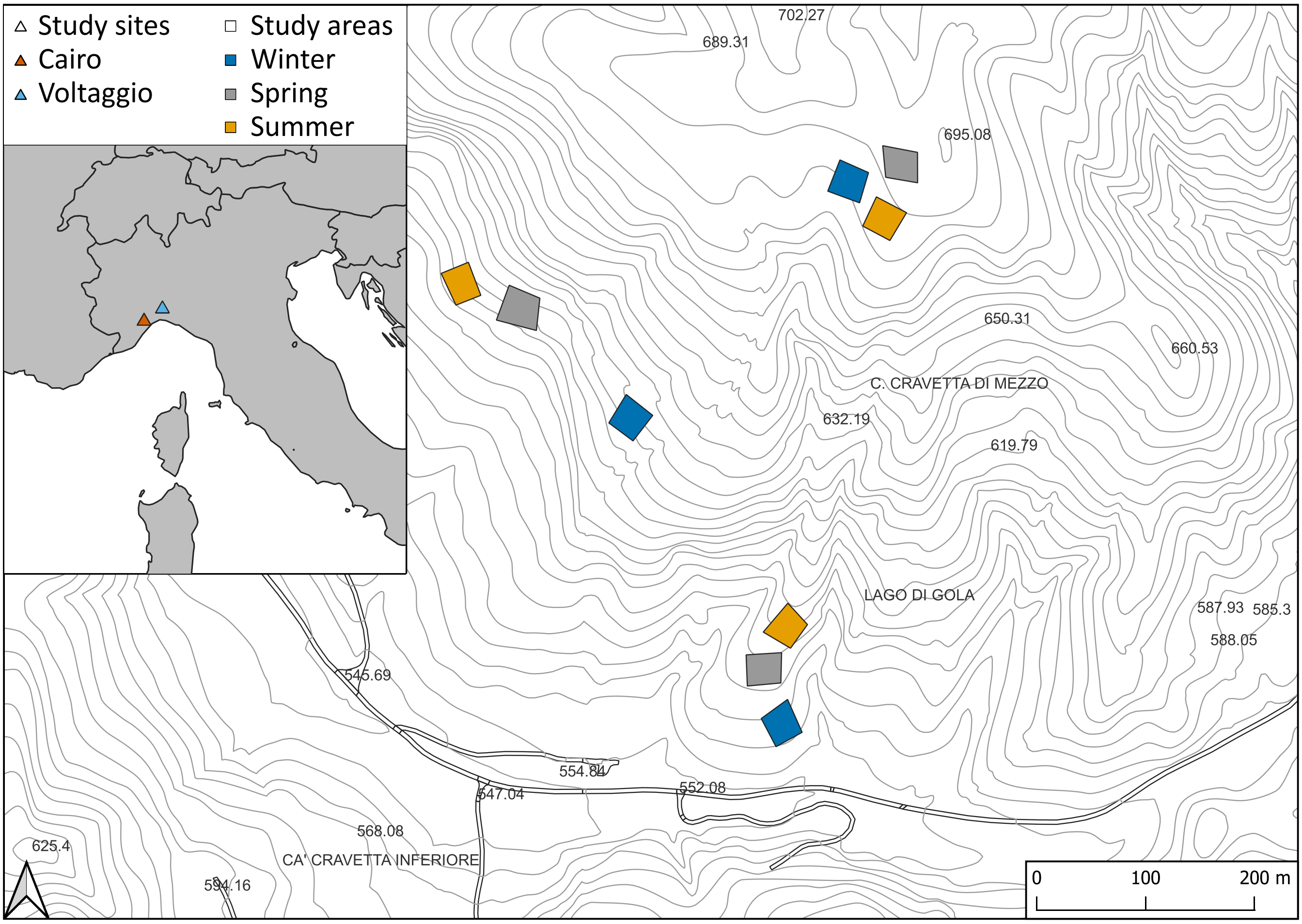

Fig. 1. Upper right corner: Location of experimental sites (Cairo in red and Voltaggio in light blue). Background map: example of sampling design (Winter, Spring, and Summer treatment in blue, grey, and orange, respectively). The map shows the Cairo sampling plots.

released grouped rather than isolated to promote their ecological function. The coppicing was carried out in three different seasons – winter (March), spring (May), and summer (August) - complying with local forest regulations (Table 1), except for the coppicing season being the experimentation topic.

Post-treatment monitoring was conducted during the dormant period for three consecutive years after the cut (2022, 2023, 2024 - t1, t2, t3). At each sampling time we collected data on stump and shoot status (dead/alive), number of shoots per size class (shoot height 0–25; 25–50; 50–75; 75–100; 100–125; 125–150; 150–200; 200–300; 300–400; >400 cm), height of the five tallest shoots (cm), and ungulate browsing (damaged/not damaged). A stump was considered dead if no living shoots were found, while a shoot was considered dead if broken at the insertion, totally dry, or grazed to the ground with no green buds left. At each sampling time, the height of all shoots from each stump was manually measured with a rigid ruler classified according to the defined size class and counted. Size classes were derived and simplified from Motta (2003) which focused on ungulates browsing. The height class width was set to 25 cm for all classes up to 150 cm, which was identified as the inflection point of the grazing curve (Motta, 2003). Beyond this threshold, the class width was increased to 50 cm, and eventually to 1 m. The five highest living shoots were precisely measured either with the rigid ruler or the Vertex 5 if the height exceeded 4 m. Maximum heights were measured from the five tallest shoots of each stump at sampling time. Each shoot was also visually checked for apical damages caused by ungulate bites; other damages, such as breakage or natural shoot detachment were not accounted for. Consequently, for each size class, four values regarding the shoot number were collected: n. living non-damaged, n. living damaged, n. dead non-damaged, n. dead damaged.

2.3. *Statistical analysis*

Pre-treatment data were used to investigate dendrometric stand characteristics, such as stem and stump density, mean square diameter, mean alive stem height, max alive stem height, and basal area and volume (Tabacchi et al., 2011) per hectare. Data collection discerned between living and dead biomass highlights their ratio in terms of density, basal area, and volume. Previous studies (Pividori and Motta-Frè, 1997; Giudici and Zingg, 2005) observed that stump resprouting capacity is positively correlated with their size – basal area and number of stems. Accordingly, we assumed the ratio of the basal area between dead and total stems of a stump as a proxy of stump vitality (Giudici and Zingg, 2005; Vergani et al., 2017). Analogously, we referred to the ratio of the basal area between dead and total stumps as a proxy of stand vitality (Larson and Franklin, 2005; Maringer et al., 2016).

Post-treatment data were used to investigate whether coppicing season affected chestnut regeneration capacity by addressing stump mortality, shoot growth (shoot number and shoot height), and shoot mortality to identify differences and similarities among coppicing seasons and trends through time.

Stump mortality was assessed by calculating, over the entire plots, for each combination of season, time and site, the ratio between dead and total experimental stumps. Additionally, stump mortality was analysed by evaluating cutting seasons and site effects significance (Eq.1).

Table 1

Extract of current prescriptions on chestnut coppice management in the two Regions within which experimental sites are located.

Regulation	Piedmont	Liguria
Current Forest Regulations	DPGR 4/R 2015	RR 1/1999
Min. rotation time (years)	10	12
Max. rotation time (years)	n.d.	n.d.
Standards release	10 % of canopy cover*	≥ 60 trees[a]
Other species to release	*Release of other species up to 25 % of residual canopy cover. If the canopy cover originating from other species does not reach 10 %, this value must be reached by releasing chestnut trees.	All species different from chestnut must be released as standards.
Standards spatial distribution	Isolated or clustered[b]	Uniform or clustered
Max. extension (ha)	5	-
Coppicing epochs	a) 01/10 – 15/04 up to 600 m a.s.l. b) 15/09 – 30/04 between 600 and 1000 m a.s.l. c) 01/09 – 31/05 above 1000 m a.s.l.	a) 01/10 – 15/04 up to 800 m a.s.l. b) 01/10 – 15/05 between 800 and 1200 m a.s.l. c) 01/10 – 31/05 above 1200 m a.s.l. c bis) 01/09 – 30/06 for chestnuts stands with canopy cover > 75 % regardless of the elevation. Coppicing epochs (a, b, c) are extended by 15 days for stands located on the Po Valley side of the region.

[a] In chestnut forests it is not mandatory to release standards of this species, but all other species must be released as standards.

[b] Maximum cluster size is 200 m^2, distance among clusters is at least 1.5 x max height.

The distribution of stump mortality, assessed visually, showed a lognormal shape and was confirmed by testing the logarithm of the data for normality (Shapiro-Wilk test). In view of this, we employed a Generalized Linear Mixed Model using the *Template Model Builder* (glmmTMB) R package (Brooks et al., 2017) to implement the zero inflated data modelling (Brooks et al., 2017), which is also suggested in Pesendorfer et al. (2019).

The response variable *dead stumps* was modelled using coppicing season (*season*), sampling time (*time*), experimental site (*site*), total number of stumps (*total stumps*), and as a random effect, sampling plot (*area*) as response variables. The zero-inflation model was implemented according to the sampling time (*time*) variable.

$$\begin{gathered} glmmTMB \\ (dead\ stumps \sim season * site + season * time + total\ stumps + (1|site/area), \\ zi = \sim time, \\ \text{family} = \ \text{log}\ normal) \end{gathered} \tag{1}$$

Shoot growth and mortality were assessed by observing the shoot distribution of frequency in the defined size classes. Two separate analyses were performed, the first addressed shoot growth considering only living non-damaged shoots (Eq. 2), while the second focused on shoot mortality considering only dead shoots (Eq. 3).

Shoot number distribution was assessed visually and by means of the ‘descdist’ function of the package *fitdistrplus* (Delignette-Muller and Dutang, 2015). Since the sampling approach included a fixed grid of several categories (shoot vitality and class size) where the absence of shoots was indicated as zero, the shoot number distribution followed the typical count pattern, exhibiting an extremely skewed distribution (skewness > 4) and an excess of zeros. For these reasons, models to predict shoot number were employed as well as the glmmTMB, while the model family was chosen accounting for the great difference between mean and variance of the shoot number, which led towards a Generalized Poisson distribution for both shoot growth and shoot mortality models. The chosen family, differing from the strict Poisson distribution, helped in handling the overdispersion of the residuals.

We modelled the response variable ‘shoots number’ according to the following variables: coppicing season, sampling time, experimental site, shoot height class (*size class*), total number of stems per stump before treatment (*stems pre*), basal area ratio between dead and total stems at stump scale before treatment (*dead-to-total stem BA*), and, as random effect, sampling plot. In addition, the shoot mortality model included the total number of living shoots, both damaged and not damaged, for each size class (*shoot alive*).

$$\begin{gathered} \text{glmmTMB} \\ (alive\ shoots\ nr \sim season * time * site + season * size\ class + time * size\ class \\ + stems\ pre + dead - to - total\ stemBA + (1|site/area), \\ zi = \sim 1, \\ \text{family} = GeneralizedPoisson) \end{gathered} \tag{2}$$

$$\begin{gathered} \text{glmmTMB} \\ (dead\ shoots\ nr \sim season * time + season * size\ class + season * site + stems\ pre \\ + dead - to - totalstem\ BA + shoot\ alive + (1|site/area), \\ zi = \sim 1, \\ \text{family} = Generalized\ Poisson) \end{gathered} \tag{3}$$

Additionally, shoot growth was investigated by analyzing the maximum heights reached by each stump towards the season and experimental site. This analysis was split into two sub-analyses, one targeted the mean max height (*MMH*), defined as the mean of the five highest living shoots of each stump (Eq. 4), while the other targeted the absolute max height (*AMH*), defined as the height of the highest shoot of each stump (Eq. 5).

The MMH and the AMH were modelled similarly to previous models. GlmmTMB was used to model predicting variables, employing the Tweedie family, after testing the response variable distribution. In both models, the chosen variables were: coppicing season, sampling time, and ratio between damaged and total shoots (*shoot ratio*), and, as random effect, sampling plot.

$$\begin{gathered} \text{glmmTMB} \\ (MMH \sim time * season + shoot\ ratio + (1|site/area), \\ \text{family} = tweedie) \end{gathered} \tag{4}$$

$$\begin{gathered} \text{glmmTMB} \\ (AMH \sim time * season + shoot\ ratio + (1|site/area), \\ \text{family} = tweedie) \end{gathered} \tag{5}$$

The models employed were tested for independence and uniformity of the residuals with the *Performance* package (Lüdecke et al., 2021). This package was used also to test for collinearity of the same model with and without interactions. In addition, a test on outliers distribution was run with the function ‘testOutliers’ from the *DHARMa* package (Hartig, 2024), specifically set to type ‘bootstrap’ to avoid type I inflated error. In the stumps mortality and shoot growth and mortality models, the AIC score confirmed the need for the zero-inflation term, and by means of the ‘check_zeroinflation’ function (*Performance* package), we evaluated if the model was correctly accounting for the excess of zeros. Test metrics are reported in the supplementary material (Appendix B).

To establish the effect of the season and the site as fixed effect, we employed the ‘estimate means’ function from the *modelbased* R package (Makowski et al., 2020). Afterwards, we verified the significance of season and site in combination with the sampling time through the ‘estimate contrasts’ function (*modelbased* package). In order to account for the multiple comparisons assessment, p-values were adjusted with the Bonferroni method. In addition, the same functions were employed to assess the effect and the significance of the interaction between season, sampling time, site, and size class of living shoots and dead shoots (Table A.3, Table A.4). The 'estimate contrast' function was also used to test the interaction between season, sampling time, and site of stump mortality (Table A.2) and between season and sampling time in height analysis (Table A.5, Table A.6).

At the time of sampling, shoots were assigned a category according to their health status, namely damaged or non-damaged. Differently from living non-damaged shoots, damaged shoots constituted a minor part of our observations, mainly relevant in the first year after the treatment (Appendix A - Table A.7) and they were visually assessed through a histogram divided by size class (Fig. A.1).

All analyses were performed with *R* software (version 4.3.2).

3. Results

3.1. Pre-treatment

The pre-treatment analysis confirmed that both sites are dominated by coppiced chestnuts - 90 % in Voltaggio and 99 % in Cairo in terms of density. Full species composition is detailed in the supplementary materials (Table A.1). Table 2 presents the dendrometric characteristics of the chestnut stands, with a mean square diameter of 24 cm (range: 8–52 cm) and an average stem height of 16.4 m (range: 5.4–26.9 m). Dead stems accounted for 36 % of total stem density and 15.6 % of total volume.

Table 2
Summarizing table of stands average dendrometric characteristics before treatment. Reported data refers to chestnut only.

		Voltaggio		Cairo		Average	
Parameter	m.u.	value	s.e.	value	s.e.	value	s.e.
Stem density (total)	n ha^{-1}	1157	135	1743	99	1450	108
Stem density (alive)	n ha^{-1}	767	72	1021	44	894	51
Stem density (dead)	n ha^{-1}	390	79	722	67	556	64
Stem density (dead/tot ratio)	n ha^{-1}	31.2	4.2	41.1	1.6	36.1	2.5
Stool density (total)	n ha^{-1}	398	45	380	15	389	23
Stool density (alive)	n ha^{-1}	361	45.2	354	15.5	339	22.1
Stool density (dead)	n ha^{-1}	398	45	380	15	389	23
Stool density (dead/tot ratio)	%	18.5	4.4	7.7	1.9	13.4	2.8
Basal area (total)	m^2 ha^{-1}	46.5	3.3	47.2	2.1	46.9	1.9
Basal area (alive)	m^2 ha^{-1}	38.8	2.8	38.4	1.8	38.6	1.6
Basal area (dead)	m^2 ha^{-1}	7.5	1.5	8.9	0.8	8.3	0.8
Basal area (dead/tot ratio)	%	16.1	3.1	18.8	1.2	17.4	1.6
Stem height (mean)	m	16.3	0.4	16.4	0.4	16.4	0.3
Stem height (max)	m	17.4	0.8	17.4	0.4	26.9	-
Mean square diameter	cm	26	1	22	1	24	1
Volume (total)	m^3 ha^{-1}	372.3	23.9	373	21.7	372.7	15.7
Volume (alive)	m^3 ha^{-1}	316.8	21.4	311.1	19.8	314	14.2
Volume (dead)	m^3 ha^{-1}	55.5	11.2	61.9	5	58.7	6
Volume (dead/tot ratio)	%	14.5	2.9	16.7	1.2	15.6	1.5

3.2. Post-treatment

3.2.1. Stumps mortality assessment

Stump mortality results are reported in Table 3 and Table A.2. The first presents the trend in stump mortality across seasons and sampling times, while the second summarizes the results of the 'estimate contrast' function on differences significance among treatments with regards to time since cutting and experimental site. In Cairo, significant differences were found both between seasons and between sampling times. Indeed, stump mortality peaked immediately after the cutting (t1), with a significantly higher mortality rate in the summer cut than in the spring cut ($p < 0.01$). After the second growing season, the mortality rate dropped to near pre-cutting levels, with a significantly higher mortality in summer than in winter ($p < 0.05$) and spring ($p < 0.001$). Finally, it increased again at t3, but remained below the rate of the first year, and significant differences were found between all seasons (winter-summer $p < 0.001$, winter-spring $p < 0.05$, spring-summer $p < 0.001$), again with summer showing the lowest mortality rate, followed by spring, and winter performing the worst.

In Voltaggio, no significant differences were reported between sampling time and season, except for the lower mortality rate reported in the summer cut when compared to the spring cut ($p < 0.05$) at t3.

3.2.2. Shoots growth assessment

Fig. 2 reports the estimated mean number of living non-damaged shoots as a function of the cutting season (left) and the experimental site (right) through time, showing differences among them (asterisks indicate the differences in significance, while the lines below link the compared records). The cutting season showed significant differences between treatments. At t1, winter cut stumps resulted in the highest mean number of resprouts and summer the lowest, with all differences between seasons being highly significant ($p < 0.001$). Such a trend was inverted from the second vegetative season, with only summer and winter being significantly different ($p < 0.05$ and $p < 0.001$ at t2 and t3, respectively). Conversely, looking at the right plot, no significant differences are observable, meaning that site is not a key variable in conditioning the shoot growth in the short term.

Season and site were not enough to fully explain shoot growth, and for this reason we used a more complex model accounting for multiple variables (Eq.2) to evaluate it. Modeled results are reported in Fig. 3, showing the comparison of the mean number of living non-damaged shoots per stump by height class between the three coppicing seasons, sampling times, and sites. Detailed results of the 'estimate contrast'

Table 3
Summarising table of stump mortality expressed as the ratio between dead and total experimental stumps with regards to coppicing season, time since cutting, and experimental site.

		Dead to total stump ratio (%)	
Season	Sampling time	Cairo	Voltaggio
Winter	t0	9.5	17.8
	t1	13.3	8.1
	t2	8.2	12.8
	t3	12.9	15.1
Spring	t0	5.8	13.2
	t1	10.9	10.3
	t2	6.1	10.3
	t3	10.5	14.3
Summer	t0	5.4	11.1
	t1	13.1	16.2
	t2	5.6	8.2
	t3	6.7	9.2

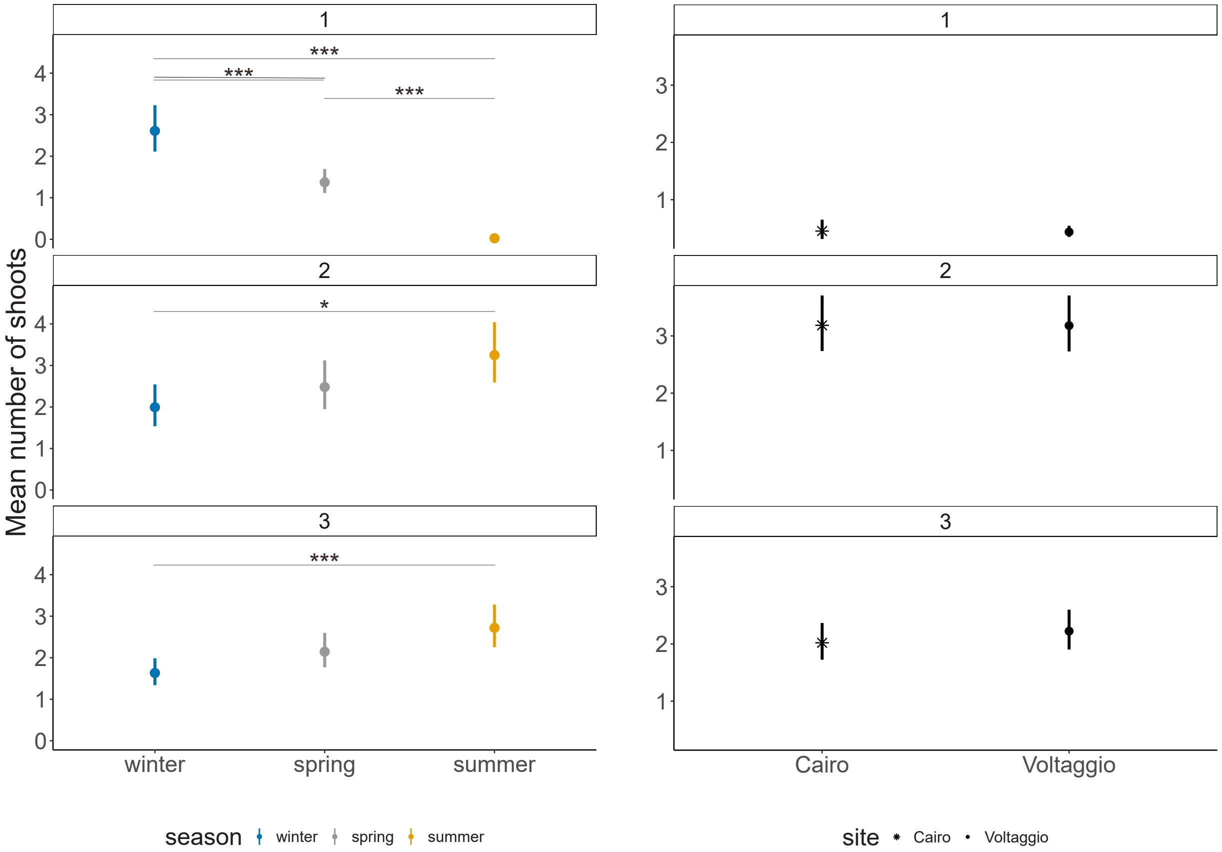

Fig. 2. Confidence interval plot used to evaluate the significance of seasonal differences (on the left) and site differences (on the right) on the number of living sprouts with regards to time since cutting (coppicing t0: 2021 - resprouts monitoring t1: 2022, t2: 2023, t3: 2024). In both plots differences significance is expressed with asterisks - *** highly significant ($p < 0.001$); ** moderately significant ($p < 0.01$); * slightly significant ($p < 0.05$). Only significant differences are reported. Where confidence bars overlap the differences are not significant. The horizontal lines below the asterisks link the compared elements.

function used to check for differences in significance are reported in Table A.3.

Results clearly show a change in the pattern of mean living shoot number from the first to the third year. After the first vegetative season (t1) no shoots exceeded the 200 cm size class. Winter-cut stumps, at both sites, showed the greatest shoot growth resulting in a higher mean number of shoots at the higher size classes with no statistically significant difference between sites. Spring, on the contrary, showed a marked difference between the sites, with Voltaggio being more productive but shorter in height. Consequently, in Voltaggio winter and spring cuts were always statistically different over time. Summer plots were always significantly different from the other tested seasons. The limited length of the growing season allowed for a shorter growth period compared to winter and spring cutting, but it was the grazing to play a key role at this stage. Indeed, 95.7 % of the total number of summer shoots were found to be damaged by apical browsing. In Fig. A.1 the distribution of frequency of grazed shoots per size class and time is reported (site was not significant, hence no distinction has been made).

From the second year onward the browsing impact already decreased drastically. Summer plots were still the most affected, but not as heavily as after the first year. This is also reflected by the distribution of the mean shoot number which shows a more similar trend among seasons. Winter distribution keeps being shifted toward higher size classes more than spring and summer (statistically different from spring and summer in class 400 at both sites) but with smoother differences (different from spring and summer only in Voltaggio in class 300). Despite the great recovery shown by the summer plots, significant differences still exist, with a higher number of shoots in the smaller size class than in the winter and spring seasons.

After the third vegetative season, seasonal shoot distributions assumed trends very alike one to each other, and almost no differences between sites were observed. Shoots reached and exceeded class 400 only in winter-cut stumps, but almost no statistical differences were observed in classes 300 and 400. In classes from 25 to 200, winter showed a lower mean shoot number compared to spring and summer, resulting in being generally significantly different from them.

3.2.2.1. *Shoots growth assessment by maximum heights.*

Shoot maximum height analysis (Fig. 4) showed that winter-cut stumps reached the highest height at any time, both as AMH and MMH regardless of the site. Spring AMH showed an almost constant absolute delta compared to winter ones (+70 cm on average), which, considering shoot growth, corresponds to a relative reduction of height difference, from + 95 % to + 21 % on average. Summer heights, instead, showed a strong increase from the first to the second vegetative season (+640 % on average), almost halving the absolute gap with winter shoots (from 130 cm to 70 cm) and nullifying the gap with spring heights, eventually surpassing them in Voltaggio. Within both sites the difference between the AMH and the MMH increased through time.

Detailed results of the ‘estimate contrast’ function used to check for differences in significance are reported in Table A.5 and Table A.6.

3.2.3. *Shoots mortality assessment*

To fully evaluate the effects of different coppicing seasons on chestnut resprouting capacity, we also observed shoot mortality. The analysis process via the ‘estimate means’ function (Eq.3) was analogous to what had been applied for the living shoots (Eq.2). Results are graphically reported in the supplementary materials, Fig. A.2, along with the table reporting the ‘estimate contrast’ function results

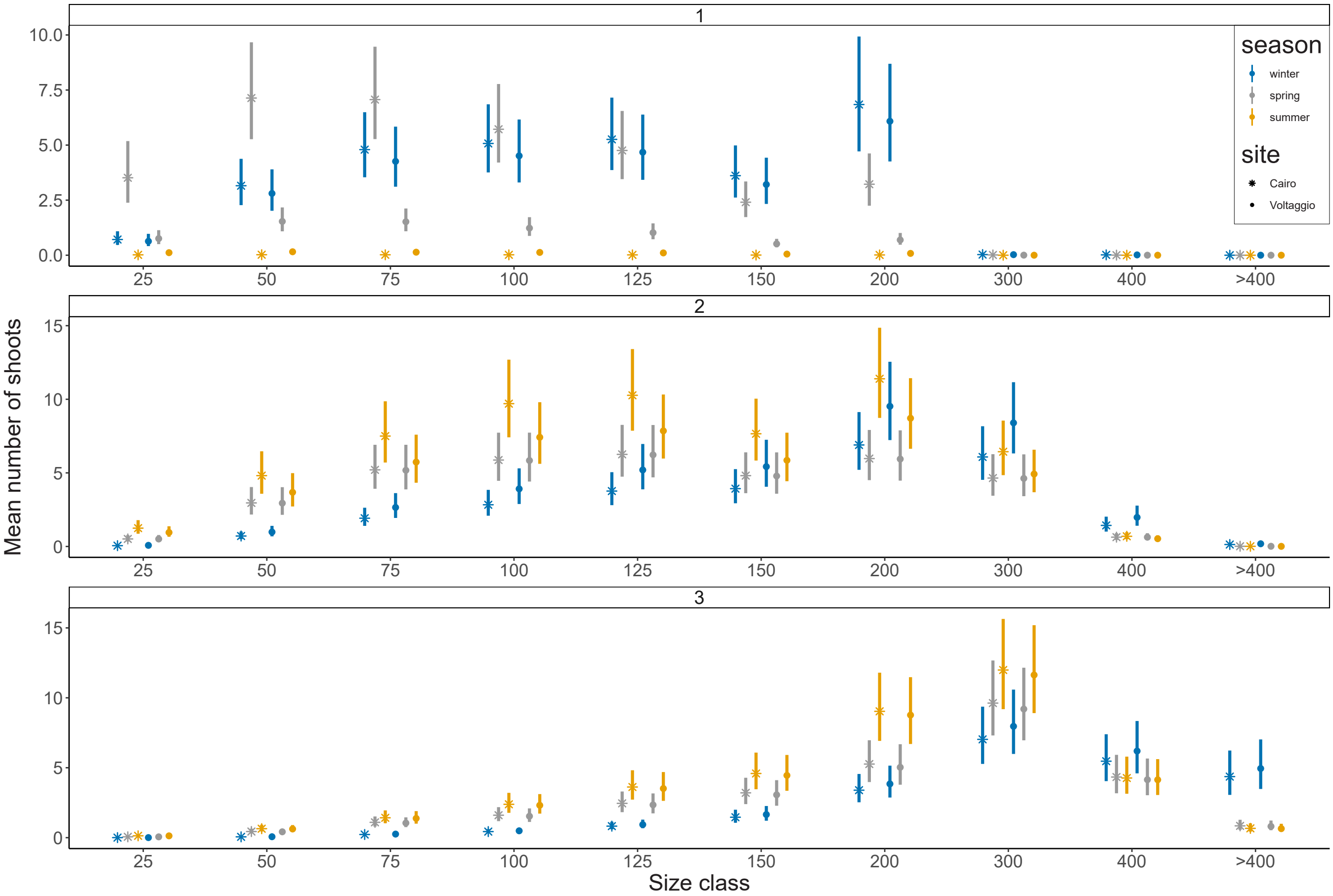

Fig. 3. Confidence interval plot used to evaluate differences significance among coppicing seasons (winter, spring, and summer) on living, non-damaged shoot number per size class (shoots height in cm) with regards to time since cutting (coppicing t0: 2021 - resprouts monitoring t1: 2022, t2: 2023, t3: 2024) and experimental site (dot: Cairo Montenotte and asterisk: Voltaggio). Ordinates axis "Mean number of shoots" refers to the estimated marginal means of the number of shoots per size class. Where confidence bars overlap the differences are not significant. To help with reading the plot we reported the detailed results of the 'estimate contrast' function used to check to check for significant differences between seasons in the Supplementary materials (Table A.3).

(Table A.4) expliciting difference in significance between the tested seasons over time and site.

Shoot mortality showed the highest sensitivity to the coppicing season one year after the cut, with summer differing significantly from winter and spring across all size classes. Conversely, winter and spring were statistically different only in size class 25 ($p < 0.001$ in Cairo, and $p < 0.5$ in Voltaggio).

After the second growing season, all the treatments showed the same distribution. As grazing pressure decreased (Table A.7 and Fig. A.1), summer mortality aligned with the overall trend, and seasonal differences became minimal. In Cairo, only class 25 reported a significant difference, with winter mortality being higher than spring ($p < 0.01$). In Voltaggio, classes 200 and 300 displayed significantly higher winter mortality compared to summer ($p < 0.01$) and spring ($p < 0.05$).

After the third growing season, summer mortality rate increased, though, given the high variability observed, this increase was mostly non-significant. Still, a few seasonal differences were observed. In Cairo, winter cut plots showed a mean number of dead shoots in class 25 to be significantly lower when compared to summer ($p < 0.001$) and spring ($p < 0.01$). Also in Voltaggio, in class 25, winter reported a significantly lower number of dead shoots than spring ($p < 0.05$). In Cairo, winter mortality resulted in a significantly lower number of dead shoots than in summer in classes 50 and 100 ($p < 0.01$ and $p < 0.05$, respectively), while in the other size classes, differences among coppicing seasons were non-significant. In Voltaggio, on the contrary, winter mortality was higher than spring, in classes 200 and 300 ($p < 0.05$ in both cases).

Regardless of the season and site, dead shoots were observed in all sampled classes, with the highest occurrence over time in the 50, 75, and 100 cm classes.

4. Discussions

In this study, we discussed new modalities of chestnut coppice management and tested the feasibility of year-round cutting beyond the traditional dormant season to amend the current abandonment status and mitigate the potential negative effects of climate change in these historical forest landscapes.

4.1. Stump mortality

Stump mortality results showed that chestnuts could withstand cutting throughout the year, confirming the strong and lasting resprouting capacity of chestnut trees and supporting the findings of Giudici and Zingg (2005). Within all treatments, excluding Voltaggio's spring which remained constant, stump mortality rates showed a fluctuation, with maximum values at t1, minimum at t2, and intermediate at t3. Indeed, we observed that about one-third of living stumps that did not resprout immediately after the treatment managed to resprout after the second growing season. Such a result is in line with previous studies that showed how stumps can retain their resources until the next vegetative season (Lust and Mohammady, 1973; Pyttel et al., 2013; Matula et al., 2019). Moreover, stump mortality results showed a few significant differences between coppicing seasons, especially in Cairo, with summer being significantly different from spring (t1, t2, t3) and winter (t3).

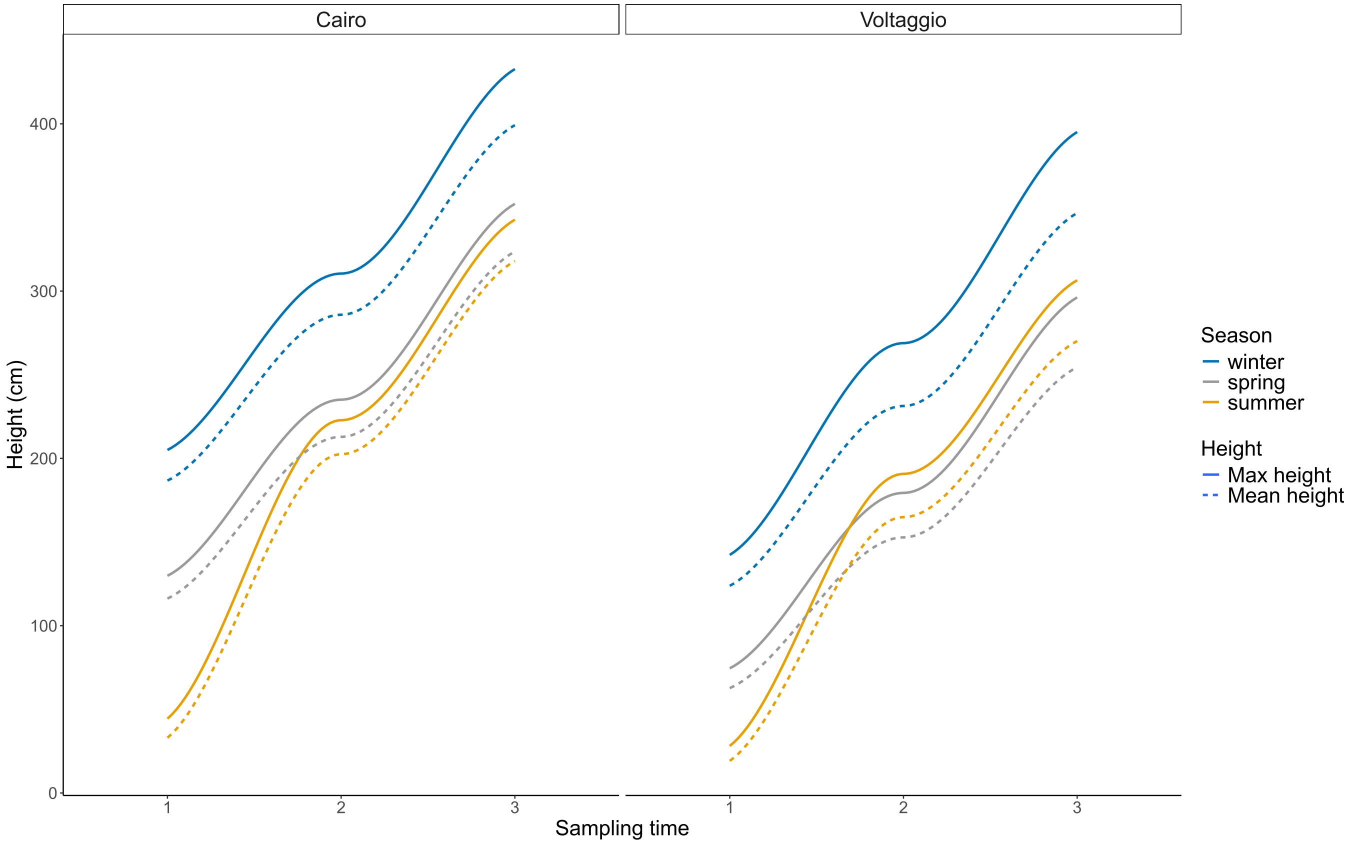

Fig. 4. Plot assessing living shoot's maximum heights as a function of the coppicing season (winter, spring, and summer), the sampling time (years from cutting: 1, 2 and 3), and the experimental site (Cairo Montenotte, and Voltaggio). Solid lines refer to absolute max heights (AMH), while dotted lines refer to mean max heights (MMH).

Interestingly, summer generally displayed significantly lower mortality rates compared to the other treatments, supporting our hypothesis that current cutting season restriction is ecologically superfluous.

A final consideration goes to the worksite management. During the field sampling, we observed a few stumps being damaged by tree felling, log handling, opening of temporary tracks, or buried by log piles. This issue suggests that, aside from the ecological aspects of the species, worksite management could play an important role in defining the success of stand regeneration (De Souza et al., 2016; Spinelli et al., 2017).

4.2. Shoot growth

The overall shoot frequency distribution across size classes over time followed the expected trend connected to natural competition dynamics of self-thinning (Westoby, 1984), with shoot density shifting from the lower size classes to the higher ones. Our first analysis targeting season and site effects on shoot growth as individual predictors showed no significant differences among sites and only a few between seasons (Fig. 2), which leaves a lot of the variance unexplained. Seasonal differences were highly significant at t1, with winter showing the highest resprouting vigor (number of living undamaged shoots and maximum heights), followed by spring. In contrast, summer exhibited the weakest performance at t1. Interestingly, this trend reversed by t2 and remained consistent at t3.

A notable feature of summer plots was the extreme peak of damaged shoots, which were grazed to heights below 25 cm (Fig. A.1). Previous studies (i.e. Cutini et al., 2011; Bottero et al., 2022) showed that sprouts or fresh saplings that are generated at the end of the vegetative season are more exposed to winter browsing. In fact, during winter, when grass availability decreases due to grass curing and snow cover, young and fresh shoots with low stem lignification and limited height (< 1.5 m, below "escape size"), as those from summer-cut stumps, become appetible and vulnerable to ungulate browsing (Kay, 1993; Ascoli et al., 2013). We did not anticipate such a high incidence of browsing on new shoots, so we did not establish fenced control plots to assess and quantify browsing damage accurately. However, our observations (Fig. A.1) indicate a decrease in browsing intensity after the second vegetative season. This trend aligns with findings from Bottero et al. (2022), whose browsing-specific study showed that browsing damage continues to decline over time, becoming negligible after a few years.

As observed in previous studies on coppicing season effects (e.g. Hytönen, 1994), shoots from winter-treated areas consistently showed higher AMH and MMH at each sampling time compared to spring and summer treatments. Such a result is attributable to the longer, first vegetative season. However, these differences shrunk over time, especially between spring and summer treatments, which became almost alike after the second vegetative season, reducing the gap with the winter-treated areas. This trend suggests a potential full offset in a few years (Ciancio and Nocentini, 2004; Bottero et al., 2022). Additionally, both analyses, shoot size class distribution and heights per sampling time, indicated that summer-treated stumps managed to recover from the browsing by the second and third years, with summer shoot height increases outpacing those of winter and spring treatments.

4.3. Shoot mortality

Ciancio and Nocentini (2004) stated that a higher shoot emission corresponds to a major mortality rate. This statement is supported by natural competition dynamics (Lowell et al., 1989; Giudici and Zingg,

2005) and by the fact that root reserves and soil nutrient availability (Ranger and Colin-Belgrand, 1996; Vergani et al., 2017) act as limiting factors for the number of shoots a stump can sustain. Our observations of both shoot production and mortality further confirm this statement. Indeed, if on the one hand, after the first vegetative season, winter and spring-treated areas showed a major number of living shoots, on the other hand, they also showed a greater mortality rate when compared to summer. Moving the focus to t2 and t3, dead shoot distribution followed natural competition dynamics for which, over time, small shoots lose the competition for light and resources to taller and more vigorous shoots (Lowell et al., 1989; Giudici and Zingg, 2005). Furthermore, as the majority of the shoots grow in height and lignification, ungulate browsing focuses on those remaining below the escape size (Ascoli et al., 2013), favoring the process of shoot selection (Bottero et al., 2022).

Finally, our results showed that the coppicing season did not result in significant differences in shoot mortality (Fig. A.2), and most importantly, summer treatment did not result in a higher mortality rate compared to the winter cutting that is currently allowed by forest regulations (DPGR 4/R, 2015 for Piedmont and RR 1/1999 for Liguria).

4.4. *Future perspectives*

Due to the significant role that chestnut forests played in the past (Conedera and Krebs, 2008), humans replaced many native forests with monospecific chestnut forests, extending their range beyond their original ecological niche (Pitte, 1987; Conedera et al., 2001; Krebs et al., 2022) (Bernetti, 1995). As a result, other species, including alien species (e.g. *Robinia pseudoacacia* L., *Ailanthus altissima* (Mill.) Swingle), might take advantage of the coppicing abandonment by entering the stand and progressively outcompeting chestnuts (Fonti et al., 2006; Motta et al., 2009; Benesperi et al., 2012; Campagnaro et al., 2023).

For this reason, along with the "future-proofness" observations reported by Conedera et al. (2021), we can infer that chestnut forests need continuous management to preserve their condition as they experience significant changes in structure and functionality when neglected (Marcolin et al., 2020), especially in a global change scenario (Conedera et al., 2021). In this regard, our findings confirmed chestnut's strong resprouting capacity (Piccioli, 1922; Piussi, 1994; Giudici and Zingg, 2005) and showed that cutting season has no significant impact on stump mortality, shoot growth, or mortality. Therefore, we advocate for the active management of chestnut coppice stands to favor land maintenance and guide forest adaptation to global changing environmental conditions, ensuring the preservation of their ecological, protective, productive, cultural, and recreational functions. However, we have to point out that while chestnuts may withstand year-round coppicing from an ecological perspective, the impact of coppicing during the vegetative season on wood technological quality (stem cracks and ring shake) is still poorly studied (Macchioni and Pividori, 1996; Fonti et al., 2002; Spina and Romagnoli, 2010; Marini et al., 2021).

5. Conclusions

This study shows the potential for adaptive management of chestnut coppices under changing conditions, supporting the idea of year-round cutting as a viable strategy, confirming the great Sweet chestnut resprouting ability, and showing that different coppicing seasons do not affect stump mortality, shoot growth, or mortality.

In most Italian regions, including Piedmont and Liguria, the coppicing season is limited to the vegetative resting season. This regulation is a heritage of traditional knowledge not supported by scientific evidence and of former social restrictions (e.g. the gentries and landlords need for workers during the growing season). The briefness of the current cutting period causes problems in the continuity of wood supply to the sawmills and to the tannin factories that have to store large amounts of wood in the square storage area with related fire and environmental risks. At the same time, local rural communities require better forest work distribution around the year.

Our results revealed only minor differences among the treatments due to the different lengths of the growing season immediately following cutting. These differences are likely to become negligible within a few years, especially as rotation periods continue to lengthen to favor larger and more valuable wood assortment. Moreover, our experiment was carried out during the driest period (2021–2023) observed in southern Piedmont in the last century (ARPA Piemonte, 2023), suggesting that, despite chestnut drought sensitivity, coppicing outside the traditional season does not have major effects on its resprouting capacity, nor on stump and shoot mortality.

There are, however, a few shortcomings that arise from summer cutting that might require future studies to deepen the understanding. Coppicing during the vegetative season can lead to several ecosystem disruptions. First, it may interfere with fauna reproductive activities, and second, tree felling and log handling often damage the remaining trees and their regeneration. Indeed, in many protected areas and Natura 2000 sites, cutting during the nesting season is prohibited. Additionally, forest workers have also reported challenges, such as major complexity in the preparation and management of the work site, difficulties working in woods with full crowns, the depreciation of leafy tree scraps intended for wood chips, and increasing summer temperatures.

In conclusion, the results presented in this study apply to submontane and montane chestnut coppices in warm, temperate, and moist areas, showing, from an ecological perspective, the feasibility of a year-round cutting system. However, due to the limited number of experimental sites, further studies are advisable to deepen the understanding of the influence of site-specific conditions on stump mortality and shoot growth and to generalize these findings to other climatic zones.

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CRediT authorship contribution statement

Bono Alessia: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Resente Giulia:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Musio Luca:** Writing – review & editing, Methodology, Investigation. **Berretti Roberta:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization. **Ascoli Davide:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Camerano Paolo:** Writing – review & editing, Validation, Project administration, Investigation, Funding acquisition, Conceptualization. **Terzuolo Pier Giorgio:** Writing – review & editing, Validation, Funding acquisition, Conceptualization. **Motta Renzo:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Vecchio Davide:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Renzo Motta reports financial support was provided by Piedmont Region. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122610.

Data availability

Raw data are available at this link: https://doi.org/10.5281/zenodo.14442132

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