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Valorizzazione del legno di castagno provenienti dai diradamenti di boschi cedui. Studio di prodotti innovativi incollati per applicazioni outdoor.

Exploitation of chestnut wood from thinning of coppice stands. Study of innovative products for outdoor applications.

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Short Abstract

The study wish to exploit as much as possible chestnut wood coming from coppice stands. The study has been divided in four parts. The first part is a long state of art on the distribution of the species in Italy and the actual main uses. In general chestnut potentialities are quite good because it covers in Italy about 7.5% of national forest surface. In some districts, especially in central-southern regions, chestnut is the only driver of sawmill economy. The use is mainly in solid beams for load bearing structures and poles. In the field of load bearing structures, research and innovation have obtained quite good results, because the species is integrated in some European standards. The most important limit in the forest chain is due to the forest management which is coppice and for this reason the size of the assortments is often small reducing many opportunities to have high value products. There is the need to boost innovation looking to the most important strengths of the species which are natural durability and the chance to extract from the biomass valuable chemical components like tannins. The study area was located in Monte Amiata in 5 coppice stands, different in some characters and dendrometric parameters (stool/ha, shoots/stump etc.). In the second part of the work it was taken into account the threat of climatic changes and the role of silviculture, looking if the actual silviculture will be able to guarantee the necessary resilience of the species to the actual climatic changes. The study was carried out by means of dendrochronology and isotopic content. The obtained results of stable isotopes shows that stands were sensitive to minimum temperature, especially in March and April, with a positive effect on WUEi and the stand with the highest competition between shoots and between stumps was the most sensitive to climate parameters, testified by an increase in WUEi. The third part of the investigation has considered the effect of stand characters affected by forest management on the main wood physical, mechanical and chemical parameters (density, shrinkages, compression and MOR). It has been showed as in chestnut stands, physical and mechanical wood properties seem more related to individual behaviour than to stand features, even if moderately positive correlation between the number of stools per hectare and wood density, along with a negative correlation of shoot height and diameter with density were founded. In the fourth part the assortments coming from coppice were glued using a mixture of two adhesives, polyvinyl acetate (PVAc) and melamine-urea-formaldehyde (MUF) with cellulose nanocrystals (CNC) and tannins. The aim is to promote innovative composites made by small assortments and with a more natural aspect. The results have shown as the addition of CNC to PVAc, increase the shear tensile strength and the strength after the aging cycle of wetting and wood drying. By the promising results in dry ambience it seems also possible to test in the future the substitution of urea in the formulation of MUF adhesives and in synthetic polyvinylacetate with CNC or CNC and Tannin. Unfortunately these bio-based additives for wet test do not reveal the same encouraging results.

Keywords: dendrochronology, isotopes, water-use efficiency, chestnut tree physiology, wood quality, adhesives, CNC, MUF, tannin, adhesives, glues, low sized timber, sustainability, chestnut resilience.

Extended abstract

Exploitation of chestnut wood from thinning of coppice stands.

Study of innovative products for outdoor applications.

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The doctoral thesis research project aims to exploit chestnut wood from thinning of chestnut (*Castanea sativa* Mill.) coppice stands. Especially first thinning is rarely performed because not convenient by the economic point of view and the final product has no demand in the current market. The aim is to enhance this resource, starting from the role of wood as environmental bioindicator (relating mainly to the competition in the stand) and looking for innovative glued products glued for outdoors applications, exploiting the natural durability of the species.

Valorizzazione del legno di castagno provenienti dai diradamenti di boschi cedui. Studio di prodotti innovativi incollati per applicazioni outdoor.

Questo progetto di tesi di dottorato mira a valorizzare il legno di castagno proveniente dal primo diradamento del bosco ceduo. In modo particolare i primi diradamenti risultano ad oggi pratica poco applicata perché poco vantaggiosi sotto il profilo economico, in quanto il prodotto che se ne ricava non ha attualmente domanda di mercato. L'obiettivo prefissato è quello di valorizzare questa risorsa, partendo dal ruolo del legno come bioindicatore ambientale, soprattutto considerando la competizione all'interno del soprassuolo e le possibili pratiche selvicolturali. Inoltre sono esplorati impieghi del legno con prodotti innovativi incollati per applicazioni all'esterno, riuscendo così a sfruttare la durabilità naturale della specie.

Key words: Chestnut forest-chain, wood-glued, first thinning, wood quality.

In agreement with PhD thesis project previously described (Marini, 2017), this document reports the main results of activities concerning:

Phase 1 Dendrometric characterization of forests area in Amiata mountains chestnut coppices (Field measurement and thinning test). Effect of Environment and stand competition on growth and wood quality.

Phase 2 Physical and mechanical characterization of chestnut wood of shoots from the first thinning.

Phase 4. Bonding test, mechanical test, delamination tests.

Phase 5. Correlation with dendrometric characters.

In addition to planned activities reported in Marini (2017) *PhD Dissertation Project* (PhDDP), fundamentals and innovative activities were realized:

- Stable isotope content of $\delta^{13}C$ and $\delta^{18}O$ of tree rings were measured
- To investigate morphology of glue line on 7 different application with scanning electron microscopy (SEM) analysis was carried out.
- FT-IR spectrometers (Fourier Transform Infrared Analysis) of wood samples
- Py GC-MS analysis of pyrolysis coupled to a gas chromatograph–mass spectrometer system (Py-GC/MS) allowed to characterize the structure of chestnut

The paper wish to make a summary on the state of the art of silviculture and wood use of sweet chestnut (*Castanea sativa* Mill.) species in Italy with its strengths and weakness. The main wood quality defects which limit the use of species for many other wood products are listed. In order to boost the chain it is mandatory to make efforts for a more versatility in use, that means to be care of the management system and to obtain stems available for different final products. A list of possible actions are considered in order to boost the use of the target species, which is one of the best opportunity to develop the short supply chain. The second aim was to check the responses of chestnut trees to climate conditions and the role of stand structure and management. Correlations with climate parameters were investigated and principal component analysis was performed using as variables site-characteristics and tree growth parameters. Moreover we studied how site conditions and forest management affect dendrometric parameters of young shoots of chestnut (*Castanea sativa* Mill.) coppices and verifying these relationships in five study areas.

Study area

The study was conducted on Monte Amiata, a lava dome located in the Province of Siena, Tuscany, central Italy, with an altitude between 990 and 1145 m a.s.l. (Fig. 1) The site is characterised by medium to high fertility due to the volcanic matrix of the soils. The parent material is a trachyte lava with a high silicate content and poor in basis; the slope is generally gentle but a few outcrops are present; erosion and landslides are absent. Brown and sub-acid soils of good physical structure are prevalent. According to the map of the Tuscany soil (http://sit.lamma.rete.toscana.it/websuoli/), the soil is *Andic Dystrudepts coarse-loamy, siliceous, mesic, deep, very soft, non-gravelly, well drained.*

Monte Amiata is an important area for chestnut cultivation in Italy, because of the high growing stock and the economic relevance of wood and fruit production for local communities. Chestnut forests cover 7'500 ha in Monte Amiata, with half the area (3'500 ha) managed for wood production under public ownership. The forests are located mainly in the eastern side of the region at 800 to 1200 m a.s.l. Chestnut forests tend to be monospecific and are of anthropic origin; secondary species are rare or absent. The study was carried out on five different stands, in young chestnut coppices of about 12–15 years old: they are: Cipriana (C1), Sant'Antonio (A2, A3), Le Decine (D4) and Acquagialla (G5). The main dendrometric parameters were measured on five representative circular sampling areas, with a ray of 15 m: number of stumps, number of shoots, diameter at breast height (DBH), height of shoots, number with their respective diameters and heights of standards were measured. From a dendrometric point of view, areas differs each others by slope, stumps and shoots per hectar.

Chestnut forest owners usually apply rotation ages (from 16 up to 22 years), one thinning is carried out usually at 12-14 years.

Materials and Methods

Physical and mechanical wood properties

Fifteen shoots were selected and cut on each stand. From each shoots, sample logs of 40 cm length were taken. The samples were then conditioned at the temperature of 20±2 °C and at 65±5% relative humidity until the boards reached an equilibrium moisture content of roughly 12%. Then test specimens were cut from these rough boards with the dimensions of 20×20×30 mm. For each stand total shrinkage (βV) and wood density at 12% Moisture ($\rho 12$), were measured. The specimens were soaked in distilled water for 72 h to ensure that their moisture content was above the fiber saturation point. Then their dimensions were measured in the three principal directions with a digital caliper to the nearest 0.001 mm. Specimens were weighed to the nearest 0.001 g for saturated weight and the saturated volume was calculated based on these dimension measurements. Finally, the samples were oven-dried at 103 ± 2 °C to 0% moisture content. The prepared samples were then conditioned at the temperature of 20±2 °C and at 65±5% relative humidity until the specimens reached an equilibrium moisture content of about 12%. By the original board, a sample of 50x50x20 mm according to UNI EN 1534 was cut in order to measure hardness by the Brinell method. According to UNI ISO 3787 specimen of 20x20x30 mm were prepared in order to calculate compressive strength ($\sigma 12$), and UNI ISO 3133, samples of 20 x 20 x 300 mm, for measure bending strength (MOR). Samples were cut one for each shoot and they were localized at an estimated age of 11-14 years.

Dendro-isotopic analysis

In each of the five selected areas, five disks were selected that showed the best correlation with the average TRW of that area. In order to carry out the isotopic measurements, in the five trees from each area, the annual growth rings formed in 2004–2016 were separated from each other. After weighing them, the samples were ground in a hammer mill (MF 10 basic Microfine grinder drive, IKA Werke), using a mesh size of 0.5 mm to ensure homogeneity. The $\delta^{13}C$ and $\delta^{18}O$ stable isotope compositions were measured at the IRMS Laboratory of the University of Campania "Luigi Vanvitelli", following standard procedures (Battipaglia *et al*. 2017). The analysis of carbon stable isotopes in rings is a powerful tool for the annual estimation of WUEi given that the $\delta^{13}C$ value reflects the ci/ca ratio, where ci is the partial pressure of CO2 in leaf intracellular space and ca is the partial pressure of CO2 in the atmosphere (Farquhar *et al*. 1982; Battipaglia *et al*. 2017). Indeed for the further processing, it was decided to use WUE instead of $\delta^{13}C$ value.

Adhesives, additives and gluing conditions

Different types of commercial adhesives, for structural and non-structural applications (Table 1), were used as such as reference formulations and as a base for the preparation of 7 different formulations containing CNC and/or tannin. As reference adhesives, polyvinyl acetate (PVAc) adhesive, according to (EN 204, 2016) use class D3, and for the use for structural purposes, a melamine-urea-formaldehyde (MUF) adhesive system with liquid hardener was used. The different adhesive formulations were mixed by hand at room temperature according to the compositions given in Table 1 just before gluing. In order to introduce a further comparison, the PVAc adhesive was also mixed with polyurethane (PU) glue, according to custom usage of a local wood processing company that assisted with the gluing experiments (Mattioli Legnami srl, Viterbo, Italy), as a base for another CNC-modified adhesive formulation. The protocol renders the original PVAc adhesive suitable for exterior applications with exposure to weather (durability class D4 according to (EN 204, 2016) . CNC were purchased from CelluForce Inc. (Montreal, Canada) and chestnut tannin (Saviotan®) was used from Nuova Rivart (Radicofani, Italy).

Bonding procedures generally followed UNI EN 302-1 2013 as well as according to instructions given by the adhesives' manufacturers. After manual application of the requested amount of glue (130 g/m^2 PVA and 250 g/m^2 MUF) using an aluminum spatula, the chestnut wood panels were bonded in parallel orientation and tangential direction and pressed for 90 minutes at 50 bar (5 MPa) and ambient temperature. After pressing, the glued samples were dried in standard climate at 20 °C and 65% relative humidity (RH) according to UNI EN 302-1 2013.

Table 1: Adhesive formulations based on commercial adhesives and cellulose nanocrystals and tannins as additives used for gluing experiments.

Adhesive formulations	Adhesive ID	CNC [%]	Tannin [%]
Polyvinylacetate adhesive (PVA) + Cellulose Nanocrystals (CNC)	2 (PVAc-CNC)	5	0
PVA	1 (PVAc)	0	0
PVA + polyurethane (PU) adhesive + CNC	3 (PVAc-PU-CNC)	5	0
PVA + CNC + Tannin (T)	4 (PVAc-CNC-T)	5	5
Melamine-urea-formaldehyde (MUF) adhesive + CNC	5 (MUF-CNC)	5	0
MUF	6 (MUF)	0	0
T + CNC	7 (T-CNC)	5	70

Statistical processing

All statistical analyses were carried out using Past 3 software. The differences among the five studied areas from the dendrometric point of view were subjected to the analysis of variance (ANOVA) and principal component analysis (PCA). The former was carried out to check whether the five areas were significantly different in their dendrometric values. In the PCA, some autocorrelated parameters were excluded so as to clearly identify the multivariate analysis. Finally, a correlation was performed between the climatic data (monthly) and stable isotope datasets and TRW. In order to process a correlation function. PCA analysis and correlation was also performed to see if dendrometric parameters affect wood physical and mechanical properties.

Conclusion

This is the first study to focus on the dendroisotopic composition of chestnut trees, and the results contribute to a better understanding of the physiology of the species. In a future climate change point of view this aspect will become fundamental for resilience of this species. The work highlighted that chestnut tree-ring growth is not particularly influenced by climate while minimum temperature showed a positive relation with both WUEi and $\delta^{18}O$, particularly their responses to climate are influenced by stand-characteristics and forest managements. Forest managements should be innovated with new silvicultural approaches, where the site, social and economic conditions allow it, can exploit the full potential of the sweet chestnut. However, a substantial change in the sweet chestnut coppice management is fundamental: the transition from a "silviculture waiting" or articulated in sporadic interventions to an "active, participatory and sustained silviculture" is needed. Based on this it is possible initiate new management perspectives considering the effect of the forest management on final wood parameters, infact this work found that there is a positive relationships between the number of stools/ha and density, and a negative one among shoot dominant height and basal area with wood density. Among the five studied stands, the main difference in the physical characters is wood density, that influence mechanical strength and consequently limits its use. The chance of chestnut wood to be more used in innovative design products is a suitable pathway towards diversification

On this work we added CNC and tannin to the PVAc glue increased the shear strength of the prepared lap-joint test specimen compared to the use of pure PVAc glue, when no additional post-treatment than conditioning in standard climate was applied. Thus, development of new adhesive formulations including bio-based additives as CNC and tannin, which substitute synthetic polyvinylacetate, for their utilization in dry ambience appears promising.

INTRODUCTION

The sweet chestnut (*Castanea sativa* Mill.) forests cover about 2.5 million hectares in Europe. 70,3% is in France and Italy; Spain, Portugal and Switzerland account for a further 9.7%; the remaining 11.0% is scattered in several other countries. Most forests (79%) are composed by pure stands and managed for wood production (Conedera *et al*. 2004). As a species, chestnut is to be considered native to many parts of Southern Europe although it originally was only a component of the mesotermophilous mixed deciduous forest (Bernetti 1995; Conedera *et al*. 2004). Then, its role as dominant tree species and geographical spread is due to strong human impact. Even the prevailing of the coppice system (83%) in the management of European chestnut forests for wood production can be seen as the result of the long term cultivation (Conedera and Krebs 2007). Chestnut plays an important role in Italian forestry, both due to its extension in the national territory (about 800’000 hectares) covering nearly 2.6% of the country total area and 7.5% of the national forest area (Tabacchi *et al*. 2005; Corona *et al*. 2017; Rete Rurale Nazionale 2018), timber and fruit productions. Data from the National Forest Inventory (Tabacchi *et al*. 2011; Rete Rurale Nazionale 2018) show that 91% of Italian chestnut area is concentrated in a few regions: Piedmont (169'075 ha), Tuscany (156'869 ha), Liguria (110'278 ha), Lombardy (82'872 ha), Calabria (69'370 ha), Campania (53'200 ha), Emilia Romagna (41'929 ha) and Lazio (35'003 ha).

The most prevalent management for wood production is coppice (75.2%), with a clear cutting at the end of rotation and standards release. Rotation length differ among the regions but the most frequent period is 14-15 years old. In 1950, 62% of total chestnut stands were cultivated for fruits whereas 38% were managed as coppiced for timber (Boggia 1986). Today, that situation has reversed and about 590’000 ha (81%) are grown as coppice. Notwithstanding the numerous risks of attack of pathogens, wherever it grows, chestnut wood has been an important resource for local communities as it is the only tree species able to give origin to a branched forest-wood chain compared to oak and beech, which are the species more represented in the Appennine forests together with chestnut. Actually oak and beech forests in the Apennines are mainly used as firewood (Manetti *et al*. 2017).

Silvicultural guidelines consider early and frequent thinnings, the treatments are not so frequently applied.

Chestnut wood has a significant role in the economic activities of some territories. Inventory data (Tabacchi *et al*. 2005) indicate that chestnut has a very high production potential in Italy, estimated at about 140 million m^3 (177 m^3 ha^{-1}) with a current increase of 6.3 m^3 $ha^{-1}year^{-1}$. Despite the species is fast growing the size reached by the timbers at the end of the rotation period cannot be

considered satisfying the chance to have many wood products. Nevertheless more products can be obtained by chestnut coppices such as: beams, floor boards, joists, small joists, poles for bioengineering and agriculture, tutors, telecommunications poles, vineyards ponds, firewood.
Wood presents a lot of defects, ring shake is a limiting factor for some end uses but likely it is the most studied defect for chestnut (Becagli *et al*. 2006; Spina and Romagnoli 2010; Romagnoli *et al*. 2012). The most part of the studies on ring shake applied to forest management indicates that regular early thinning (below 10 years) is one of the most important forest management operation, but also genetic issues and provenance play an important role (Fonti *et al*. 2002; Vinciguerra *et al*. 2011) in the probability or not to have ring shake in timbers. The curvature of the logs is a further recurrent defect which makes difficult to obtain assortments of high length. The curvature is affected by the number of shoots and by the height of the stumps compared to the ground level. Curvature in the logs obliges the operators to shorten the logs (Romagnoli *et al*. 2012). The most important wood end-use is load bearing and poles that means the most part of the processing is limited to the sawmills. Because of the specific market of the structures, sawmills are not so much interested to introduce kiln dry cells in their plants and very few are interested to have innovations such as heat treatment. The most part of sawmills involved in this field are chestnut-centric, i.e. they work only chestnut. They use local material but sometimes they import from surroundings regions or from close countries such as France (Manetti *et al*. 2017). For instance, only one-third of the timber used in Lombardy comes from the same region, even if there could be enough wood to satisfy the local needs. The remaining two-thirds of supply mostly come from Eastern Europe, due to its competitive prices and good quality (Mirabella *et al*. 2014). Many efforts have been in order to exploit some chestnut wood products mainly for structural purposes. The work has been successful because chestnut now occupies a significant role in the frame of European woods used for structural purposes and it is possible to use it with a CE certification of the beams, due to an ETA which makes possible to certify the use for structural purposes of the beams "Uso Fiume". Indeed Federlegno, the Italian industrial association which brings together many companies operating with wood, got an European Technical Approval (ETA-12/0540), so the companies which were inside the Consortium got the marking CE in the assortments.
A new impulse on this field came from machine grading of mechanical strength profile, which allows for a more quantitative yields, better quality beams with higher grading in mechanical stress, reduced classification times, and greater guarantees of repeatability (Brunetti *et al*., 2013). This challenge would be a great impulse for chestnut forest-chain, because the product could be used also outdoor and substitute the spruce glued beams. In Spain chestnut glulam have already produced

and marketed CE label by an ETA approval, but in that period the standard rules were different and it would have been possible to get success for CE certification.
At the same time, furniture which was one of the main product of chestnut in the past, is not more appreciated by costumers, while the possibility to obtain veneers may deserve further attention.
Chestnut is surely a species which better fits the concept of cascade use. Even if the chance to have an enough supply of wood make the species a potential feedstock for energy (Colantoni *et al*. 2013; Delfanti *et al*. 2014), before considering this final end use a lot of valuable products can be obtained. Tannin wood extractives are one of the most important byproduct since their use is ubiquitous in many field applications and even the residues of tannin extraction could find a new life (Panzella *et al*. 2019). New attempts in the field of biochar could improve the rationale use of residuals. Chestnut processing residues have been also increasingly used for energy purposes, not only in terms of biomass but more recently for pellets production (extracting tannins firstly). In spite of wood potentiality of chestnut wood (mechanical properties, aesthetic, durability), the available assortments do not reach the full exploitation for potential use because of technical and economic reasons. One of the most relevant technical reason is coppice management system, that it does not allow to have assortments of high dimensions, especially in diameter.
Regarding economic reasons for increasing wood quality, because of the negative stumpage cost, the owners rarely make thinning. Thinning can be a big support reducing the request of water and nutrients and increasing wood quality with less ring shake defect, decreasing the occurrence of abrupt changes in growth are those that inexorably trigger the ring shake (Spina and Romagnoli 2010).
It is fundamental valorize small log deriving from chestnut coppices, studying at the same time the main gaps and perspectives of the chestnut forest wood chain, the main strengths and weaknesses of the species also looking to the possible effects of climatic changes.
By this assumptions the main objectives of the PhD thesis are:

1. To produce a state of the art of the chestnut forest wood value chains in Italy, outlining the main gaps and perspectives.
2. To assess the resilience of the species to climatic changes through the relationship between climate parameters and tree-ring width (TRW). For the first time the study of the isotopic content will be applied to the chestnut shoots in coppice.
3. To look the effect of dendrometric parameters of chestnut (*Castanea sativa* Mill.) stands on wood quality. The main physical and mechanical properties have been investigated and related to the site condition such as stools/ha, number of shoots/stool etc.
4. To start a rethinking of the use of chestnut wood for new products, testing on thin

chestnut wood layer different glues. Namely the purpose was to check the effect of synthtetic adhesives and natural based compounds such as tannin and cellulose nanocrystals in a pure or mixed solution with synthetic products on bonding properties. The main purpose is to start a process which is addressed to have more ecofriendly products and possible innovative composite.

In order to boost the chain it is mandatory to make efforts for a more versatility in use, that means to be care of the management systems and to obtain stems available for different final products.

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CHAPTER 1

GAPS AND PERSPECTIVES FOR THE IMPROVEMENTS OF SWEET CHESTNUT FOREST-WOOD CHAIN IN ITALY: A COMMENTARY

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GAPS AND PERSPECTIVES FOR THE IMPROVEMENTS OF SWEET CHESTNUT FOREST-WOOD CHAIN IN ITALY: A COMMENTARY

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Abstract

The paper wish to make a summary on the state of the art of silviculture and wood use of sweet chestnut (*Castanea sativa* Mill.) species in Italy with its strengths and weakness. The potentialities are quite good because sweet chestnut cover in Italy about 800’000 hectares, nearly 2.6% of the country total area and 7.5% of national forest surface. In some districts, especially in central-southern Italian regions, sweet chestnut is the only driver of sawmill economy. The use of this species in Italy is mainly based on solid beams for load bearing structures and poles. In the field of load bearing structures, research and innovation have obtained quite good results, because the species is integrated in the European standard rules with the same relevance of most used species like spruce. Diversification in wood products is lacking in sweet chestnut, both considering the sawmills which are very often chestnut-centric and for considering the types of final products. This aspect is the main threat for the exploitation of the species together with the general observation that in Italy it has been a decreasing in the number of sawmills which have ceased their activity, due to a general economic crisis, mainly affecting the traditional building sector, and to a quick change of the market. The main wood quality defects which limit the use of species for many other wood products are listed. In order to boost the chain it is mandatory to make efforts for a more versatility in use, that means to be care of the management system and to obtain stems available for different final products. A list of possible actions are considered in order to boost the use of the target species, which is one of the best opportunity to develop the short supply chain.

Keyword: short supply chain, coppice, bioeconomy, silviculture, Mediterranean country.

Introduction

Sweet chestnut (*Castanea sativa* Mill.) plays an important role in Italian forestry, both due to its extension in the national territory (about 800'000 hectares) covering nearly 2.6% of the country total area and 7.5% of the national forest area (INFC, 2005; RaF Italy 2017-2018). This species is present along a gradient from southern to northern regions having a very important productive value. In some districts, especially in central-southern regions, sweet chestnut is the only driver of sawmill economy, being an alternative competitor of other timber species like Pines (*Pinus* spp.) or Norway spruce (*Picea abies* Karst.) in other central-northern regions of Italy. In spite of wood quality (mechanical properties, aesthetic, durability), the available assortments do not reach the full exploitation for potential use because of technical and economic reasons.

In recent times, the need to activate short supply chain has been increased, but this principle is basically applied to the biomass for energy purposes (Becagli *et al*., 2010; Delfanti *et al*., 2014; Paletto *et al*., 2019; Pieratti *et al*., 2020); conversely, woodworking is more difficult because the chain is much more branched (Mirabella *et al*., 2014) and the requirement of technical rules are sometimes mandatory especially for structural purposes. In this case, technical requirements are not always fulfilled by sweet chestnut; indeed companies have to sustain some costs to obtain the European Technical Approval (ETA). The incorporation of sweet chestnut wood in the European criteria satisfying the use of structural purposes, started later compared to spruce. Indeed chestnut had to recover the time lost because for examples some methods of wood working (i.e. Uso Fiume) were not considered in the European standards - because considered traditional of specific regions of Italy. Furthermore chestnut has captured less interest because occupying a more restricted market niche.

A short wood-supply chain has a lot of advantages such as a reactivation of silviculture value added related to different wood-working and commercial activities (Romagnoli *et al*., 2019) and with a short supply chain you have the chance to increase the economy of the territory. Species of short supply chains sometimes show better characters than what it can be expected (De Angelis *et al*., 2018; Romagnoli *et al*., 2015) because of the new advances in wood modification (Romagnoli *et al*., 2015). The present study evaluates and briefly discusses the actual strengths and weaknesses of sweet chestnut timber chain in Italy and the possible improvements for a better ecological and economic sustainability of the whole sector and a true application of the concept of the short-supply chain according to the most recent trends.

Wood management

The majority of Italian sweet chestnut stands (91%) are concentrated in a few regions (Tabacchi *et al*. 2005; RaF 2018): Piedmont (169'075 ha), Tuscany (156'869 ha), Liguria (110'278 ha), Lombardy (82'872 ha), Calabria (69'370 ha), Campania (53'200 ha), Emilia Romagna (41'929 ha) and Latium (35'003 ha). The prevalent management for wood production is coppice (75.2%), with a clear cutting at the end of rotation and standards release. The length of the rotation and number of standards to be released are ruled by regional regulations; minimum allowed rotation length ranges from 8 to 15 years (Table 1). The Regional Forest Regulations also identify the minimum number of standards to be released, which can range from 30 to 80 units per hectare. The size of the regulated forest compartments ranges from 5 ha to 20 ha. Thinning is not always prescribed in Latium (Regional Law 7/2005), Tuscany (R.L. 2003), Piedmont (R.L. 2011), Lombardy (R.L. 2007), Liguria (R.L. dated 22/01/1999), Calabria (R.L. 2011) and Campania (R.L. 11/96 more recently updated in 2017). Table 1 illustrates the basic characteristics of selected management regulations promoted by Regional Authorities in Italy. These examples are representative outlines of the lack of national harmonization of the sweet chestnut forestry management system.

Table 1: Rotation period of Sweet chestnut coppices according to the Regional Forestry regulation (from Manetti *et al* 2017, modified)

Sweet chestnut region of origin	*Min. rotation age (year)*	*Max. rotation age (year)*	*Standards to release N° ha^{-1})*	*Max extension of cutting area (ha)*
Piedmont	10	N.D.	grouped	5
Tuscany	8	50	30	20
Liguria	12	N.D.	60 (optional)	N.D.
Lombardy	15	N.D.	50	10
Lazio	14	35	30	20
Campania	12	N.D.	30	N.D.
Calabria	14	35	30	10

Standards may have twice (2t) or three times (3t) the rotation age of the shoots although a rotation age of 3t has become sporadic in the last decades. The role of standards in sweet chestnut coppice stands is considered relevant by sweet chestnut management rules. According to regional rules, standards would be selected from the dominant trees, possibly of gamic origin, even if the gamic regeneration in sweet chestnut coppices is very rare due to the dense canopy cover with a powerful phenotypical structure (Manetti and Amorini 2012). Indeed most of standards are selected among the shoots and not always they are selected among the best ones (Figure 1).

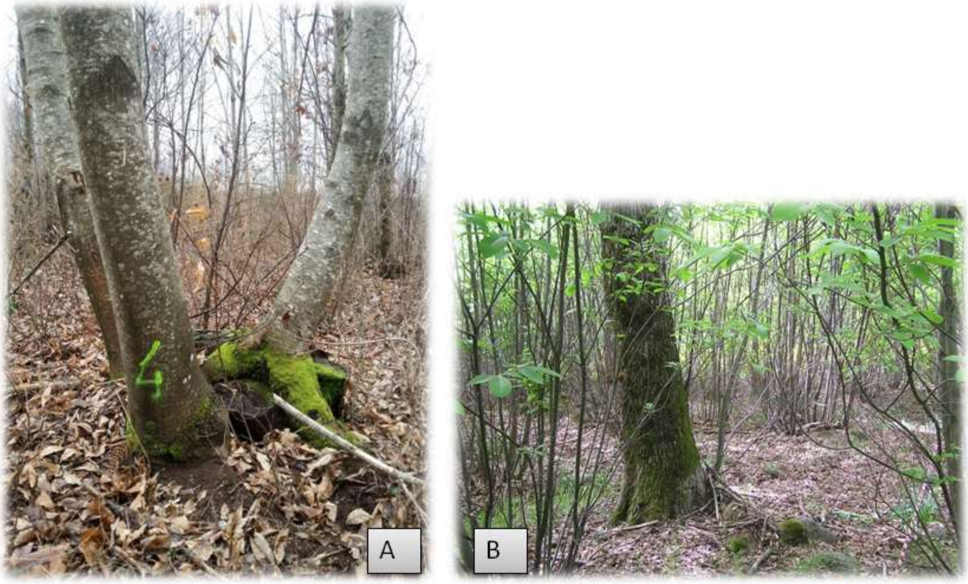

Figure 1: A) Shoot released in the stool B) Standard born from seed (gamic origin)

The presence of standards was typically observed in Italy for sweet chestnut woodlands, but in more recent times their ecological and functional role is subject to inherent debate because the presence of standards has demonstrated to be not vital for the survival of the sweet chestnut coppice. Indeed Manetti and Amorini (2012) indicate that the presence of standards negatively affects the development of the coppice, and increases the mortality of the shoots, limiting the dimension of their diameter, disqualifying shoots socially and depressing the sprouting by the stools. The only dimension positively influenced by the presence of standards is the average height of the shoots. Starting with this point of view, new experiments based on grouped standards can be carried out (for extensive references see Tab. 2).

On the contrary, some forest owners and companies consider standards an important part of sweet chestnut management in order to obtain beams and boards of larger size at the end of coppice rotation, and therefore to diversify wood products which can vary from poles to lumber. Really, one of the main problems affecting the use of timber from standards is the defect of ring shake, a predisposition of cracking along the ring when internal growth-induced tensions are released through the tree falling or the subsequent drying process (Fonti *et al*., 2002; Mutabaruka *et al*., 2005; Becagli *et al*., 2006; Spina and Romagnoli, 2010; Romagnoli and Spina 2013; Romagnoli *et al*., 2014).

Table 2: Basic definitions of standard release in sweet chestnut coppice.

Authors	*Results*
(Manetti and Amorini 2012)	"…the coppice in the absence of standards is not only more productive but also shows greater efficiency, stability and soil coverage …" Forest@ 9: 281-292 (2012)
(Bianchi *et al.* 2009)	"…30-50 aged standards can advertisely affect the growth of the future coppice". ARSIA, Tuscany Region, Florence.
(Fiorucci 2009)	"…standards represents the emblematic case of how the scientific world has failed to adequately support to the political one and to have a consistent impact on sectorial legislation." Forest@ (6): 56-65. - doi: 10.3832/efor0572-006
(Zanzi and Sulli 1995)	"…the issue of excessive standards is not the result of refining research over the time, but rather the regulatory response to political, social and often also the emotional demand of public opinion". Sherwood 7: 7-11.
(Zanzi *et al.* 1993)	"…until the end of 1800 the standards function was essentially linked to the production of lumber or fruit and branches for animal husbandry". Rivista di Storia dell'Agricoltura 1: 109-121.
(Corona *et al.* 1986)	"…too high number of standards damage coppice development". Annali Accademia Italiana Scienze Forestali 35: 123-158.
(Merendi 1942)	"… even if the standards are completely missing, there is no fear that thinning phenomena will be known, as it it well known the exceptional vitality of this wonderful plant that emits stool even when it is cutted in a state of extreme old age". La Rivista forestale Italiana 1-3: 33-36.

Some new silvicultural approaches, alternative to short rotation, can diversify and improve the wood products, enhance the protective function, the environmental and biodiversity conservation, maintain the social component and cultural heritage in rural areas. The main forestry techniques (future tree-oriented silviculture and stand silviculture), developed to fulfill the functions defined above, can be summarized in the extension of rotation time (till 30-50 years) and in the planning of early (8-12 years) and frequent thinning (every 7-10 years) to allow a regular growth of the released shoots (Manetti *et al*., 2009, Manetti *et al*., 2017). In particularly, the single tree-oriented silviculture can maximize the site and the individual potential through an early selection of a low number of future trees (80-150 per hectare) and making the crown of the candidate completely free by removing all the main competitors whereas no treatment is carried out in the remaining stand. Subsequent thinning will be carried out to permit a free growth of crown.

The stand silviculture is characterised by a high intensity (50% of the shoots left) from below thinning, throughout the stand. The guidelines concerning this silvicultural approach consist in early and frequent thinning that allow sun-driven and fast growing species such as the sweet chestnut to constantly display a well-developed dominant canopy layer (Manetti *et al*., 2009).

Wood owners and forestry companies

Ownership of sweet chestnut woods is mainly private (80%), overly fragmented and organized in relatively small parcels, nearly 1.5 ha on average. The majority of private property is individual, and the cases of association are relatively scarce, making it difficult to adopt policies of common interest and resulting in insufficient and inconsistent supply of local quality materials (Gajo and Marone, 2000). The situation has a strong limit for industries needing an abundant wood supply: however, the small and medium-sized processing companies have survived over time especially when related to the structural building production.

Traditionally, the system of sale is the standing forest at the end of the rotation period both for private and public owners. Because of the negative stumpage price, the owners rarely make thinning, while renting the stand to the forest companies. This could stimulate cultivation of additional forest surfaces, because at the end of rotation, it could be possible to get a material of improved quality. Sweet chestnut forests have sometimes a poor tending because of their location inside natural sites having a more strict regulation and a more evident abandonment of sweet chestnut stands because of the lack of interest of the private owners. Such lack of cultivation has produced coppices with a high presence of shoots in the same stools and sometimes tall stools above the ground level with troubles in harvesting and thinning procedures (Figure 2).

Figure 2: Chestnut stools above the ground level

Production characteristics

Inventory data (IFNC, 2005) indicate that sweet chestnut has a very high production potential in Italy, estimated at about 140 million m³ (177 $m^3\ ha^{-1}$) with a current increment of 6.3 $m^3\ ha^{-1} year^{-1}$ on average (Table 3). Sweet chestnut is generally considered highly productive in optimal environmental contexts, being almost comparable with fast-growing species. In some geographical areas like Cimini Mountains in Latium, on the best fertile sites it is possible to reach mean increment of 20 m^3 ha^{-1}, at ages of 15-16 years. Tables of assortments have been not updated for Italy. Cantiani (1965) reports a production of 36% poles, 26% tannin, 18% saw timber, 12% other uses, 8% barrel slates for sweet chestnut coppice. This is one of the major gaps in the knowledge in order to operationally improve the chain.

Although important divergences in these studies, basic differences in basal area, volume and number of shoots depending on the provenance can be highlighted. Dendrometric values are very dependent on the number of shoot/ha and site conditions (soil fertility, slope, altitude, etc.). Additionally several pathologies can influence forest productivity, such as the most recent attack of *Dryocosmus kuriphilus* Yasumatsu on sweet chestnut - that commonly reduces wood production (Palmeri *et al*. 2014; Ugolini *et al*. 2014; Ferracini *et al*. 2019; Gehring *et al*. 2018; Gehring *et al*. 2020), plant vitality (Quacchia *et al*. 2008), the bark canker (*Cryphonectria parasitica*), and the ink disease (*Phytophtora cambivora*).

Table 3: Growth potential of sweet chestnut coppice stands in Italy

Author/s	Geographic Area	Dendrometric and dendroauxometric parameters
Gasparini & Tabacchi 2011	Italy	Mean volume of stools and bigger branches: 180.4 m^3 ha^{-1}. (Annual increment: 6.8 m^3 ha^{-1} $year^{-1}$.Phytomass aboveground: 118.1 Mg ha^{-1})
Caldart, 1931	Cimini Mountains (Lazio)	MAI among 9 and 20 m^3 ha^{-1} $year^{-1,}$ depending on site fertility
Cantiani, 1965	Cimini Mountains (Lazio)	Maximum mean annual increments: 20 m^3 $ha^{-1}$$year^{-1}$
La Marca, 1981	Irno's Valley (Campany)	Maximum MAI: 19 m^3 ha^{-1} $year^{-1}$ Maximum MAI: 13 m^3 $ha^{-1}$$year^{-1}$ (12 years in the third fertility class)
Eccher& Piccini, 1985	Lombardy	MAI: 6.3 m^3 ha^{-1} $year^{-1}$ (20-25 ages)
SAF, 1985	Lazio	Mean amount of biomass: 110 m^3 ha^{-1}. Mean increment: 8 m^3 $ha^{-1}$$year^{-1}$ (13 mean years)
Bernetti, 1987	Tuscany	MAI in best site conditions variable between 4 to 8 m^3 ha^{-1} $year^{-1}$.
Hofmann et al., 1998	Tuscany	Stand volume: 170 m^3 ha^{-1}
Cutini, 2001	Amiata Mountain (Tuscany)	MAI: 17.6 and 12.8 m^3 ha^{-1} $year^{-1}$ respectively for 15 and 38 years.
Amorini and Manetti, 2002	Monte Amiata (Tuscany)	MAI: 10.9 m^3 ha^{-1} $year^{-1}$ (23 mean ages)
Ciancio et al., 2004	Calabria	MAI: 16.3 m^3 ha^{-1} $year^{-1}$ (13-15 years); MAI: 14.2 m^3 ha^{-1} $year^{-1}$ (-30 years); MAI: 12.0 m^3 ha^{-1} $year^{-1}$ (43-45 years)
Nosenzo et al., 2006	Monte Tovo (VC)	MAI: 8.3 m^3 ha^{-1} $year^{-1}$ (50 years)
Nosenzo, 2008	Torino, Biella, Vercelli, Novara Cuneo (Piemonte)	Mean basal area: 30-35 m^2 ha^{-1}.Mean diameter: between 13 cm e 30 cm. Mean height between 13 m e 20 m. Biomass: 300 m^3 ha^{-1}
Angelini et al., 2013	Viterbo (Lazio)	MAI: culmination between 18 e 22 years, with values between 7.2and 13 m^3 ha^{-1}
Maziliano et al., 2013	Presila di Catanzaro (Calabria)	Stand volume: between 90 e 630 m^3 ha^{-1} respectively for 9 and 50 years coppices. Culmination of mean increment at 25 years: 16 m^3 ha^{-1} $year^{-1}$. CAI culmination apparently at 15 years (21 m^3 ha^{-1})
Mattioli et al., 2016	Bracciano, Oriolo Romano, Sutri (Lazio)	Number of shoots: between 1.942 and 11.445 ha^{-1}; Mean diameter: between 4 and 16 cm. Basal area: between 17.54 m^2 ha^{-1} and 41.86 m^2 ha^{-1}. Number of standards: variable between 36 and 91. Mean diameter: between 24 and 46 cm.Mean age:6 to 22.
Travaglini et al., 2015	Chianti (Toscana)	CAI:between 6.7 and 4.7 m^3 ha^{-1} $year^{-1}$ respectively at 20 and 30 years.
Manetti et al., 2016	Amiata Mountain (Tuscany)	Number of shoots: between 736 e 968 ha^{-1}. Mean diameter: 7.2 cm. Basal area: between 23.43 m^2 ha^{-1} and 25.61 m^2 ha^{-1} (11 years)
Manetti et al., 2016	Colline Metallifere (Tuscany)	Numbers of shoots: between 888 and 1324 ha^{-1}. Mean diameter: between 9.7 and 10.4 cm. Basal area: between 18.23 m^2 ha^{-1} and 29.55 m^2 ha^{-1}at 17

MAI =Mean Annual Increment;CAI= Current Annual Increment

Wood quality, forest management and planning

Boosting the economy based on the processing of sweet chestnut timber must start from product quality, we would assume that the maximum versatility is the only path to respond to rapid changes in the market and to environmental risk. Cascade use of wood can represent another important principle which must be considered, especially under the assumption of circular economy, representing the great connection among quality/versatility and forestry management. The main limitation of sweet chestnut wood quality is size, ring shake and curvature of the logs, all defects that can be reduced by good suitable silvicultural approaches.

About size, more details are given in Table 4 according to the most used products, and depending on the final product although longer rotation was demonstrated to be the first objective of sweet chestnut industry. Ring shake is a limiting factor, likely it is the most studied defect for sweet chestnut (Spina and Romagnoli 2010; Romagnoli and Spina 2012, Becagli *et al*., 2006). The most of the studies on ring shake applied to forest management indicates that regular early (8-10 years) and intense thinning is one of the most important forest management operation, but also genetic issues and provenance play an important role (Fonti *et al*. 2002; Vinciguerra *et al*., 2011). Ring shake in sweet chestnut makes wood suitable to poles and roundwood for bioengineering, or for energy purposes, excluding more valuables products derived from such procedures. The curvature of the logs is affected by the number of shoots and by the height of the stools compared to the ground level. Curvature in the logs obliges the operators to shorten the logs. The irregular shape of the shoots especially due to big knots or sweet chestnut canker can further limit the length of the logs (Figure 3).

Figure 3: a) Curvature of the lumber, b) trimmer machine, c) chestnut cancer where the bole is eliminated, d) lumbers.

Wood Technology, processing and market

The relaunch of a production has to consider processing costs, from harvesting to the final product. Logging cost is dependent on infrastructures, viability being one of the main factors. Among these, road network is crucial in Italy, it has been estimated as more than 75% of the national sweet chestnut supply territories have inadequate road network (Baldini *et al*., 2003). Harvesting operations are also affected by slope and rough terrains especially in abandoned sweet chestnut sites. Additionally, lack of viability increases the risk of damage to the trunk during thinning operations.

Another trouble is in the machines for forest operations which are often outdated, even if, in more recent times, a latent evolution towards more efficient systems (such as yarder or shuts) has been observed in Central and Southern Italy. The most forest harvesting system is “tree length system”: sometimes wood is cut in shorter assortments like small poles for agriculture. Woody production goes to the first sawmill, which are interested in minimizing wood processing and primary transport of full plants (Manetti *et al*., 2017)

The most important production of wood end-use stops in the sawmills which produce load bearing structures or poles. The most advanced sawmill structure has a trimming-selecting machine, but the length of the assortments still requires a lot the experience of the operator (see Figure 3) in order to reduce the machining losses and to gain the best products as a market request. Innovation in this field includes recent end trimming machines which work in the sawmills of sweet chestnut making possible the cross-cut in short assortments. Machines, however modern, are not recent and there are new models in the market that can achieve higher productivity with higher safety standards. The competitiveness of the enterprises strongly depends on the innovation capacity, the development of new products and services, and the improvement of the overall process quality (Massa and Gessa, 2011).

In general the number of sawmills is decreasing in Italy for ceased activity, and many sawmills which work sweet chestnut wood have focused their production exclusively on local sweet chestnut, activating an independent chain that goes from forest utilization to the sale in the regional/local market. Sometimes they are not so much interested to introduce new structures like kiln dry cells, or some innovation like thermo-treatment plants. They are more oriented to traditional assortments and the most part of sawmills involved in this field are chestnut-centric, i.e. they work only sweet chestnut. For these reasons most companies, especially medium and large, use import timber (Manetti *et al*., 2017) of sweet chestnut. For instance, only one-third of the timber used in Lombardy comes from this region, even if there could be enough wood to satisfy the local needs.

The remaining two-thirds mostly come from Eastern Europe, due to its competitive prices and good quality (Mirabella *et al*., 2014). The worker have their niche market and this is one of the most important issue in order to develop a forest-wood chain able to survive to the more evident import of wood products based on spruce and/or other imported species.

Furthermore the sawmills, due to their reduced size, do not have the opportunity to invest in innovation because they suffer the strong competition of imported wood including spruce. For this reason, it is necessary to boost them taking advantage of various financial tools based on innovation project (e.g. through rural development plans). Actually there are not reliable statistics about the use of chestnut wood and the volume produced in the different regions, and the different sawmills. Looking to the activity in research and implementation projects, it can be assumed that Piedmont, Tuscany, Latium and Veneto regions are the most developed in chestnut wood working in Italy.

Sweet chestnut wood Products

A list of the most important products obtained directly by the sawmills is reported in Table 4, related to the estimated size in diameter and length of the original logs.

Table 4: A list of basic traditional sweet chestnut uses (Romagnoli *et al*., 2013)

Assortments	***Diameter (cm)***	***Length (m)***	***Use***
Beams	>20	>4	Carpentery, Building
Beams	>20	2-4	Joinery, furniture
Floor boards	>20	0.80-2.00	Parquet
Joists	17-24	(3) 4-5	Carpentry, building
Small joists	12-16	2-4	Carpentry, building
Poles for bioengineering	15-25	4	Environmental restoration
Poles for agricoltures	6-15	Variable depending on the use	Support for vine
Tutors	2-5	1-2	Support for young plants
Telecommunications poles	12-15 (base); 9 (tip)	7-12	Support for electric lines
Vineyards ponds	3-7	2-4	
Firewood	Variable	1	Firewood, chips
Small shoots	-	-	Bread oven
Tannins	≥10	1	Industry

Poles for bioengineering and telecommunication do not require any special care or working process except debarking by automatic machines. Pole production is interesting because it is also related to the typical Italian production of vineyards. In Piedmont region, the use of treated wooden poles in substitution of concrete is recommended in the disciplines of production (PDO-PGI) (Piedmont Region 2003, 2019). Chestnut poles have an higher added value from this perspective because their high natural durability don't make mandatory a chemical wood preserving treatment. In fact in the handbook of biological viticulture in Tuscany (2009), chestnut wood poles are highly recommended (Mazzilli and Braccini, 2010). One of the most interesting issue in order to make a better standardization in the sweet chestnut chain at least in the national market is the local name related to poles which make difficult to promote a national and international market, which ask for a

common terminology and comparable technical standards. Some weaknesses must be cited for sweet chestnut poles because it has been showed as sometimes durability is not high as expected in small assortments (Militz *et al*., 2003).
Another product that has been extremely successful in the past is the sweet chestnut pole for telecommunications, ruled with the reference standard "UNI 3514 and UNI 3515 (1984)” in Italy. At the moment, there is a critical use for telegraphic poles which require dimensional and regularity of the stem not easily available for Italy. So wooden telegraphic poles have been replaced in the most favorable situation by impregnated pine and larch poles.
The most important recent innovation in sweet chestnut regards load bearing structures, and it is due to the efforts of Italian researchers who have inserted the beams of the species in the package of European standards which assess the structural products under the CE certification mark. The technical standard EN 14081-1 is related only to the structural assortments with rectangular cross section, and in many Italian regions the working process is related to “Uso Fiume” assortments (i.e. square edged chestnut logs with wane along all the length of the beam). Federlegno, an Italian industrial association which brings together many companies operating with wood, got a European Technical Approval (ETA-12/0540), so the companies which were inside the Consortium got the marking CE in the assortments. The biggest limitations are in the standard rules for structural purposes, including the size of the joists. At national level, it is still possible to apply UNI 11035 Part 1, Part 2, Part 3: the assortments must be traded inside the national boundaries and their size must be measured, and not treated at nominal size. In this field, there is a lot of confusion among some professional figures who do not know how to apply the European standards and, in order to avoid bureaucratic problems, they prefer to use more consolidated products like beams of rectangular assortments of other species like pine or spruce.
Machine grading of mechanical strength profile could be a new impulse on this field, which allows for a more quantitative yields, better quality beams with higher grading in mechanical stress, reduced classification times, and greater guarantees of repeatability (Brunetti *et al*., 2013). Using this instrument sweet chestnut load bearing beams are able to face the competition with more present species like spruce, because they can obtain a higher grading. The potential of machine grading is not always known by the sawmill workers and actually it is considered expensive by some of them; for this reason the formation of consortium among the producers would have to be supported.
It is evident that major gaps in the chain of load bearing structures have been coped and sometimes they are on the way of solutions. The gap on this field is more on the promotion of the product and on the right knowledge of its performance. At the same time, furniture, which was one of the main

production of sweet chestnut in the past, is not more appreciated by costumers, while the possibility to obtain veneers may deserve further attention. The sweet chestnut chain is actually experiencing the disappearance of many companies due to the economic recession and the low ability to make innovation according to the mandatory requirements in this field. This is a disadvantage for the loss of an important know-how, but this context meets the chance to have companies bigger, modern and organized, which are able to face the competition of other sectors, countries and wood species.

In the more recent times some projects have allowed to test some prototypes of glulams (Brunetti *et al*., 2014). This challenge would be a great impulse for sweet chestnut forest-chain, because the product could be used also outdoor and substitute the spruce glued beams. In Spain, sweet chestnut glulam have already produced and marketed CE label by an ETA approval, but in that period the standard rules were different and it would have been possible to get success for CE certification. In Italy, this pathway must be more assessed together with other hardwoods, like beech (*Fagus sylvatica* L.), which have been already considered by the market of structural beams.

Sweet chestnut is surely a species which better fits the concept of cascade use. Even if the chance to have an enough supply of wood make the species a potential feedstock for energy (Delfanti *et al*., 2014; Colantoni *et al*., 2013; Zambon *et al*., 2016), before considering this final end use a lot of valuable products can be obtained. Tannin wood extractives are one of the most important byproduct since their use is ubiquitous in many field applications (Table 5) and even the residues of tannin extraction could find a new life (Giovando *et al*., 2019). In chestnut they are a part of the large category of hydrolysable tannins (Vázquez *et al*., 2009; Giovando et al., 2019). Tannins are heavily investigated and now they are well known for the many well appreciated properties. The traditional use of tannin was for leather to increase its life-span by tanning; because of their antioxidant and astringent features they are useful also for pharmacological products and in cosmetic industry (Aires *et al*., 2016). Furthermore, they are also added to animal feed as they acts against pathogens (Krueger *et al*., 2010). Remarkable applications are also in the environmental issue because they can absorb heavy metals from aqueous solutions (Akunwa *et al*., 2014; Fan *et al*., 2014). Finally, it is mandatory to take adhesives into account; in fact, tannins have been, and still are, a meaningful part of natural adhesives and coatings (Spina *et al*., 2013; Aires *et al*., 2016; Santos *et al*., 2017). All these applications, besides the fact that tannins have a natural origin, make them an important resource to follow the concept of sustainable development and circular economy (Zikeli *et al*., 2018; 2019; 2020) reusing crop and wood industrial waste is a major achievement against environmental issues (Aires *et al*., 2016; Ham *et al*., 2015; Kim *et al*., 2015; Vázquez *et al*., 2008). Earlier studies have evaluated where extractives are located in wood, providing differentiated and sometimes contrasting results. New attempts in the field of biochar could improve the rationale use of residuals. Sweet chestnut processing residues have been also increasingly used for energy purposes, not only in terms of biomass (chipboard, in some territories also for pellets production, which even if properly tannins extracted has good characteristics as fuel.

Table 5: A list of topics related to tannins usage

Authors	Topics related to tannins
(Spina 2007), Li et al. 2013, Pizzi 1978, Pizzi et al. 1996, Pichelin et al. 1999, Santons et al. 2017, Spina et al. 2013, Vázquez et al. 2012, Pizzi 2003).	Tannin adhesives
(Zhou et al. 2013, Zhou and Pizzi 2013)	Wood/foam
(Rezar et al. 2017, Buccioni et al. 2017, Bilić-Šobot et al. 2016, Minieri et al. 2016, Liu et al. 2016, Lee et al. 2016, Carreño et al. 2015, Maisak et al. 2013, Gai et al. 2011, Budriesi et al. 2010).	Pet diet
Kolayli et al. 2016, Sorice et al. 2016, Zhan et al. 2017, Wani et al. 2017).	Medical properties
(Bargiacchi et al 2012)	Fertilizer
(Jaén et al. 2011, Beltrán et al. 2009).	Iron antioxidant

Discussion

Silvicultural priorities are to guarantee higher resilience of the species to face climatic changes and the actual and forthcoming pathogens adversities, in order to ensure good rate of production in the next years and a continuous interest by the companies. Resilience can be obtained increasing biodiversity and structural diversity in forests, and selecting the best materials. Biodiversity has already been assessed as a potential indicator of health in sweet chestnut forests. An increase in biodiversity may be reached also by implementation of thinning operations, by isolating the crowns, enhance the diameter increase and promote the production of seed (Mattioli *et al*. 2016). Thinning can be a big support reducing the request of water and nutrients and increasing wood quality with less ring shake defect. From this las point of view, thinning decrease the incidence of abrupt changes in growth which inexorably trigger the ring shake (Spina and Romagnoli, 2010; Marini *et al*., 2019).

The thinning will be of a selective type, depending on the upper plane of the forest cover and it is aimed at reducing density and coverage (Manetti *et al*., 2017). The main challenge is to make thinning sustainable by the economic point of view, that means to add further value to the obtained product, e.g. biochar or glued products which could be of interest for the local territory. Well-weighted thinning protocols could also improve the resilience of the stands to the actual climatic changes (Marini *et al*., 2019). A further solution is to sell the single lot (concession) leaving the management to the final end user. The final end users, will have care of the forest in order to get the best wood quality at the end of the rotation. A further possible action which can become a best practice is to promote organizations of local market through "virtual landing" with the aim to have a continuous and quantitatively adequate logs. For small and medium enterprises networks, Massa and Gessa (2011) introduced the Quality Function Deployment methodology (QFD) in the wood sector which appear a fine opportunity to boost chestnut value chain. The idea is to view a supply chain, or a SME network as a Virtual-Enterprise, where each actor represents a fundamental member for the realization of the final product, like different departments in a complex industry.

It seems harder to plan a reconversion of coppice stands towards a high forest management. Some silvicultural operations are supposed to increase the efficiency of coppices, they can be resumed in the lowering the height of the stools (high stool height limit the shoot sprouting and make more difficult thinning and forest harvesting operations), or reducing the stool amount inside the forest (less competition for resources and shoots with regular shape). These silvicultural operations are really expensive and it is not reasonable to assume that such measure would be adopted by the private owners without any strong public economic support.

A short-term approach to relaunch the use of the material also towards products of more added values is the imperative versatility of the final end use. By this point of view it is possible to formulate a table in which the quality of assortments is assessed at the landing to boost the versatility in the use of the species in other products instead to stop to produce load-bearing structures and poles. The visual grading is already used for operational management of some valuable species such as oaks and beech (EN 1316-1:2013).

Conclusion

In this commentary, the state of art and the main gaps of the forest–wood chain have been retraced, the main strengths and weaknesses can be resumed in the table 6:

Table 6: Main strengths and weaknesses of sweet chestnut forest chain in Italy

STRENGTHS	WEAKNESSES
Acceptable supply for Italy	The species is threatened by pathogens
Good quality timber (mainly without ring shake), suitable for many applications if well managed.	Size and shape in stems reduce wood quality and the chance to be used for more products
Good know how of the companies in wood working	Not so much appreciated by the customers for uses which are different from the structural purposes.
Environmental sustainable: low carbon foot-print, durable, suitable for wood value chains	Not yet used for modern composite products (glulams etc.), at the moment in this field only prototypes are present
Wood residues can be used to extract valuable products (tannins)	Not so much diversification in the products
Integral part of the landscape as sweet chestnut management.	The characters are not so well known by other figures working, with wood products (architects, engineering)
Use for structural purpose in line with European standards	The number of sawmills at national level is decreasing and they are involved in sweet chestnut-working they are not diversified in their production.
Suitable for short forest-wood supply chain	There is a lack of reliable statistics on wood assortment production, use and market

What are the possible action to support the sweet chestnut value chain: short supply chain should be considered on the base of advantages and quality of the species, i.e. thinking at the use of local wood and making safer the economic activities which are related to sweet chestnut wood exploitation looking also to the low carbon footprint. A further support could come from the assessment of “local value chain” (producer and customer in the same territory, that means km 0). Moving the customers to the use of local production, with the aim to revisit the traditional uses of wood can be particularly appropriate. From this point of view, restoring and requalification of historical building by using chestnut wood it might be an opportunity. Starting by the short and/or local supply chain and looking forward the European market might be the right strategy for the re-exploitation of chestnut value chain. Innovation is mandatory for our sawmills, meaning at least to improve their technology in order to give a material with a high degree of finishing and able to face with the high finishing of other species (i.e. poles of *Pinus sylvestris* or telegraphic poles of other species). To use mechanical stress grading, e.g. working with a kiln-drying system, would be a further step. The first is because of a use at higher stress grading values, while the second is in order to reach higher stress certification for construction according to the standard rules. Business networks, such as the Interregional Agreement for the Increase in Woody Harvest in Verona Woodland in 2016, consolidate product innovations and support services to businesses, and promote "sponsorship" actions that can give preference to the "Use of sweet chestnut wood in a marketing perspective of 100% Italian wood" and in light of "proximity product", also for the production of works funded with public support. A proper wood supply chain cannot be exhausted by the production of a quality product, but it should be implemented by collaboration at different institutional levels, for instance, by boosting the local use of sweet chestnut wood both as public procurement and in private consumer. Requalification of historic buildings with pre-existing structural sweet chestnut elements, consistent with the local tradition, is a final issue that deserves further attention.

The chance of chestnut wood to be more used in innovative design products is a suitable pathway towards diversification. A more active coworking with architects has to be pursued also by means of implementation projects considering the different steps of processing: from the first to the next wood transformations. Wood of lower quality could be implemented in structural uses looking to Engineering design (Frese and Blaβ 2014).

The application of innovative silvicultural approaches, where the site, social and economic conditions allow it, can exploit the full potential of the sweet chestnut. Through silviculture it is possible to produce high quality logs with high diameters, regular growths and poor defects. However, a substantial change in the sweet chestnut coppice management is fundamental: the transition from a "silviculture waiting" or articulated in sporadic interventions to an "active, participatory and sustained silviculture" (Manetti *et al*., 2009) is needed. Active silviculture means that the choice of the different options requires a particular attention to the local context. A participatory and sustained silviculture is needed because the prevalence of private owners should drive management towards shared silvicultural practices and establishing associations or consortia.

The sustainability of management will be expressed when it will be possible to program silvicultural modalities and interventions where the attention is not only to the immediate economic income, direct and limited to the single property, but where all the other functions and benefits are enhanced (the true concept of multipurpose function). From this point of view ecosystem services can be considered a valuable tool to relaunch the chestnut timber value chain they can act as an alternative in low quality forest stand and in addition to the productive function of chestnut coppice stands (Vacchiano *et al*., 2018). Chestnut wood is durable in time and for this reason it has a major potential playing as carbon stock for centuries.

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CHAPTER 2

Impact of climate, stand growth parameters and management on isotopic composition of tree rings in chestnut coppices

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(*Article*)

Impact of climate, stand growth parameters and management on isotopic composition of tree rings in chestnut coppices

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Abstract:.

Research Highlights: Chestnut trees (*Castanea sativa* Mill) growth and their responses to climate are influenced by stand-characteristics and managements. This study highlighted that chestnut tree-ring growth is not particularly influenced by climate while minimum temperature showed a positive relation with both WUEi and $\delta^{18}O$.

Background and Objectives: The aim is to check the responses of chestnut trees to climate conditions and the role of stand structure and management.

Materials and Methods: Stands with 12–14-year-old shoots were studied using dendrochronological and isotopic ($\delta^{18}O$ and $\delta^{13}C$) approaches. Correlations with climate parameters were investigated and principal component analysis was performed using as variables site-characteristics and tree growth parameters.

Results: Correlations between TRW, tree-ring $\delta^{18}O$ and $\delta^{13}C$-derived intrinsic water-use efficiency (WUEi) revealed stand-dependent effects. Highest Correlations were found between TRW and tree-rings isotopic composition. Chestnut was sensitive to high minimum temperature in March and April, with a negative relationship with TRW and positive relationship with WUEi. $\delta^{18}O$ signals were not significantly different among stands. Stand thinning had a positive effect on WUEi after 1–2 years. Stand competition (indicated by shoots/stump and stumps/ha) positively influenced both WUEi and $\delta^{18}O$

Keywords: Tree-ring width; climate change; water-use efficiency; $\delta^{13}C$; $\delta^{18}O$; chestnut tree physiology.

1. Introduction

The European chestnut (*Castanea sativa* Mill.; Fagaceae) has a long tradition in Europe; first written evidence of chestnut management is given in Theophrastus in the 4th century BC. Nowadays, the chestnut area devoted to timber production is 1.78 million hectares, corresponding to 66% of the total chestnut-growing area (Conedera *et al*. 2004) , mainly in Italy, Spain, Portugal, France and Switzerland. Management systems and intensities highly vary among countries although most of the area (79%) is managed as coppice stands (Conedera *et al*. 2004). Traditional chestnut coppices consist in short-rotation systems (5-25 years according to the targeted specific product) for the production of small to medium-sized poles (Manetti *et al*. 2017). This type of management allow to maximize the very high resprouting capacity of the stools and the remarkable initial growth-rate of the shoots, as well as recognizing the suitability of chestnut tree as a multipurpose species for landscape enhancing and conservation in rural, mountain and marginal area (Manetti *et al*. 2001)

In Italy, chestnut coppices (589’362 ha) are important not only for wood production (Spina and Romagnoli 2010; Romagnoli and Spina 2013; Romagnoli *et al*. 2014; Romagnoli *et al*. 2019b), but also because they represent an essential element of the culture and rural landscape, providing protection and ecosystem services essential for human well-being and conservation of resources (Mipaaf 2009; Manetti *et al*. 2017).

The species shows remarkable plasticity (Romagnoli *et al*. 2011), although adequate ecological conditions must be guaranteed for its healthy development. In particular, the annual minimum rainfall should not be less than 600 mm with optimal growth conditions found in areas where precipitation is above 900–1000 mm. The species can withstand long periods of drought only if it grows in soils able to retain high moisture content, thereby reducing negative effects on tree growth (Becagli *et al*. 2006). The current trend in climate, with a considerable increase in water stress during summer across the entire Mediterranean Basin (Lionello 2012), could cause a loss of growth and wood productivity, in particular in stands located at lower altitudes.

Silviculture and thinning practices can mitigate the effect of climatic stress. Thinning can have a positive effect on tree growth, improving stand resilience and resource use efficiency (Becagli *et al*. 2006; Manetti *et al*. 2016), as well as the physiological responses of trees to drought (Sohn *et al*. 2016). Thinning in chestnut has proved also to increase wood quality conditions (Spina and Romagnoli 2010; Romagnoli and Spina 2013).

Tree-ring features, such as tree-ring width (TRW) and tree-ring carbon and oxygen stable isotope composition, have proved to be powerful tools when investigating the impact of climate on the growth and physiology of tree species. Indeed, stable carbon isotopes ($\delta^{13}C$) is mainly controlled by stomatal conductance during carbon fixation (gs) and the rate of photosynthesis (A), both of which are driven by environmental conditions (Farquhar *et al*. 1982; Farquhar *et al*. 1989). $\delta^{13}C$ in tree rings has been used to study long-term aspects of tree physiology in addition to sensitivity to climatic parameters. For example an increase in $\delta^{13}C$ could indicates stomatal closure and reduced conductance to prevent water loss during drought (Battipaglia *et al*. 2010; Battipaglia *et al*. 2014) or could be due to changes in photosynthetic rates affected by irradiance during cool and wet periods coppices (Voelker *et al*. 2016). This research aims to verify the responses of chestnut trees to climate conditions and the role of stand structure and management. Five stands, differing for shoots and stumps number and density have been selected on Monte Amiata. We hypothesized that tree growth and WUEi would be influenced by stand- characteristics and by the applied management, with thinning practice that could have a positive effect on productivity.

2. Materials and Methods

2.1 Site description

The study was conducted on Monte Amiata, a lava dome located in the Province of Siena, Tuscany, central Italy, with an altitude between 990 and 1145 m a.s.l. (Fig. 1) The site is characterised by medium to high fertility due to the volcanic matrix of the soils. The parent material is a trachyte lava with a high silicate content and poor in basis; the slope is generally gentle but a few outcrops are present; erosion and landslides are absent. Brown and sub-acid soils of good physical structure are prevalent. According to the map of the Tuscany soil (http://sit.lamma.rete.toscana.it/websuoli/), the soil is *Andic Dystrudepts coarse-loamy, siliceous, mesic,* deep, very soft, non-gravelly, well drained.

Monte Amiata is an important area for chestnut cultivation because of the high growing stock and the economic relevance of wood and fruit production for local communities. Chestnut forests cover 7’500 ha in Monte Amiata, with half the area (3’500 ha) managed for wood production under public ownership. The forests are located mainly in the eastern side of the region at 800 to 1200 m a.s.l. Chestnut forests tend to be monospecific and are of anthropic origin; secondary species are rare or absent. In Italy, chestnut forests are usually managed by coppicing in a coppice-with-standards system, with the rotation age varying between regions. Forest management is different depending on ownership. In forests under private ownership, rotation is 16–20 years without thinning, with the number of standards greater than 100/ha. In forests under public ownership, rotation is usually 24–30 years, and there are generally two thinning events, the first when the coppice is 6–8 years old and the second when it is 12–15 years old; the number of standards is usually 30–50/ha. For economic reasons, the first thinning is usually not carried out. The stands investigated in this study are under public ownership.

2.2 Climate

Climate data for the period 2004–2016, recorded at the Le Vigne meteorological station in Piancastagnaio, Province of Siena (450 m a.s.l.; 723370 E UTM, 4744226 N UTM), about 2.5 to 4.5 km from the investigated stands, show an annual rainfall of 1117 mm and an annual average temperature of 13.2 °C.

The Bagnouls–Gaussen diagram (Fig. 1) for the period 2004–2016 shows a positive peak in precipitation in November as well as an absence of drought during the summer. Maximum temperatures were reached in July and August, and minimum temperatures in January and December. Precipitation decreased in April, followed by an increase in May. The sum of precipitation data shows an oscillating trend during the 2004–2016 period (Fig 2), with two significant negative peaks, in 2007 (one of the most severe droughts in recent years; (Romagnoli *et al*. 2018b) and in 2011. Positive peaks occurred in 2008, 2010 and 2014. Mean annual temperatures show an increasing trend, especially in the last few years.

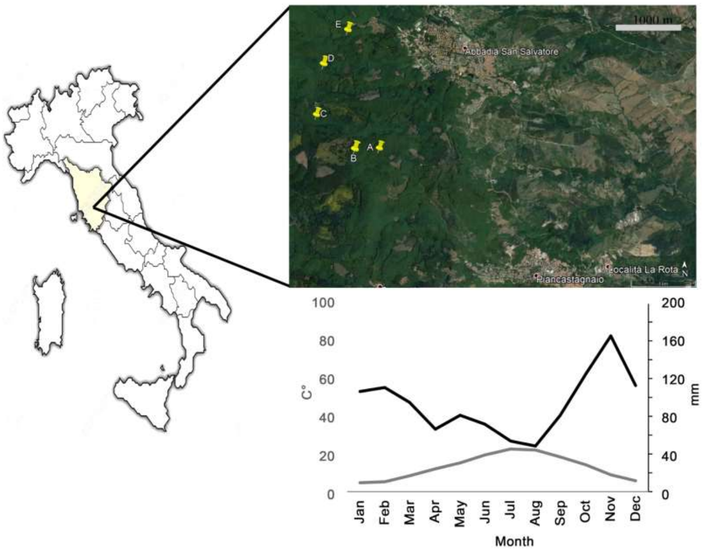

Figure 1: Study site in central Italy and Bagnouls Gaussen climatic diagram of Piancastagnaio (SI) meteo station related to the period 2004-2016.

We studied five different stands of young chestnut coppices 12–15 years in age. The stands were Sant'Antonio (stands A and B), Cipriana (stand C), Le Decine (stand D) and Acquagialla (stand E).

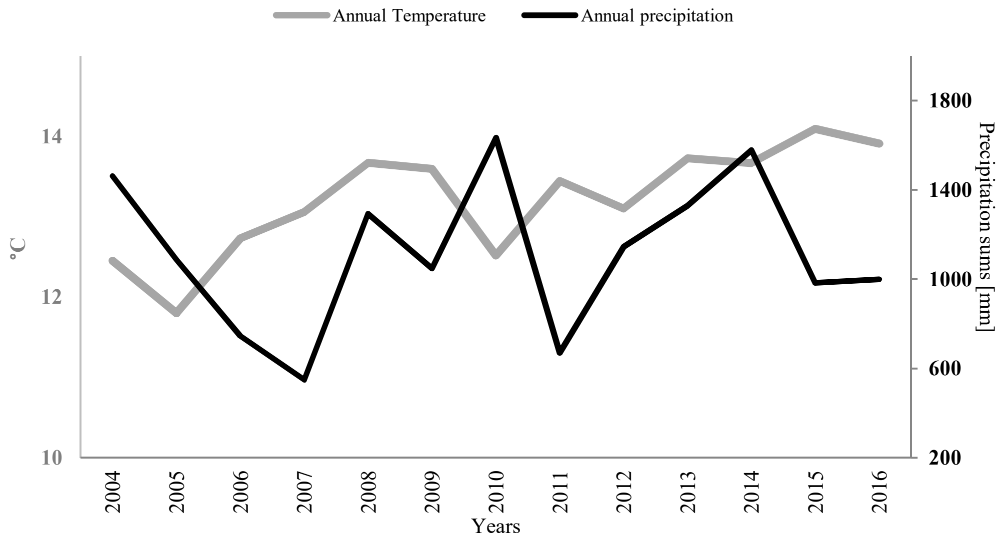

Figure 2: Climatic diagram of the mean annual temperature and total amount of precipitation for Piancastagnaio meteo station.

2.3 Growth stand conditions

The main dendrometric parameters were measured on five representative circular sampling plots with a 15 m radius. The parameters were number of stumps, number of stems, diameter at breast height (DBH), mean height of stems and the number of standards in the coppice, with their diameters and heights. In each stand, 15 old dominant shoots from different stumps were randomly selected and a disc from each stem was samples at 1.30 m above ground.

2.4 Dendrochronological analysis

Tree- ring width (TRW) was measured using a LINTAB device (RINNTECH, Heidelberg, Germany), to an accuracy of 0.01 mm, using a Leica MS5 stereomicroscope. Two orthogonal radii per disc/shoot were measured. The 15 tree-ring series from each stand was graphically and statistically cross-dated according to standard procedures in dendrochronology (Fritts 1976). Because the series were short, correlation coefficients and statistical synchronization between individual series were considered. A mean curve was built using TSAP-WIN Professional software (RINNTECH) representative of each stand, averaging the raw ring width measurements. Descriptive dendrochronological parameters were calculated, i.e. mean TRW (and standard deviation) and mean sensitivity, a measure of the mean relative change in the width of adjacent rings, calculated as the ratio of the difference in ring width between year t+1 and year t and their average according to the following formula:

$$\frac{(\mathrm{TRWt+1-TRWt})}{(\frac{\mathrm{TRWt+\quad+TRWt}}{2})} \quad (1)$$

The autoregressive moving average (ARMA) model (Corona *et al*. 1995) was used to remove growth trends and enhance the climate signal in the raw data for TRW. The model is frequently used in dendroclimatological analysis (Romagnoli and Codipietro 1996; Romagnoli *et al*. 2018b), and is based on estimation of the autocorrelation functions describing year-to-year changes in annual ring width. The term AR refers to the order of the autoregressive model applied to the tree ring series, while MA refers to the order of the moving average model. The autocorrelation analysis of the tree-ring series suggested selection of model 2.0, considering simple correlation and the partial autocorrelation profile, in the software PAST (PAleontological STatistics, University of Oslo). Indeed after the second order the autocorrelation between tree rings becomes negligible, whilst the moving average model in our investigation was not applicable due to the shortness of the tree ring series. Mathematically, AR2 and MA0 in the ARMA model can be expressed as:

$$\mathrm{TRW} = \varphi_1\mathrm{TRWt\text{-}1} + \varphi_2\mathrm{TRWt\text{-}2} + a, \quad (2)$$

where a is the residual part obtained by subtracting the modelised part (φ1TRWt-1 + φ2TRWt-2) from the TRW raw data. It corresponds to the random variation which is related to the action of climate. The coefficient φ is the autocorrelation value and it ranges from 0 to 1.

The dendroclimatological analysis was carried out using climate data from the Le Vigne meteorological station, i.e. monthly precipitation (mm) and average monthly minimum and maximum temperatures (°C). The data were organised from October of the previous year (t−1) to September of the current year (t) into a dataset of 12 monthly independent variables, obtaining three different matrices: monthly precipitation, monthly maximum temperature and monthly minimum temperature.

2.5 Dendroisotopic analysis

In each of the five stands, five discs were selected for isotope analysis using the Gleichläufigkeit (GLK) measure which evaluates the proportion of agreement/disagreement in interannual growth tendencies between trees (Eckstein and Bauch 1969). The five selected discs showed the best cross-dating (GLK >70%) with the corresponding average plot chronology. The annual growth rings formed in 2004–2016 were manually separated from each other with a razor blade under a microscope. The annual wood ring was milled and homogenised in a hammer mill (MF 10 basic Microfine grinder drive, IKA-Werke), using a mesh size of 0.5 mm. Cellulose extraction was avoided since it has been demonstrated to be not necessary for ecophysiological and dendrochronological studies that analyse the response of trees to environmental changes recorded within the sapwood, i.e. in a relatively short period (Weigt *et al*. 2015; Riechelmann *et al*. 2016; Valor *et al*. 2018). The $\delta^{13}C$ and $\delta^{18}O$ compositions of tree rings were measured at the IRMS Laboratory of the University of Campania "Luigi Vanvitelli", following standard procedures (Battipaglia *et al*. 2017).

The analysis of stable carbon isotopes in tree rings ($\delta^{13}C_{TR}$) is a powerful tool for estimation the magnitude of carbon Discrimination ($\Delta^{13}C$)

$$\Delta^{13}C\ (‰) = (\delta^{13}Ca - \delta^{13}C_{TR}) / /1 + \delta^{13}C_{TR}/1000) \quad (3)$$

where $\delta^{13}Ca$ is the isotopic value of atmospheric CO_2 and can be estimated for the period 1990–2003 from (McCarroll and Loader 2004), and measured values for the period 2004–2016 are available online (http://www.esrl.noaa.gov/gmd/).

Following Farquhar *et al*. (1982), carbon discrimination during CO_2 fixation of C3 plants is linearly related to the ratio of intercellular to atmospheric [CO_2] (c_i/c_a) by the equation:

$$\Delta^{13}C\ (‰) = a + (b - a) ci/ca, \quad (4)$$

where a is the fractionation for $^{13}CO_2$ as a result of diffusion through the air (4.4‰) and b is the fractionation during carboxylation (27‰). Combining Eqs. (3) and (4) ci can be calculated using ca, the concentration of CO_2 in the atmosphere, estimated for each year and obtained by NOAA (Mauna Loa station; http://www.esrl.noaa.gov/).

Intrinsic water use efficiency (WUE_i), is defined as the ratio of assimilation rate (A) to stomatal conductance for water vapour (g_w)(Ehleringer *et al*. 1993)

$$WUEi = A/gw \quad (5)$$

Since gw=1.6 gc(gc is the conductance for CO_2) and given that the net carbon uptake by diffusion through the stomata (A) follow Fick's law,

$$A = gc\ (ca - ci), \quad (6)$$

Then we calculate WUE_i combining Eqs 4,5, 6

$$WUEi = A/(g_c\ 1.6) = (c_a - c_i)/1.6 = c_a(b - \Delta^{13}C)/1.6(b - a) \quad (7)$$

Several studies suggested caution in simplistic interpretations of WUEi based on interspecific variation in $\delta^{13}C$, when comparing plant species with wide-ranging leaf anatomy or physiology (Seibt *et al*. 2008; Gessler *et al*. 2014). However, it has been demonstrated that $\delta^{13}C$ can be used as a 'relative index' of WUEi in order to rank species occupying the same environment (Moreno-Gutiérrez *et al*. 2012; Altieri *et al*. 2015; Moreno-Gutiérrez *et al*. 2015; Battipaglia *et al*. 2017).

2.6 Statistical analysis

Data were analysed using Past 3 software. Since the data were not normally distributed, dendrometric differences between the five studied stands were explored through a post-hoc nonparametric test (Mann-Whitney U test) of the dendrometric variables: number of shoots in each stump (SS), shoot dominant height, number of stumps per hectare, and stand volume per hectare (volume/ha).

Moreover, principal component analysis (PCA) was used to obtain information on dendrometric variables across the test sites.

The matrix was built considering for each shoot two individual parameters, basal area (g) and the number of shoots in samples stump. To the shoots of the same stand it was associated the dominant height, the number of shoots/ha and the number of stumps/ha

Finally, Pearson correlation analysis was performed to assess the relationship between the independent variables, monthly climate data from October of year t−1 to September of year t, and the dependent variables, mean isotopic series of the five stands and the residual AR model for TRW over the 2004–2016 period. We performed correlations with $\delta^{13}C$ corrected data to verify the coherence with WUEi correlations and since the main results didn't change, we decide to show only the latest.

3. Results

3.1 Dendrometric characteristics

The main dendrometric parameters of the five chestnut coppice stands on Monte Amiata are reported in Table 1.

Table 1: Dendrometric characteristics of the studied stands of chestnut at Monte Amiata.

Stand	A	B	C	D	E
ALTITUDE (m)	990	1030	1145	1100	1030
Exposure	SE	SE	SE	SE	SO
Slope (%)	0	30	0	30	40
Age (years)	15	11	12	15	11
Shoots Dominant height (m)	14.9	15.3	13.6	13.8	14.0
Stools ha^{-1}	580	623	780	1047	962
Shoots ha^{-1}	3480	3860	4810	2845	5210
Shoots/Stump	9.8	8.25	8	4.2	9.1
sd	*3.6*	*2.4*	*4.5*	*1.5*	4.0
Shoots dbh (m)	9.6	10.6	8.9	10	7.0
sd	*2.9*	*2.91*	*2.87*	*2.02*	2.0
Standards ha^{-1}	70	113	56	70	110
Volume (m^3 ha^{-1})	193	269	220	156	136
G (m^2 ha^{-1})	25.41	34.20	29.95	22.42	20.31
Tree Ring Width (1/100mm)	372.95	355.34	403.78	314.75	338.2
sd	*147.75*	*172.74*	*140.75*	*98.34*	125.8
Mean Sensitivity	0.36	0.3	0.27	0.31	0.4

To sum up, the most important outcomes were that stand D, thinned in 2014, was characterised by the lowest stem number (2.7 stems/stump), low basal area and number of stumps/ha. Despite the apparent high growth potential, as assessed from the dominant height of the stems (14.0 m at 11 years), stand E exhibited low productivity in terms of basal area (20.31 m^2ha^{-1}) and reduced growth (mean DBH = 7.0 cm).

The nonparametric Mann-Whitney U test confirmed that the number of shoot/stump (SS) in stand D was significantly lower than the SS of the other stands examined (Table 2). Furthermore, stand E had a significantly lower mean DBH and shoot basal area. The widest tree ring was in stand C, the narrowest in D, and the highest mean sensitivity was in A and E (see Table 1). There were no significant differences in dendrometric variables between A, B and C stands.

The PCA highlighted the results obtained by the nonparametric test (Fig. 3), with stand C located at an intermediate position respect to the other stands in terms of dendrometric variables, showing the widest distribution of shoots along the PCA axes.

Table 2: Mann-Whitney analysis of different dendrometric characteristics of the five stands. ***=p<0.001; **= p<0.01; *=p<0.05. D= diameter; g= shoot basal area; SS shoot/stumps

	A	**B**	**C**	**D**	**E**
A	A			D* g* SS***	D*** g***
B		B		SS***	D*** g***
C			C	SS	D*** g**
D				D	D*** g** SS***
E					E

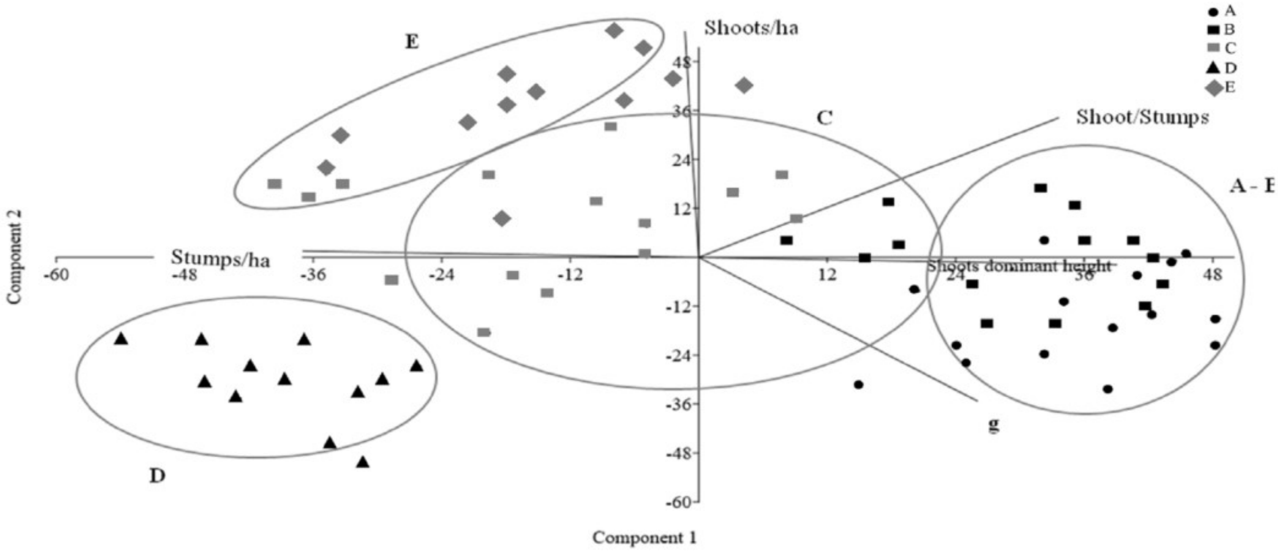

Figure 3: PCA of dendrometric variables.

E and D stands were distinct from the other stands. A and B stands were in the same group, and were quite close, because they were very close to each other. With the first two main components, the PCA was able to explain 67.72 % of the variance. The first principal component was associated positively with shoot dominant height and negatively with stumps/ha, whereas the second principal component was associated with the variable shoots/ha. The number of shoot/stump determined the different position along the two PCA axes for stand E.

3.2 Dendrochronology and dendroclimatology

The TRW series revealed a similar trend among all stands, with a strong decrease in TRWs, which is characteristic of coppice stands where regeneration is mainly vegetative, and growth is highly related to boosting by the stump (Fig. 4a). Interannual variability was quite low; the mean curve for stand D was below the curves for the other stands, and the TRWs of the stand were comparable to those of the other stands in 2011 (the dendrochronological curve for stand D crossed that for stand B, and it reached TRW values of A, B and E stands). A weak effect of the thinning carried out in 2014 was seen as a subsequent increase in ring width. Positive TRW peaks common to all stands occurred in 2009 and 2015, while common negative peaks appeared in 2010, 2014 and 2016.

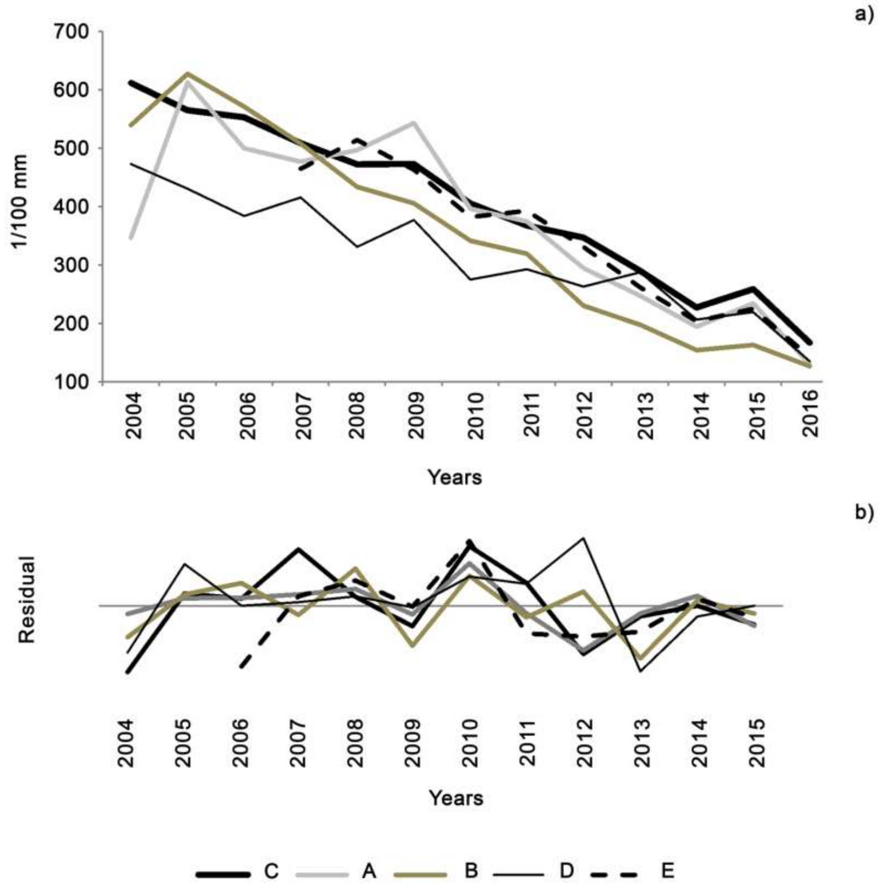

Figure 4: a) Raw TRW series of the five stands of chestnut coppices at Monte Amiata; b) Residual values of TRW by ARMA model.

The correlation function of the AR residuals of TRW and climate parameters in all five stands (Fig. 5) shows that chestnut tree-ring growth is not particularly influenced by climate (the correlation coefficients were not significant). Growth was affected mostly by minimum temperature (Fig. 5a) rather than by maximum or mean temperature (data not shown). Only stands A and B showed significant correlations between climate and growth. TRW in A had a significant positive correlation with December (t−1) precipitation (r = 0.59), stand B had a significant positive correlation with minimum temperature in November (t−1). Interestingly, both stands were characterised by the lowest number of stumps/ha (see Table 1). In stand E, a reduction in tree ring growth was associated with high precipitation in April, while increased growth may be ascribed to the high mean temperature in May. However, even if the relationship was not significant, a negative correlation with minimum temperature in March and April and a weak correlation with precipitation in December of year t−1 were reported in all stands.

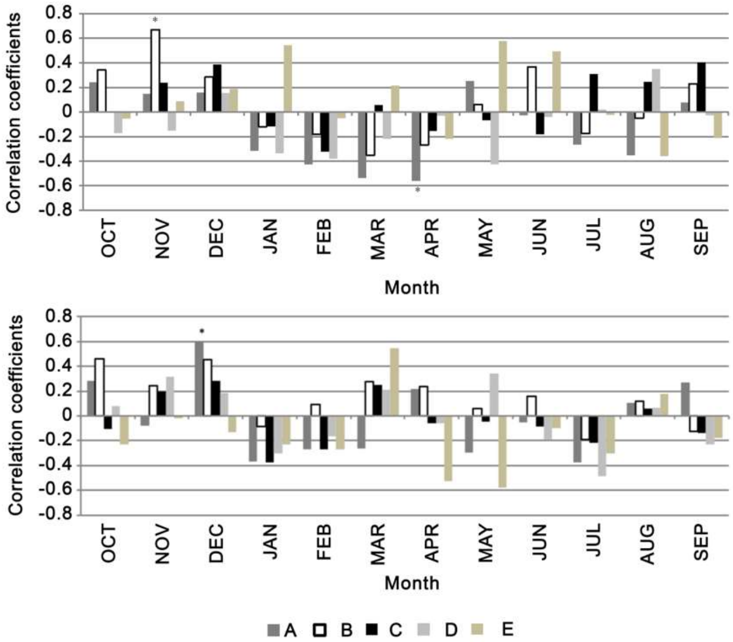

Figure 5 Correlation function of TRW with a) mean Minimum Temperature and b) precipitation for each stand

3.3 Stable isotopes

Figure 6a shows the temporal variation in $\delta^{18}O$, with a common minimum or negative annual trend during 2012 and 2014. Figure 6b shows the WUEi values, calculated from $\delta^{13}C$. The curve indicates a generally increasing trend in the last growth years, with a peak in 2015. At stand level, the E WUEi curve lay below the other stand-specific mean curves until 2013–2016. WUEi for stands A and D (Fig. 6b) increased, D was thinned at 2014, showing an opposite trend in comparison to the curves for the other stands.

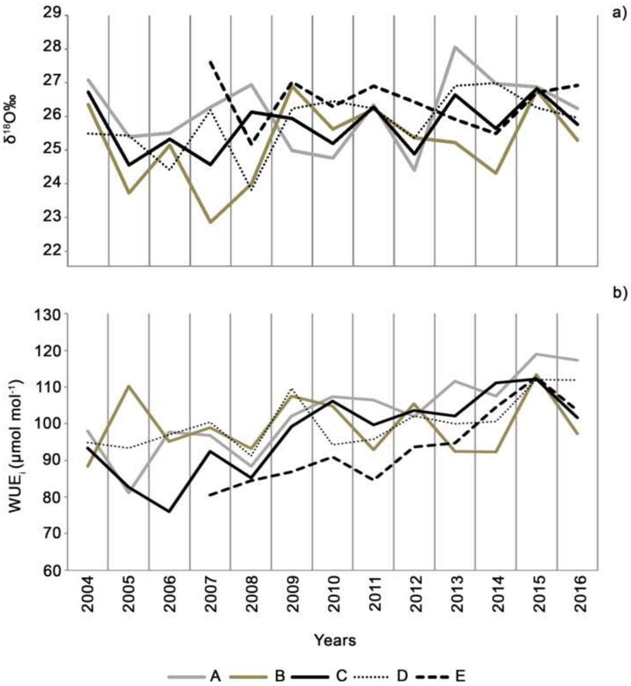

Figure 6: a) $\delta^{18}O$ time series and b) WUEi time series for each stands

$\delta^{18}O$ values of the five stands (Fig. 6a) showed high annual variability during the study period, with a positive peak in all the stands in 2015 except in the stand D. WUEi shows an evident increasing trend in the stands A, C and E, in the stand D an abrupt increase is in 2015 which is prolonged in 2016 year. ANOVA and correlation tests were performed to assess the differences between stands in all stable isotope data (data not shown). Only one significant result was obtained; $\delta^{18}O$ differed between stands E and B. This means that, in general, neither WUE_i nor $\delta^{18}O$ differed significantly between stands.

The most representative correlations between climate parameters and stable isotopes in chestnut (Fig. 7) were those between WUEi and minimum temperature, which showed the most frequent and significant responses. The response to minimum temperature was generally positive for both WUEi and $\delta^{18}O$. The most important signals were the significant positive correlations between WUEi and October–November (t−1), March–April and June–July minimum temperatures. Based on the $\delta^{18}O$ data (Fig. 7d), the temperature effect appears to have been delayed, because there was a positive correlation also in August and September (Fig. 7b). Less agreement was observed in the response to precipitation between the different stands for both isotopic values.

At the stand level, we observed a strong positive correlation between WUEi and December (t−1) minimum temperature for stand B, a positive correlation between $\delta^{18}O$ and March precipitation for C and A, a positive correlation between $\delta^{18}O$ and February precipitation for D, and a strong negative correlation between $\delta^{18}O$ and September precipitation for D and E.

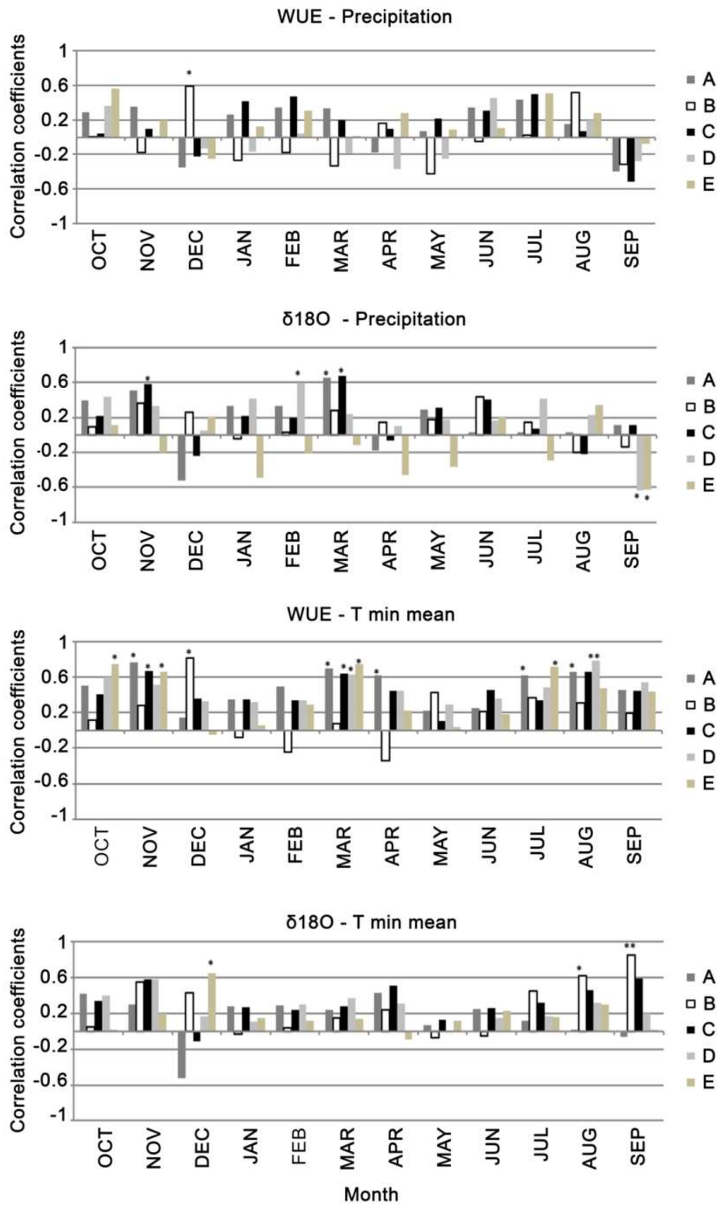

Figure 7: Correlation among climate parameters and stable isotopes

4. Discussion

4.1 Species signals

The dendrochronological series of the examined stands were short and a weaker climate signal was expected due to the strong impact of vegetative regrowth from stumps. Chestnut is characterized by relatively wide tree rings (Spina and Romagnoli 2010; Romagnoli and Spina 2013; Romagnoli *et al*. 2014), and it is not a particularly sensitive species in terms of dendrochronology (Romagnoli *et al*. 2004). Moreover, is not much studied from the dendrochronological point of view (Jarman *et al*. 2018), and physiological studies of the species are also quite rare (Fonti *et al*. 2007;

Matteo *et al*. 2010; Čufar *et al*. 2011). Based on dendrometric parameters, the selected stands in our study were found to be quite different from each other, mainly in the number of stumps/ha and the number of stems/stump. Different dendrometric parameters affect chestnut stem competition, and they may also influence the effect of climate parameters on growth. The PCA analysis in this study highlighted a different situation in stand E (highest number of stems, lowest DBH and volume/ha) compared to stand B (highest DBH, higher number of stems/stump, greatest dominant stem height, few stumps/ha) and D (Fig. 3).

Tree rings are a valuable archive of environmental information because wood formation is regulated not only by intrinsic factors, such as gene expression and hormonal signals, but also by climate variables, such as temperature and precipitation (Fonti and Giudici 2001; Schrader *et al*. 2003; Schrader *et al*. 2004; Deslauriers and Morin 2005; Gričar *et al*. 2011; de Micco *et al*. 2012; Romagnoli *et al*. 2018a).

In this study, TRW was not particularly sensitive to climate; in contrast, tree- ring isotope composition showed a stronger relationship with climate parameters. Previous studies showed that isotopes seem to be more sensitive to climate because they allow more efficient capture of signals of the plant–environment interactions (Petrucco *et al*. 2017). There are no previous records of $\delta^{18}O$ and $\delta^{13}C$ for chestnut, in addition, very few studies have dealt with chestnut wood characteristics in relation to climate parameters (Ciampi 1951; Génova and Gracia 1984; García-González and Fonti 2006; Fonti *et al*. 2007; Romagnoli *et al*. 2011). Thus, analyzing the relationships between climate parameters and TRW and stable isotopes, it was possible to extract common signals at the investigated stands ,which may be related to the ecology of chestnut. Minimum temperatures in March and April were positively related to WUEi in almost all the stands (except stand B) and $\delta^{18}O$, while a negative correlation resulted between minimum temperatures and TRW in the same period. This latter result agrees with the studies of Genova and Gracia (Génova and Gracia 1984), which also showed a negative correlation between March temperature and TRW. As reported in Cufar *et al*. (2011) and Romagnoli *et al*. (2011), the first earlywood vessels develop before the resumption of photosynthetic activity, and their formation depends on site characteristics and climatic conditions of the current year. At the latitudes of central Italy, earlywood formation starts in the first two weeks of April, and the onset of cambial division is estimated to be in the first days of April (Čufar *et al*. 2011; Romagnoli *et al*. 2011). Warm minimum temperatures hasten the onset of growth and prevent freezing-induced embolism in oak species with ring-porous wood (Cochard and Tyree 1990; Hacke. Uwe 2001; von Allmen *et al*. 2015; Pérez-de-Lis *et al*. 2017), thereby boosting the formation of earlywood vessels, which are mainly responsible for resources use efficiency in ring-porous species (von Allmen *et al*. 2015). Fonti *et al*. (2007) also showed a positive correlation between formation of earlywood vessels and minimum temperatures, and determined initial vessel appearance. Castellani (1979) estimated that the radial growth of Italian chestnut at the latitudes of the stands we examined started from March when the mean temperature exceeded 8 °C. If the minimum temperature is too high in Monte Amiata, earlywood vessel size is reduced, causing a decrease in TRW.

During the full growing season in late spring and midsummer, chestnut is not affected by the amount of precipitation, which is not particularly limiting in the Monte Amiata area. In July (stands A and E) and August (stands A, C and D), WUEi shows a positive correlation with minimum temperatures. Latewood formation and lignification in chestnut occur in that period (Reynolds-Henne *et al*. 2009; Čufar *et al*. 2011; Romagnoli *et al*. 2011), and it is well known that cell wall thickening and lignification rates increase with temperature (Pérez-de-Lis *et al*. 2017). Although water is not thought to be a limiting factor in this area, periods of drought stress with a risk of cavitation can result in a small number of latewood vessels (Romagnoli *et al*. 2018a) and more fibre cells where carbon is stored. Furthermore, the increase in WUEi depends on stomatal sensitivity which seems, in general, greater in ring-porous than in diffuse-porous species (Ouyang *et al*. 2017).

Mean temperatures and precipitation in autumn positively affected TRW in the following year in stands A and B, respectively. The effects of previous autumn–winter climatic conditions on the growth of ring-porous species have been evaluated in oak (Corona *et al*. 1995; Romagnoli and Codipietro 1996; Romagnoli *et al*. 2018a). Carbon allocation to tissues and water accumulation in soils increase earlywood production with the carbon stored during the previous growing season (Gea-Izquierdo *et al*. 2012). Interestingly, in previous studies, a negative correlation between WUEi and winter temperature has been shown for ring-porous species; however, this contrasting pattern is due to the drier conditions prevailing at the analyzed site, causing high temperatures to induce high respiration rates as well as consumption of stored carbohydrates (Gea-Izquierdo *et al*. 2012).

A global increase in WUEi in the last few decades has been recorded, based on WUEi curves. The phenomenon has been ascribed to the global CO_2 increase (Peñuelas *et al*. 2011). Although the trees we studied were generally in a healthy condition, the increase in WUEi may indicate a common adaptation to drought in Mediterranean species (Ferrio and Voltas 2005; Battipaglia *et al*. 2014). Since our trees are very young and they all experienced the same environmental conditions, growing in the same site, Monte Amiata, we prefer to focus on the comparison between the stands, instead of speculating too much on the absolute value of WUEi increase.

The $\delta^{18}O$ data are more stable through time, and the correlation between $\delta^{18}O$ and climate parameters is less significant. The oxygen isotope composition of tree rings is largely determined by the isotope composition of source water (i.e. precipitation) and evaporative effects on leaf water enrichment (Roden and Ehleringer 2000; McCarroll and Loader 2004; Treydte *et al*. 2014). The stability of the $\delta^{18}O$ signal may mean that the plant has access to the ground-water table with little variability in $\delta^{18}O$ (Battipaglia *et al*. 2009). In addition to high transport efficiency due to large vessels, the main traits of ring-porous species are lower responsiveness of transpiration to soil drying and higher potential for water uptake from underground sources due to a deeper root system. The behavior of chestnut is quite similar to that of other ring-porous species because of its isohydric response and the deep root system of stumps (von Allmen *et al*. 2015), rendering the species less sensitive to possible climatic stress. However, the source water signal can be modified by large variability in evaporative enrichment in drought-adapted Mediterranean species with tight stomatal regulation of transpiration (Ferrio and Voltas 2005), and stomatal regulation may be seen as one possible functional adaptation against drought. Other parameters can affect climate–isotopic content relationships. Reynolds-Henne *et al*. (Reynolds-Henne *et al*. 2009) ascribed the variance in tree-ring $\delta^{18}O$ not to a simplistic effect of temperature, but to its interaction with the ecological setting and physiological and biochemical properties of the tree.

4.2 Stand signals

At the stand level, E had the highest number of stems/ha and a high number of stumps/ha, so that it had the worst conditions for resource competition. Stand E was significantly climate-dependent compared to the other sites, showing significant correlations between WUEi and the climate parameters (Fig. 7a). The mean WUEi curve for stand E was below the curves for the other stands (Fig. 6b), while its TRW was comparable (see Fig. 4a). Therefore, despite the apparent high competition, tree-ring growth, as assessed by TRW, was not compromised, probably because of water availability. However, there was an abrupt change in the slope of the WUEi curve for E in the last three years, possibly related to the increase in minimum temperature in this period, making it necessary for trees in this site to adopt a strategy to increase their water-use efficiency. The PCA (Fig. 3a) showed that the dendrometric parameters of A and B stands were very similar; they were the most productive stands, but the correlations between their isotopic content and climate showed some dissimilarities.

Stand B was characterized by a small number of stumps/ha and the highest number of stems/stump. In this site, WUEi was highly related to both minimum temperature and precipitation in December t−1. The high minimum temperature of autumn t−1 may have facilitated carbohydrate allocation to tissues (Castagneri *et al*. 2018), which may in turn have supported the formation of a wider tree ring in the following spring. The smaller number of stumps in this stand may have allowed more efficient water accumulation during winter (positive correlation with precipitation), due to less competition between the root systems of the stumps, compared to the other stands. The smallest number of stumps occupying the stand, together with a high number of shoots/stump, may have made B the only stand sensitive to temperature, as determined by the positive correlation between $\delta^{18}O$ and minimum temperature. In fact, $\delta^{18}O$ showed a positive correlation with minimum temperature at the end of the summer when chestnut wood formation had almost ended (Čufar *et al*. 2011; Romagnoli *et al*. 2011) but the lignification process was still going on in some stands. The higher $\delta^{18}O$ may indicate a state of water stress, which may have been caused in part by a low canopy layer and by some site-specific conditions such as an evident slope (Ouyang *et al*. 2017) which was not present in stand A.

Stands A and C are comparable in their responses to climate. They showed a species-specific positive response of WUEi to minimum temperature, but they were also characterized by a positive correlation between $\delta^{18}O$ and March precipitation. Higher precipitation in the study site may be related to late-winter frost damage which causes early cavitation (Umebayashi and Fukuda 2018).

Stand D was located in the only site where thinning was carried out in 2014, two years before sampling. Currently, the stand has the lowest number of stems/stump. After 2014, D (Fig. 6b) showed an increase in WUEi that may be attributable, partially, to a higher overall increase in photosynthetic efficiency (Seibt *et al*. 2008; Moreno-Gutiérrez *et al*. 2012) as seen in ring-porous species. Indeed, even if the increase in WUEi, was recorded also in other stand, such as A, stand D starts to increase WUEi as soon as after the thinning practice and not before. Further, this increase has not resulted up to now in an evident increase in productivity, as has been demonstrated for other Mediterranean species (Peñuelas *et al*. 2011). Stand D generally did not show any correlations between TRW and climate; thus, the stand it is located in appears not to be significantly sensitive to climate. However, the WUEi of the stand was highly susceptible to the high minimum temperature in August, a period characterised by the driest conditions. Furthermore, in the thinned stand D, a slight increase in ring width, which reached the values of the other stands, was observed during 2015, testifying to the effect of thinning. Information on the role of thinning in WUEi is scarce and contradictory (Fotelli *et al*. 2003). For example, di Matteo *et al*. (2010) showed an increase in $\delta^{13}C$ after thinning in *Quercus cerris* L., another ring-porous species, while Martin-Benito *et al*. (2010) reported no variation in WUEi after moderate thinning. Therefore, whether thinning has an impact on isotopic content and water use efficiency needs further exploration and a long term study.

5. Conclusions

This is the first study to focus on the dendroisotopic composition of chestnut trees, and the results contribute to a better understanding of the physiology of the species. Stable isotopes in chestnut proved to be much more sensitive to climatic variation than tree-ring width. They provided better information on stress factors and possible indications of best practice for forest management to avoid the loss of physiological performance and functionality. The selected coppice stands were quite distinct from each other, mainly in terms of the number of stumps/ha and the number of stems/stump; only one stand had been thinned, but common climate signals, which are related to characteristics of the species, were detected in the investigation. Climate was not particularly limiting for growth in the Monte Amiata area, although an increasing trend in minimum temperature was observed. All the stands were sensitive to minimum temperature, especially in March and April, with a positive effect on WUEi. The signal was related to the formation of earlywood vessels, which are the main transport elements in the species. During summer (July and August), the stands showed an increase in WUEi.

Past forest management practices are reflected in part in the relationships between isotopic content and climate. The stand with the highest competition between shoots and between stumps was the most sensitive to climate parameters, testified by an increase in WUEi in the latter years of the study. This stand would have needed to store carbohydrates in the previous autumn for growth; however, if temperatures in December were too high, carbohydrate consumption could have exceeded carbohydrate accumulation.

The only stand experiencing high transpiration at the end of the summer had low vegetation coverage on soil due to the small number of stumps/ha and high competition due to the high number of stems/stump, as well as a significant slope absent in other stands.

Because of increasing minimum temperature over the last few years, it is expected that trees will need to adopt a strategy to decrease processes such as cavitation and embolism; the impact is expected to be more evident in stands characterised by high competition.

Thinning could play an important role, even at sites currently not experiencing strong climatic stress. Indeed, even if our dataset is not exhaustive, we could observe that thinning increases WUEi mainly during the summer months. The reason may be a more efficient use of water resources compared to stands with a denser canopy and a higher number of stems. This confirms the role of thinning for increasing water use efficiency in chestnut coppice stands under changing climatic conditions.

Author Contributions:

Conceptualization all the authors. Methodology: F.M. and M.C.M. field measurement, G.B. isotopic analysis, F.M., M.R., statistical processing. Writing and editing F.M., G.B., P.C., MR, C.M. All people listed as authors approved the final submitted version AND agree to share collective responsibility and accountability for the work.

All people meeting the authorship criteria are listed as authors.

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CHAPTER 3

Influence of forest stand characteristics on physical, mechanical properties and chemistry of chestnut wood

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Influence of forest stand characteristics on physical, mechanical properties and chemistry of chestnut wood

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ABSTRACT

Site conditions and forest management affect dendrometric parameters of chestnut (*Castanea sativa* Mill.) coppices, but there is modest knowledge on the effect of stand dendrometric characters on physical and mechanical wood characteristics. The aim of this study was to verify these relationships in five study areas of chestnut coppices that were 12-14 years old. Wood density, compression strength, bending strength and shrinkage were measured shoots of 5 different stand in a vulcanic site in Monte Amiata (Central – Italy). Investigated stands differ in number of stools/ha and dominant height, diameter/basal area of the shoots. The main difference in the physical characters among the stands is density. The initial results of the study showed that physical, mechanical wood characters are more dependent by the shoot than by the site. There is a positive relationships between the number of stools/ha and density, and a negative one among shoot dominant height and basal area with wood density. Spectroscopic profile by FTIR has not showed relevant differences among the stands.

1. Introduction

Wood quality can be described by many characteristics, and according to the classical meaning, it is related to the final use of wood (Jozsa and Middleton 1994; Romagnoli *et al*. 2014; Russo *et al*. 2019), affected by tree phenotype, like stem shape and bearing, stem curvature crown shape development as well as number and size of branches. From a technological point of view, wood quality is related to wood defects but also to some physical and mechanical parameters, like wood density, shrinkage, and mechanical properties (Militz *et al*., 2003, Kiaei *et al*. 2011; Genet *et al*. 2013). In recent times, wood quality based on physical and mechanical properties has also assumed a new meaning because they are considered proxy descriptors of tree resilience to climatic changes (Rathgeber *et al*. 2006; Romagnoli *et al*. 2018). The study of the environmental and site characteristics that determine wood physical and mechanical properties is quite complex because of the influence of many other factors, i.e., tree age, genetics, etc. (Nocetti *et al*. 2010; Nocetti *et al*. 2012), and the inter-correlation among the parameters, such as the most known effects of wood density on mechanical strength (Bergès *et al*. 2000; Guilley *et al*. 2003). Nevertheless, forest management and site descriptors have proved to impact the most representative physical and mechanical features in wood. The research in this field is much more developed in conifers (Munoz *et al*. 2014; Elaib *et al*. 2015; Fernandes *et al*. 2017; Rozas 2001; Hein and Dhote 2006; Kint *et al*. 2012) than in hardwood species; the related papers consider forest stands both with ring porous species, like oaks (Hing *et al*. 2015; Genet *et al*. 2013) and diffuse porous rings (Rocha *et al*. 2016). The few references on coppice and chestnut deal with the effect of silviculture to phenotypic characters and wood defects (Manetti *et al*. 2009; Lanvin and Reuling 2016; Spina and Romagnoli 2010), though certain papers have characterized wood provenance from the chemical point of view (Vinciguerra *et al*. 2011) or explored the effect of mechanical properties on ring shake (Romagnoli and Spina 2013).

In the future, stand attributes derived from silviculture operations will play a major role because of changing wood quality, and they could mitigate the impact of climatic changes, also affecting the wood-based economy of territories. From this point of view, wood chemical characteristics, both considering wood extractives and cell wall main components, are sometimes under-evaluated compared to the more macroscopic characters (physical and mechanical properties) and will assume a crucial role.

Wood chemistry is responsible for many properties, the most important being durability (Thaler *et al*. 2014; Militz *et al*. 2003; Moscatelli *et al*., 2009), which in chestnut seems less connected to the character of wood structure (Thaler *et al*. 2014)

Indeed, wood chemistry is quite related to climatic changes and the lignification process in chestnut, which has demonstrated to be site- and climate-dependent (Romagnoli *et al*. 2011; Novak *et al*. 2013), meaning the relationships among climate-stand character, wood chemistry and wood properties have a different interconnection compared to the actual state of the art.

The aims of this paper were to validate the influence of site growth conditions as assessed by forest and dendrometric measurements on physical and mechanical wood properties and chemical composition in chestnut coppices. Chemical analysis has been carried out by means of FTIR spectroscopy, which has the major advantage of being quite a speed system to investigate wood chemistry. FTIR spectroscopy associated with wood density measurements has proven to be a promising alternative to traditional methods for screening of individual- or species-specific resistance to embolism in angiosperms (Savi *et al*. 2019). This investigation represents the first attempt at dealing with these aspects for new perspectives on chestnut.

The material of the investigation is wood from young thinned shoots and one of the further possible impacts of the research is to lead to a new perspective on the alternative use of young shoots to firewood and poles with different various final products and the chance to modify the silvicultural approach in chestnut coppice stands (Manetti *et al*. 2017) also looking towards a more significant development of the short supply chain (Romagnoli *et al*., 2019; Marini *et al*., 2019b).

1. Material and methods

1.1. Study site

The study was carried out in some publicly owned young chestnut coppices (10-15 years) on Monte Amiata, Siena (Central Italy) growing in a range of altitude between 990 and 1145 m a.s.l. on volcanic soil. Monte Amiata (Siena) is an important area for chestnut cultivation; the species grows here under ecologically suitable conditions (Manetti *et al*. 2010). Climate data for the period 2004–2016 from 'Le Vigne' meteorological station (450 m a.s.l.; 723370 E UTM, 4744226 N UTM) show an annual rainfall of 1117 mm and annual average temperature of 13.2°C. Vegetation is characterized by chestnut dominance. Traditional forest management involves coppicing with standards with a rotation age of 20-22 years, and a thinning from below between 12- and 15-years old, only under public ownership.

1.2. Field sampling

The main dendrometric parameters were assessed in five circular sampling areas, with a ray of 15 m, located in Cipriana (sample area C), Sant'Antonio (A and B), Le Decine (D) and Acquagialla

(E). Diameter at breast height of all trees and a sample of 15 tree heights representative of the diametric classes were measured in each sample plot.

For the suppressed and intermediate stand layers, 15 shoots with diameter at breast heigth (dbh)>10 cm were selected and harvested in each plot. The materials were used for the characterization of chestnut wood deriving from small and medium size trees that are ordinarily eliminated by thinning.

1.3. Physical and mechanical properties

From each thinned shoot, sample logs of 40 cm in length were taken and one board was cut according to a radial pathway. The samples were then conditioned at the temperature of 20±2 °C and at 65±5% relative humidity until the boards reached an equilibrium moisture content of roughly 12%. One sample in each board containing approximately rings from 4 or 5 to 10 cm from the pith was cut with a size of 20×20×300 mm. The sample was used to measure bending strength (MOR). Furthermore, two cubic samples of size 20 x 20 x 30 mm were sampled in order to measure density at 12% (ρ_{12}) and compression strength (σ12) according to UNI ISO 3787 and total shrinkage (βV). By the original board, a sample of 50x50x20 mm according to UNI EN 1534 was cut in order to measure hardness by the Brinell method. For this last test, a 10-mm diameter carbide ball was pressed with a force of 1000 N into the test sample for 15 seconds, and the load was applied to the tangential face and at the end, the diameter of the footprint was measured.

1.4. FT-IR analysis

Before FT-IR analysis, chestnut wood samples, randomly selected, were ground in a cutting mill (IKA MF 10.1, IKA Were GmbH & Co. KG, Staufen, Germany) to pass through a 0.5 mm sieve and then oven-dried for three hours at 60°C (FD 115, Binder GmbH, Tuttlingen, Germany). Potassium bromide (KBr) pellets (diameter 13 mm) were prepared with a sample concentration of 2% using a Specac mini-pellets press at 2 bar for 5 min (Specac Inc., Fort Washington, USA). FT-IR spectra were recorded in absorption mode in the range of 4000-400 cm^{-1} with resolution of 4 cm^{-1} using a FT-IR-4100 FT-IR spectrometer (Jasco Corporation, MD USA).

All FT-IR spectra were baseline-corrected and normalized to the most intense peak of the spectra (1053 cm^{-1}) using Jasco Spectra Manager software (v2.14.02). Peak height and area were measured with the same software after constructing a baseline connecting the lowest data points on either side of the respective peak (Pandey and Pitman 2003).

1.5 Statistical analysis

Statistical analyses were carried out with Past p3 (PAleontological STatistical software, version 3.09, University of Oslo, Norway) in order to determine the effect of dendrometric parameters on physical and mechanical properties.

The differences among the five studied areas from the dendrometric perspective were subjected to analysis of variance (ANOVA) and principal component analysis (PCA). The former was carried out to determine whether the five areas were significantly different in their dendrometric values.

2. Results

2.1 Coppice forest characteristics

In table 1, the main dendrometric attributes of the five sampled coppice stands are shown. The stands, on the whole, are quite different from each other. Based on field measurements, the relationship among DBH and tree height were performed (Figure 1). Plots A and B have a similar density in terms of number of stools and shoots, which are significantly lower than the values of plots C and E. Plot D has a number of shoots/ha much lower than the other owing to thinning, which was performed at year 2014 at a reduction of at least 50%. Therefore, it can be thought that the number of individuals before thinning in area D was similar to that of area E.

Comparing the values of Table 1 and comparing with the graphs in Figure 1, it can be assessed that stand density differences are reflected in the average diameter. The lower stand competition allows the shoots to grow larger in diameter.

Plots A and B also had similar values of dominant height, hence site fertility, compared to the other three stands. This is confirmed by the comparison between the height-diameter curves (Fig. 1). In plot C, the differentiation into social classes was less marked, so the curve is flatter, probably as a consequence of the high density and low fertility.

With reference to the auxological model of the Cimini Mountains, a group of volcanic reliefs located just south of Mount Amiata in a similar environmental context (Angelini *et al*, 2013), with a site index slightly higher (A and B sample plots) and slightly lower (C, D and E) than 17 at a reference age of 25 years can be attributed. Therefore, the studied stands grow in conditions of average soil fertility in the context of volcanic reliefs of central-western Italy.

SAMPLE PLOT	A	B	C	D	E
ALTITUDE (m a.s.l.)	990	1030	1145	1100	1030
Exposure	SE	SE	SE	SE	SO
Slope (%)	0	30	0	30	40
Site index	17	17	17	17	17
Stools (n° ha^{-1})	580	623	780	1047	962
Shoots (n° ha^{-1})	3480	3860	4810	2845	5210
Shoots - top heigth (m)	14.9	15.3	13.6	13.8	14,0
Shoots dg (cm)	9.6	10.6	8.9	10	7
Volume (m^3 ha^{-1})	193	269	220	156	136
Basal area (m² ha^{-1})	25.41	34.20	29.95	22.42	20.31

Table 1: Dendrometric parameters of chestnut studied stands on Amiata mountain

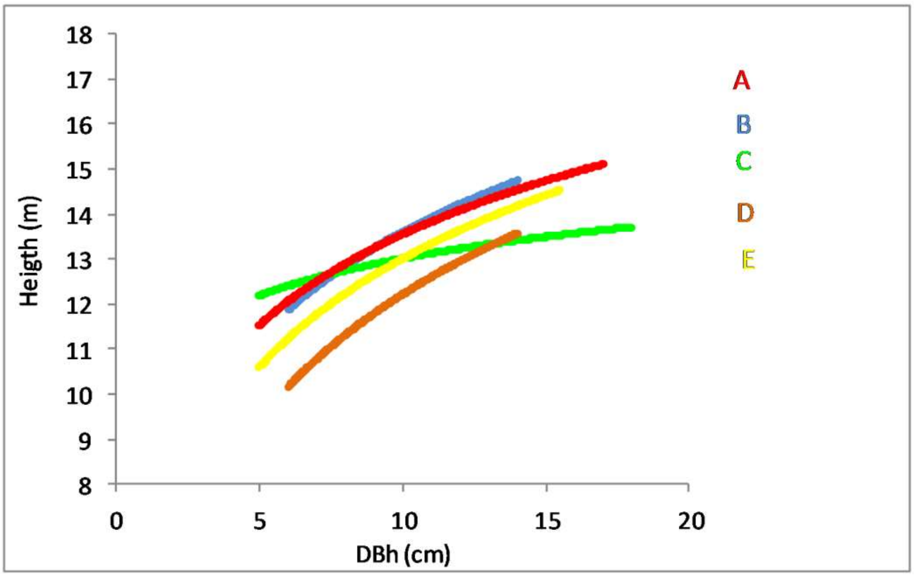

Figure 4: Height-diameter curves of the five chestnut coppices on Amiata mountain. DBH = diameter at breast height

2.2 Physical and mechanical wood properties

The mean values of the physical and mechanical properties of the wood from each site are reported in Table 2,

Area		**βV (%)**	**ρ_{12} (kg/m^3)**	**σ_{12} (MPa)**	**MOR (MPa)**	**HB (MPa)**	**RW (mm)**
A	MEAN	10.00	562	49.41	86.75	25.96	4.60
	SD	*0.96*	*38.20*	*5.13*	*15.20*	*2.71*	*0.11*
B	MEAN	9.92	557	46.59	87.89	21.94	4.10
	SD	*0.78*	*42.50*	*3.30*	*17.70*	*5.74*	*0.10*
C	MEAN	9.98	592	51.67	88.35	23.87	4.40
	SD	*1.19*	*42.70*	*4.17*	*14.80*	*5.24*	*0.09*
D	MEAN	10.68	641	54.26	97.55	28.92	4.10
	SD	*1.35*	*45.70*	*6.01*	*18.20*	*2.19*	*0.10*
E	MEAN	10.36	614	51.11	89.66	31.86	4.40
	SD	*1.27*	*34.80*	*5.49*	*13.40*		*0.11*

Table 2: Physical and mechanical characteristics of chestnut wood of Amiata provenance. Wood density at 12% moisture (ρ12), total shrinkage (βV), compression strength (σ12), bending strength (MOR), Brinell hardness (HB) and ring width (RW)

Wood density was highest in the D stand, while the lowest density value was found in B. The D stand also had the highest βV, MOR and σ_{12}, while the lowest values were in B (except for MOR). The D site had the highest variability in all the measured physical and mechanical parameters as assessed by standard deviation values.

	A	B	C	D	E
A			ρ_{12}**	SS*** ρ_{12}** σ_{12}**	D*** BA***
	B		ρ_{12}** σ_{12}***	SS*** ρ_{12}*** σ_{12}*** *HB****	D*** BA*** ρ_{12}*** σ_{12}***
		C		SS*** ρ_{12}***	D*** BA***
			D		SS*** ρ_{12}** *MOR***
				E	

Table 3: ANOVA of five different chestnut stands on the Amiata mountain, related to dendrometric parameters and physical wood properties. Wood density at 12% moisture (ρ12), total shrinkage (βV), compression strength (σ12), bending strength (MOR), Brinell hardness (HB) and ring width (RW). *** p<0,001 ** p<0,01 * p<0,05. D = diameter at breast heigth; BA = individual basal area; SS = shoot per stools.

The ANOVA (Mann-Whitney non-parametric test) reported in table 3 indicates that the A plot is very similar to B and E both for physical and mechanical wood properties, an high similarity was also assessed in the main dendrometric parameters in Marini *et al*. 2019a. The site that differs most from all others is D, especially for physical and mechanical wood parameters. Namely wood density ρ_{12} is the more frequently different value among the stands. According to Table 3, it can be supposed that diameter and basal area could affect density and compression strength in B and E. Also according to Table 3, it is evident that the number of shoots per stool is significantly different in D, and this is the effect of the thinning. At any rate, in this last case, the different number of shoots in each stool is not related to the differences in the values of wood technological parameters because the measured samples were located in the pre-thinning period (at ages 4-9 approximatively).

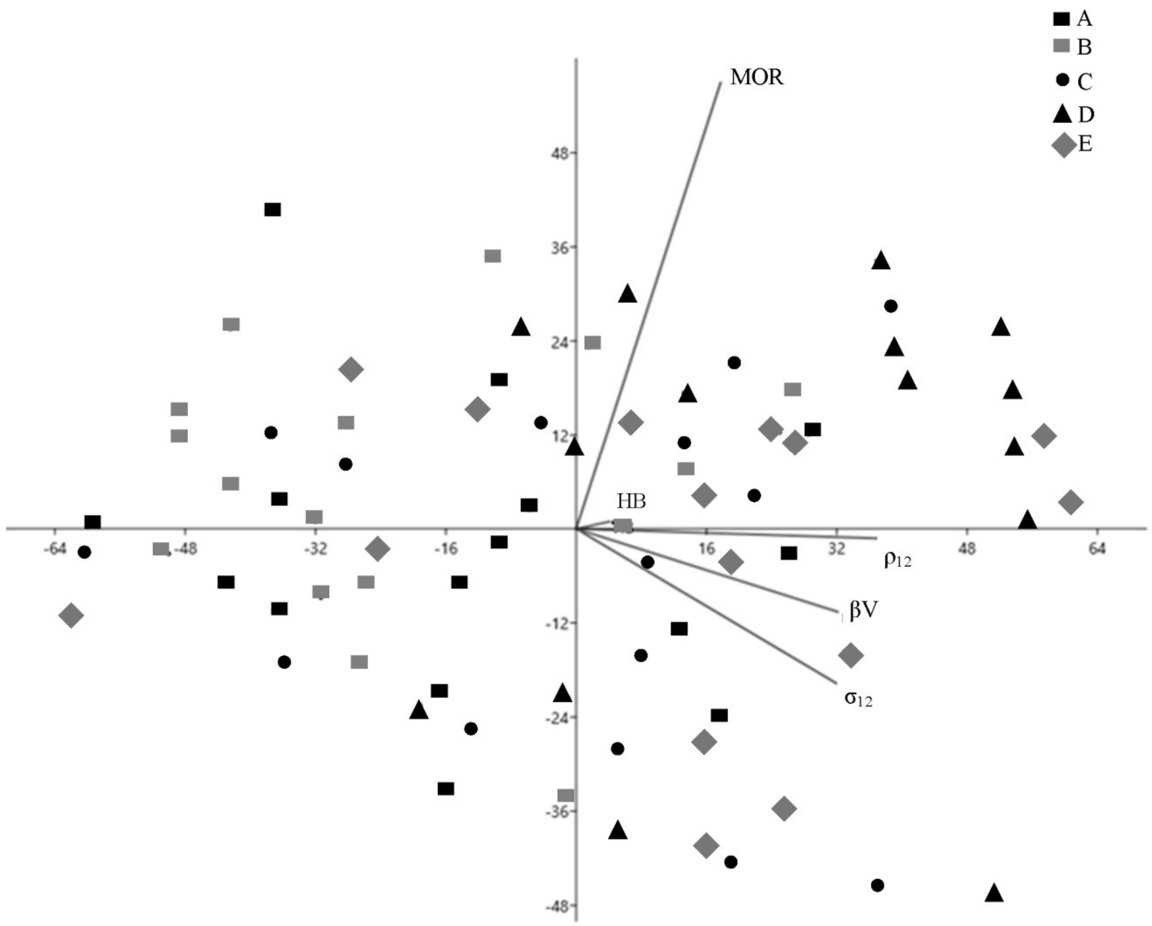

Figure 2: Principal Component Analysis of physical and mechanical wood properties of the five chestnut coppices on Amiata mountain. Wood density at 12% moisture (ρ12), total shrinkage (βV), compression strength (σ12), bending strength (MOR), Brinell hardness (HB).

The PCA of wood physical and mechanical properties does not show there to be a cluster of the samples according to the sites, demonstrating the main differences in MOR on one hand and ρ_{12}, σ_{12} and HB on the other are more drived by the individual character of each sample/shoot (Figure 2).

As the ρ_{12}, βV and σ_{12} arrays are in the same direction, they could yield information of a direct strong relationship among the variables, with reasonable shrinkages in compression strength positively affected by wood density.

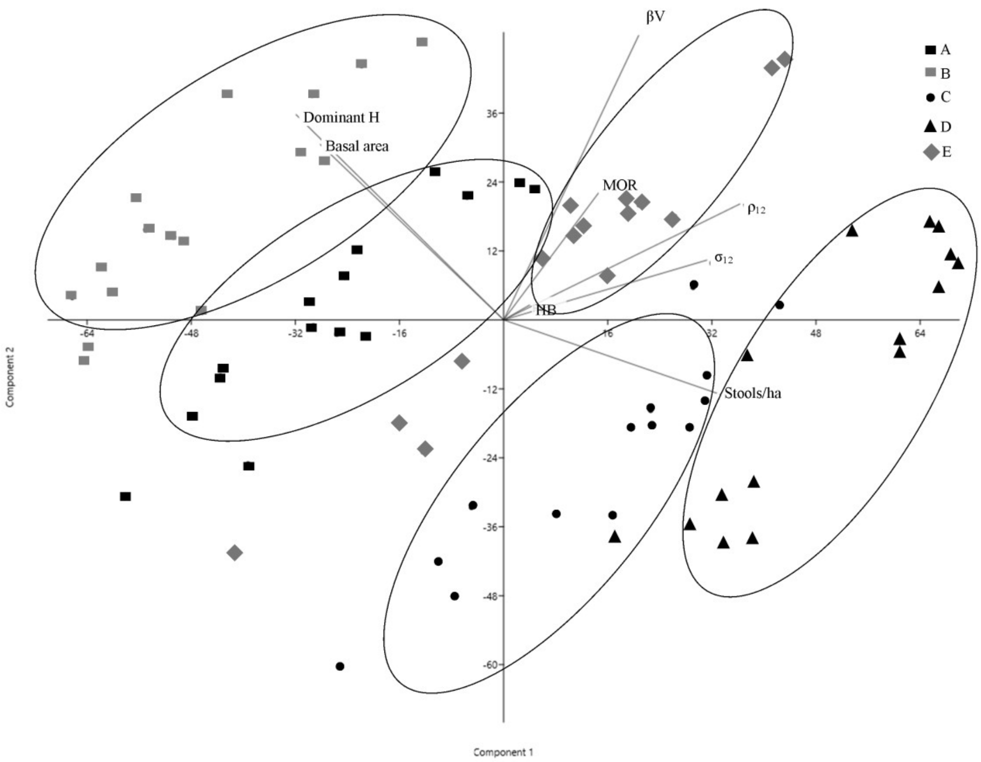

Figure 3: PCA of physical and mechanical wood properties, with principal dendrometric parameters of the five chestnut coppices on Amiata mountain. Wood density at 12% moisture (ρ12), total shrinkage (βV), compression strength (σ12), bending strength (MOR), Brinell hardness (HB), Individual shoots basal area (Basal area), stools per hectar mean value (Stools/ha), Shoots top heigth mean value per stand (Dominant H)

Adding to the PCA analysis the dendrometric parameters, such as stool per hectare, dominant height and basal area, it drives a different distribution of the samples that appear a little more grouped together when they belong to the same stand (Figure 3). By Fig. 3 it can be assessed as there is a lower number of stools per hectare, there is higher growth of the individual shoots expressed in terms of basal area and dominant height and, interestingly, all investigated physical and mechanical properties are lower. This result can be easily checked compared the values in table 1 because the stands A and B, which have the highest values of basal area and dominant height and a low number of stools per hectare are characterized by low ρ_{12} and the other related physical properties (shrinkages, compression and bending strength).

Pearson correlation between stand physical-mechanical properties with dendrometric parameters supply additional relevant information. ρ_{12} is positively correlated, significantly, to stools per hectare ($R = 0.61$; $p\text{-value}<0.005$) and negatively and significantly correlated to dominant height of shoots ($R = -0.50$; $p<0.01$). Wood density was positively and significantly correlated to the other physical parameters, βV, σ12 and HB, exhibiting correlation coefficients, respectively, of 0.56***, 0.53** and 0.72**.

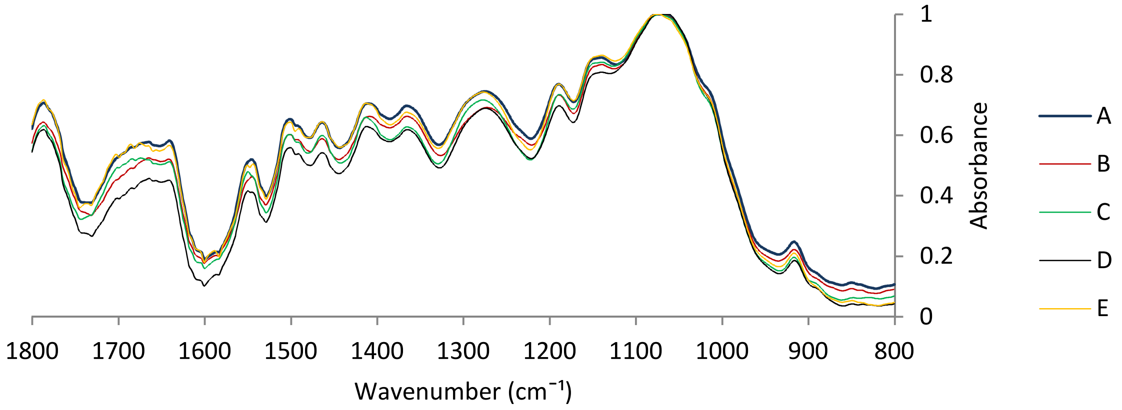

Figure 4: FTIR normalized spectra of A,B,C,D and E areas of chestnut coppices of Amiata mountain of 11-14 years old

From Figure 4, the IR spectra can be observed of chestnut representative samples that feature similar profiles among all investigated stands, which means no relevant, different chemical composition was detected in the different stands; some differences are evident in the intensity of the signals in some regions of the spectrum exclusively from site A. The peak wave numbers as reported in Pandey (1999) to be related to the lignin and cellulose IR bands as summarized in table 4. Semi-quantitative analysis based on the peak values suggest some differences in the ratio holocellulose/lignin.

Peak Wave Number (cm -1)	A		B		C		D		E	
	Height	**Area**	**Height**	**Area**	**Height**	**Area**	**Height**	**Area**	**Height**	**Area**
1740	0.226	12.900	0.281	16.488	0.208	11.556	0.264	12.823	0.232	11.003
1500	0.085	2.348	0.093	2.330	0.072	2.077	0.114	3.251	0.088	2.847
1600	0.155	9.086	0.19	12.531	0.138	9.353	0.116	10.830	0.12	6.81
1740/1500	2.65	5.49	3.02	7.07	2.88	5.56	2.31	3.94	2.63	3.86
1740/1600	1.45	1.41	1.47	1.31	1.50	1.23	2.27	1.18	1.93	1.61
1740/(1500+1600)	0.94	1.12	0.99	1.10	0.99	1.01	1.14	0.91	1.11	3.85
1500/1600	0.54	0.25	0.48	0.18	0.52	0.22	0.98	0.30	0.73	0.41

Table 4: Peak height and area of five different chestnut stands on the Amiata mountain according to Pandey (1999). 1740 cm^{-1} = Holocellulose band, 1500 cm^{-1} = Band related to wood lignin content, 1600 cm^{-1} = contributions from conjugated C-O group

Higher wood holocellulose (cellulose and hemicellulose) from site B is indicated by a strong carbonyl band at 1740 cm^{-1}. Stand E is characterized by the highest lignin content, estimated from the relative peak height and area of 1505 cm^{-1}, known as the lignin characteristic peak. The holocellulose-to-lignin ratio (1740/1500) reveals B with a prevalence of first value with respect to lignin, while in D, there is the opposite condition.

3 Discussions

The analysis of wood physical and mechanical properties in chestnut coppices of Monte Amiata has provided values comparable with those reported in other Italian provenances (Romagnoli *et al.* 2014; Spina and Romagnoli 2010; Romagnoli and Spina 2013). The values also find agreement with Militz *et al.* (2003), who refer to chestnut wood of young trees (ρ_{12} = 556 kg/m^3); the D stand has density values that are comparable to more adult trees at 31-years old at the site of Castelli Romani as reported in Romagnoli *et al.* (2014), that is a very positive result because it means it is possible to compare the physical and mechanical properties of young shoots with the more adult trees.

The selected stands differ from each other significantly in terms of certain dendrometric parameters, specifically the number of stools per hectare, the number of shoots per stool, shoot diameter and shoots height (Marini *et al.* 2019a). As evidenced by the PCA analysis, the stands do not group so much each other in the investigated wood physical and mechanical properties, suggesting that the individual (plant) behaviour prevails over the stand characteristics.

Nevertheless wood density by ANOVA proves to be significantly different among some of the stands and a negative correlation was established between wood density and dominant height and diametric growth this last can be associated to the ring width parameter (TRW). Noteworthy in recent times also in other ring-porous species, like *Quercus*, the well known positive correlation between tree ring width (i.e., growth) and density (Zobel and Van Bujten 1989) has evidenced to be reconsidered because it has been shown to be poor or even absent (Sousa *et al*. 2018). According to the obtained results, it seems possible to indicate stand density, here represented by the number of stools/ha, as a factor affecting moderately and positively wood density. Few references deal directly with the effect of forest stand density on physical and mechanical wood properties, and the few results available in the references do not seem comparable at all with our study. In planted Eucalyptus (Rocha *et al*. 2016), for example, a higher tree spacing has shown to increase in wood density, exactly the opposite of what we obtained in our study. Noteworthy the obtained result is consistent with previous research on chestnut (Romagnoli *et al*. 2014), which shows that higher competition negatively influences TRW (i.e., diameter and basal area), and there is also a negative correlation among TRW and wood density. The result obtained with the investigated chestnut coppices can support forest management decisions pertaining to the investigated wood technological characteristics. Lower competition expressed as the number of stools/ha and higher tree height decreases the value of wood density and subsequent mechanical properties. The example is in the D stand which is characterized by low values in the height tree curves, and for the opposite, the highest ρ_{12} and MOR. As wood density is indicated as a parameter that can increase the strength to the climatic stress (Romagnoli *et al*., 2018), we would have to assume a higher competition means greater probability of resilience. Nevertheless, the explanation seems too simplistic because other mechanisms, namely water use efficiency or transpiration might indicate better the impact of climatic changes on the species resilience (Marini *et al*., 2019a). The results boost new researches in possible correlations among ecophysiological indicator and wood technological parameters to assess the strength to the stressing environmental conditions.

Wood density has been demonstrated to be the most important variable connected to stand characteristics, while the other examined physical (shrinkages) and mechanical properties (MOR and compression strength) are posed at a secondary level and their role is determined mainly by the significant positive correlation with ρ_{12} values. The positive and significant correlation between wood density and shrinkages as well as mechanical properties find full agreement with other similar studies on chestnut from different provenances (Adamopulos *et al*. 2010; Genet *et al*. 2013; Romagnoli and Spina 2013; Romagnoli *et al*., 2014), and in general reflect the state of the art for the most ring-porous species (Zobel and Van Bujten 1989). In this case, the MOR value seems less related to ρ_{12} and this in an agreement with the study of Vega *et al*. (2017). The study is also a step

towards a link between phenotypic characters and wood physical and mechanical properties (Nocetti *et al*., 2010; Nocetti *et al*., 2012).
FT-IR techniques, including traditional infrared spectroscopy (FT-IR), has been used as a routine method for obtaining rapid information on the structure of wood constituents (Zhang *et al*. 2016). FTIR has been used more times to characterize the chemistry of wood (Faix 1992; Owen and Thomas 1989; Pandey 1999), however most published work describes softwood species' FT-IR spectra, and very little information is available regarding hardwood, particularly chestnut. This study marks the first time that FT-IR was applied to investigate wood quality in chestnut, though FTIR has not provided a difference in the quality of the peaks, testifying to a common chemical matrix among stands. As the stands are in the same geographical area and the soil has a similar chemical matrix, we had to expect this specific result because soil has supposed to play a fundamental role in wood chemical composition in chestnut (Vinciguerra *et al*. 2011). Certain differences are found among the semi-quantitative values, reflecting the ratio of cellulose to lignin. In this case, we are dealing with the amount of components in the cell walls that can be different owing to the presence of tension wood and a different cell wall formation and final cell wall thickness (Antonova *et al*. 2014; Antonova *et al*. 2019; Romagnoli *et al*., 2011). FTIR spectroscopy associated with wood density measurements has proven to be a promising alternative to traditional methods for screening of individual- or species-specific resistance to embolism in angiosperms (Savi *et al*. 2019) and for this reason, further research is needed to fully explore the potential of the technique in this field.

CONCLUSION

In chestnut stands, physical and mechanical properties seem more related to individual behaviour than to stand features. A moderately positive correlation between the number of stools per hectare and wood density, along with a negative correlation of shoot height and diameter with density, has been assessed in the investigated stands. FTIR analysis was used for the first time in such studies, but the results are promising and comparable with other techniques. This could be related also to the density studies and provide new information on resilience.
Wherever it grows, chestnut wood has been an important resource for local communities in Italy as it is the only broadleaved tree species able to offer sustainable development to a forest-wood chain compared to oak and beech, which are the other species dominating Apennine forests, which are actually mainly used as firewood.

Based on these assumptions, it is possible initiate new management perspectives considering the effect of the number of stools/ha and shoot/height as the most promising characteristics related to the wood characteristics and the possible effect on the resilience of chestnut coppice stand based on wood physical and mechanical measurements. We have to also take into account that in the investigated samples, juvenile wood is present at least partially, and this makes the research even more interesting owing to the chance to study and use young shoots in chestnut coppice.

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CHAPTER 4

Impact of bio-based (tannins) and nano-scale (CNC) additives on bonding properties of synthetic adhesives (PVAc and MUF) using chestnut wood from young coppice stands

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Impact of bio-based (tannins) and nano-scale (CNC) additives on bonding properties of synthetic adhesives (PVAc and MUF) using chestnut wood from young coppice stands

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Abstract: Sustainability and ecotoxicity issues call for innovations regarding eco-friendly adhesives in the production of biocomposite wood materials, and solutions involving nano-scale and biobased compounds represent a valid and promising target. One possible approach is to increase the performance of adhesives such as polyvinyl acetate (PVAc) or melamine-urea-formaldehyde (MUF) by means of nanoparticles in order to obtain a material with better mechanical and environmental resistance. When applying cellulose-based nanoparticles or tannin, the concept of a circular economy is successfully implemented into the forest/wood value chain, and chances are created to develop new value chains using byproducts of forestry operations. In this study, assortments coming from young sweet chestnut (*Castanea sativa* Mill.) coppice stands were utilized for the preparation of single lap joint assemblies using different commercial adhesives (PVAc, PU,MUF) and cellulose nanocrystals (CNC) and tannin as additives. The results showed that addition of CNC and tannin to PVAc or PVAc-PU glue increased tensile shear strength in lap joint tests presenting a promising base for future tests regarding the addition CNC and tannin in MUF or PVAc adhesive formulations. Unfortunately the tested bio-based additives did not reveal the same encouraging results when tested in the wet state.

Keywords: cellulose nanocrystals (CNC); tannin; new value chain; bioeconomy; short supply chain.

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1. Introduction

In the last years the necessity to substitute fossil resources with renewable ones has become one of the most important issues. Wood plays a major role from this point of view, but major challenges are associated to its more frequent use. One of the major topic is to diversify use of less known species and to boost the use of species of a short wood supply chain for the production of wood-based composite materials according to bioeconomy principles (Romagnoli *et al*. 2019). The market for biocomposites is expected to grow in future thanks to a combination of factors like sustainability and renewability of wood resources as well as the inherent mechanical resistance of wood

(Giovando *et al*. 2019; Marini *et al*. 2019a; Romagnoli *et al*. 2019). Among the species in Italy, which are cultivated in coppice stands and of interest for the short supply chain, sweet chestnut *(Castanea sativa* Mill.) represents one of the most important players (Giovando *et al*. 2019; Marini *et al*. 2019a). Actually, chestnut logs from coppice stands are mainly used as beams for structural purposes, while smaller shoots find application as poles in agriculture (Marini *et al*. 2019a; Romagnoli *et al*. 2019a). Chestnut wood is characterized by high durability (Militz *et al*. 2003; Moscatelli *et al*. 2009), attractive aesthetics, and mechanical resistance, especially when considering the ratio between its specific weight and its mechanical performance (Romagnoli and Spina 2013; Romagnoli *et al*. 2014). Indeed it is to be expected a change in its geographical distribution in future due to climatic changes occupying zones with higher altitudes and latitudes (Marini *et al*. 2019b). However, chestnut wood poses certain challenges regarding its quality due to the presence of ring shake defects (Spina and Romagnoli 2010; Romagnoli and Spina 2013), that can be only partially lowered by appropriate cultivation techniques (Mattioli *et al*. 2016). Thus, traditional uses of chestnut wood should be reconsidered and new applications might be focused on the production of biocomposite materials where through the utilization of wood adhesives also small logs could be processed into a final product with satisfying mechanical properties (Veigel *et al*. 2012; Pizzi 2016).

The most common adhesives in the 20th century used in industry for the manufacturing of wood composite panels (particleboards, plywood, oriented strand boards) include urea-formaldehyde, melamine-urea-formaldehyde (MUF), phenol formaldehyde resins (PF), polyurethane (PU) and polyvinyl acetate adhesives (PVAc) (Pizzi and Mittal 2011). PVAc adhesives showed advantages like polymerization under normal pressure, their consideration as safe and their great compatibility with wood. On the other hand PVAc are mechanically unstable and proof low resistance to moisture (Bomba et al. 2018), which is restricting their utilization to indoor conditions.

The social demand of eco-friendly adhesives implies to increase research efforts in testing less toxic, renewable and bio-based components in future adhesive formulations. Thus, substitution of certain components in synthetic adhesives by non-toxic bio-based compounds presents a valid and reasonable approach for the development of eco-friendly adhesive formulations, resulting in numerous literature reports (Lei *et al*. 2008; Stark *et al*. 2010; Mansouri *et al*. 2011; Wang *et al*. 2011; Lan *et al*. 2012; Liu *et al*. 2014; Heon Kwon *et al*. 2015; Cui *et al*. 2015; Zhang *et al*. 2016; Leng *et al*. 2017).

Cellulose as the most abundant biopolymer on our planet has been used in many applications, especially in its form of nanocellulose like cellulose nanocrystals (CNC), thanks to several advantages (high strength and low weight i.e.), representing a promising component for the development of innovative reinforced wood adhesives (Cui et al. 2015; Leng et al. 2017). Other relevant green adhesive formulations contain tannins, designed in order to reduce formaldehyde emissions (Mansouri et al. 2011; Zhou et al. 2013). Among hydrolysable tannins, chestnut tannin has demonstrated importance for industry (Giovando et al. 2019), and applying it as adhesive component for chestnut wood panels, a circular economy concept applied in forestry could be fully developed. In order to speed-up the process of utilization of natural compounds as cellulose or tannin, mixing them with synthetic adhesives can be an interesting step towards the development of fully bio-based adhesive systems.

Among synthetic adhesives, PVAc presents strong advantages as its water-solubility, biodegradability and excellent chemical resistance as well as the fact that it is considered as non-toxic for human health. The big disadvantage is the poor resistance in wet conditions and high temperatures. For this reason, several attempts with encouraging results were carried out in order to increase the performance of PVAc through the addition of CNC and other compounds. In this study with the aim for increasing strength and resistance of PVAc under outdoor conditions, the influence of tannin and cellulose nanocrystals (CNC) as additives in PVAc were investigated and compared with another important synthetic adhesive system (MUF) which is suitable for outdoor applications as well as for structural purposes. Mechanical tests were carried out on single lap joint panels made from young chestnut shoots from coppice stands, in order to show the possibility of a sustainable use of wood from a short supply chain with eco-friendly adhesives. Further, as a new diagnostic method in wood technology, ultraviolet fluorescence (UVF) analysis as a non-destructive technique that takes advantage of the visible light response of surfaces illuminated by UV radiation was applied (Cardinali *et al.* 2002). Non-invasiveness, practicality and immediate responses, thanks to newly developed LED light sources, make UVF one of the most used techniques in cultural heritage conservation sciences but up-to-date no publications regarding wood analysis can be found.

2. Materials and Methods

2.1 Wood material

Chestnut *(Castanea sativa* Mill.) wood derived from young chestnut trees with an age of 12-15 years cultivated in coppice stands on Amiata Mountain, Tuscany, central Italy. Trunks with a length of 1.5 m were cut and from each trunk, sample logs of 40 cm length were taken in order to cut boards in radial direction with 2 cm thickness and 8 cm width. The boards were then cut along fiber direction and sanded to a final thickness of 5 mm, followed by conditioning in standard climate (temperature: 20±2 °C, relative humidity: 65±5%) to reach an equilibrium moisture content of about 12% according to (UNI EN 302-1 2013).

2.2 Adhesives, additives and gluing conditions

Commercial PVAc adhesive for non-structural applications as well as a MUF adhesive system were used as reference formulations and as the base for the preparation of 7 different formulations containing CNC and/or tannin (Table 1). PVAc adhesive is classified as D3 according to (UNI EN 204:2016) and the MUF adhesive system is classified as class 1 according to EN 301:2013. In order to introduce a further comparison, also looking to the preliminary results, a bicomponent adhesive was used to modify the original PVAc adhesive by mixing it with polyurethane (PU) glue. This protocol renders the original PVAc adhesive more suitable for exterior applications with exposure to weather (durability class D4 according to UNI EN 204:2016). The new mix was used as a base for another CNC-modified adhesive formulation. CNC were purchased from CelluForce Inc. (Montreal, Canada) and chestnut tannin (Saviotan®) was used from Saviotan (Gruppo Saviola - Radicofani, Italy). CNC and tannins were mixed manually into the PVAc and MUF adhesives.

Bonding procedures were carried out according to instructions given by the adhesives' manufacturers. After manual application of the requested amount of glue (130 g/m^2 PVA and 250 g/m^2 MUF) using an aluminum spatula, the chestnut wood tangential panels were bonded in parallel orientation and pressed for 90 minutes at 50 bar (5 MPa) and ambient temperature. After pressing, the glued samples were dried in standard climate at 20 °C and 65% relative humidity (RH) according to (UNI EN 302-1: 2013). A set of 18 lap joint test pieces were prepared for each glue formulation give in Table 1.

Table 2: Adhesive formulations based on commercial adhesives and cellulose nanocrystals and tannins as additives used for gluing experiments.

Adhesive formulations	Adhesive ID	CNC [%]	Tannin [%]
Polyvinyl acetate adhesive (PVAc)	1 (PVAc)	0	0
PVAc + Cellulose Nanocrystals (CNC)	2 (PVAc-CNC)	5	0
PVAc + polyurethane adhesive (PU) + CNC	3 (PVAc-PU-CNC)	5	0
PVAc + CNC + Tannin (T)	4 (PVAc-CNC-T)	5	5
Melamine-urea-formaldehyde adhesive (MUF)	6 (MUF)	0	0
MUF + CNC	5 (MUF-CNC)	5	0
T + CNC	7 (T-CNC)	5	70

2.3 SEM analysis

After cutting to the requested dimensions for the sample holders, the glued samples were prepared at the Electron Microscopy Section (CIME) of the Large Equipment Center (CGA) of the University of Tuscia for morphological analysis using SEM. Samples were attached to aluminum stubs using conductive double-sided carbon tape and coated with gold using a Balzers MED 010 sputtering unit (Oerlikon Balzers, Balzers, Liechtenstein). SEM analysis was done using a JEOL JSM 6010 LA instrument (JEOL Limited, Tokyo, Japan), both in transversal and tangential sample direction, in order to investigate the respective glue-lines. Dimensions of glue-lines were determined on the SEM micrographs using Adobe Photoshop CS2 software package (Adobe Systems, San Jose, CA, USA).

2.4 Mechanical tests

The glued and conditioned wood panels were cut to the final dimensions of the lap joint test pieces (150 x 20 x 10 mm) in order to prepare 8 test pieces for each of the treatments A1, A2 and A3 (**Errore. L'origine riferimento non è stata trovata.**), followed by tensile shear strength (f_v) testing in a universal testing machine (Zwick Roell Z050, Germany). The values of the tensile shear strength

(f_V) of the samples were calculated using formula (1), where F_{max} is the total force at failure in Newton (N) and A is the glued test surface (200 mm^2).

$$(1) \quad f_V = F_{max}/A$$

Table 3: Type and duration of treatment prior to tensile shear testing (adapted from EN 302-1:2013).

Designation	Treatment
A1	No treatment other than conditioning in standard climate [20/65]
A2	4 days soaking in cold water at (20 ± 5) °C Samples tested in the wet state
A3	4 days soaking in cold water at (20 ± 5) °C Reconditioning in standard climate [20/65] to original mass Samples tested in the dry state

According to (UNI EN 302-1: 2013), an estimation of the proportion of test surface covered by wood fibers (graded as 0 %, 10 %, 20 %, etc., to 100 % wood failure) was carried out for each sample. For each treatment and glue formulation, average wood failure with standard deviation was determined.

2.5 Ultraviolet Fluorescence Photography

UVF instrumentation consisted of a UV-A LED light source (Madatec srl, Pessano con Bernago, MI, Italy) with a λmax of 365-370 nm, a mirrorless digital photo camera with 18 Mpx resolution (Madatec) and a HOYA UV&IR Cut filter (Kenko Tokina Co., Ltd., Nakano, Japan) . For an excellent result, it is important to apply the light source with an angle of 30-45° respect to the samples, in order to allow homogeneous illumination and make sure that the visible component is only the one emitted from the examined surface. Further, working in total darkness is mandatory and pPhotos are taken with long exposure times in order to record fluorescence deriving from the investigated lignocellulosic material with multiplied intensity.

3. Results and discussions

3.1. Morphological characterization using Scanning Electron Microscopy

SEM analysis allowed for the determination of an average glue-line thickness over the length of the analyzed sample. All glue-lines of the different glue formulations had an average thickness around 80-100 µm (**Errore. L'origine riferimento non è stata trovata.**), even if in the samples D (PVAc-PU-CNC) and G (MUF) the respective glue-lines were thicker than observed for the rest of the samples, in the case of G also due to the higher amount of adhesive applied. Interestingly, the formulations with added CNC (samples B and F) showed a thinner bond line compared to their respective control formulations (A and E), what could indicate a structurizing effect of CNC bundles involved in MUF polymerization via their methylol sidechains and orientated parallel to the wood fiber. Inclusions, which were classified as air bubbles, were observed within the glue-lines of the samples A, B and C (Figure 1). In sample A (PVAc) and C (PVAc-PU-CNC), the inclusions were rather large with a length of 175 and 200 μm, respectively, while the one in the glue-line in sample B (PVAc-CNC) was minor (40 μm). All three cases were apparently caused by surface irregularities of the wood panels, due to collapsed vessels in the ring porous structure of chestnut wood, which were observed nearby the inclusions (Figure 1).

In sample A (PVAc) the glue-line was widely attached to the wood substrate. When CNC (sample B) and CNC plus tannin (sample D) were added to PVAc, the respective glue-lines were in part detached from the interphase with the wood surfaces. Adding CNC reportedly increased the viscosity of PVAc (Veigel *et al*. 2012; Jiang *et al*. 2018) resulting in less penetration of the glue into the wood surface, thus increasing the risk for delamination.

Sample G was glued with an adhesive formulation consisting solely of tannin, CNC and water (Table 1). The respective glue-line was very well attached to the wood panels' surfaces. However, creeps were detected within the glue-line, indicating unsuccessful curing of this adhesive formulation (**Errore. L'origine riferimento non è stata trovata.**, left). Furthermore a possible auto-condensation in tannins could have affected the cohesion in the bond layer, affecting negatively the wood bonding process (Böhm *et al*. 2016). During the mixing of tannin and CNC, a dramatic viscosity increase was observed preventing successful homogenous distribution over the complete wood panel surface and thus limiting gluing performance, as it was also observed in other investigations (Pinkl *et al*. 2017; Gonçalves *et al*. 2019).

In contrast to the samples B, D and G, the glue-lines of sample F (MUF-CNC) and E (MUF) were considered as nearly perfect, as they presented well developed interphases with the wood panels surfaces and no air inclusions within the glue-line, confirming reports regarding the high compatibility of MUF resins with wood and their strong adhesion to cellulose fibers (Veigel *et al*. 2012). In sample F successful incorporation of the added CNC within the MUF adhesive matrix was observed, firstly maintaining its viscosity during mixing as well as regarding a successful glue penetration inside the wood cells. In fact, in sample F the adhesive penetrated very deeply following the parenchymatic rays which facilitated the spreading of the adhesive (Figure 1, F1).

At higher magnifications, CNC in form of bundles was detected widespread in the adhesive matrix both in PVAc and MUF, similarly to the results obtained by (Peng *et al*. 2014) (Figure 1- C1, and

Figure 2). In the SEM images of the adhesive formulation CNC-T CNC bundles were detected too, apparently in parallel orientation to the wood panel fibers which could provide additional strength of the glue-line and compensate creeps (**Errore. L'origine riferimento non è stata trovata.**, center and right).

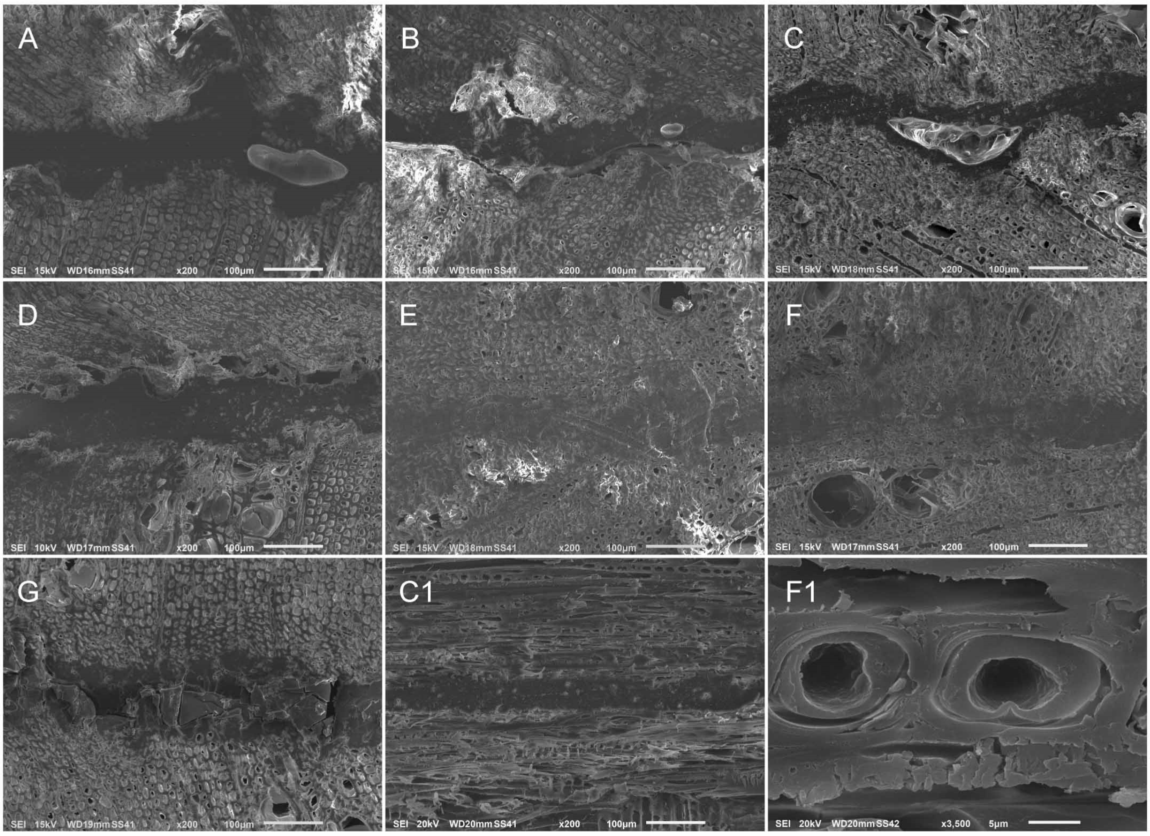

Figure 5: Transversal cuts of the glued samples using the different adhesive formulations: A (PVAc), B (PVAc-CNC), C (PVAc-PU-CNC, D (PVAc-CNC-T), E (MUF), F (MUF-CNC), G (T-CNC), C1 magnification of sample C, F1 magnification of a tangential cut of sample F.

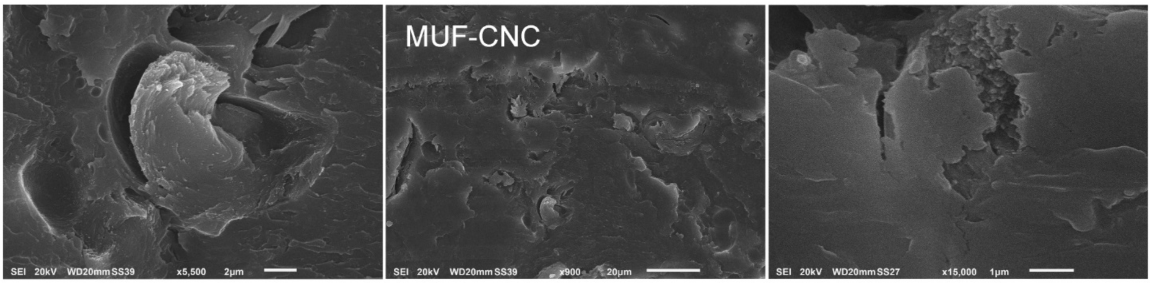

Figure 6: Bundles of cellulose nanocrystals (CNC) in a higher magnification of the glue-line of sample L (MUF-CNC).

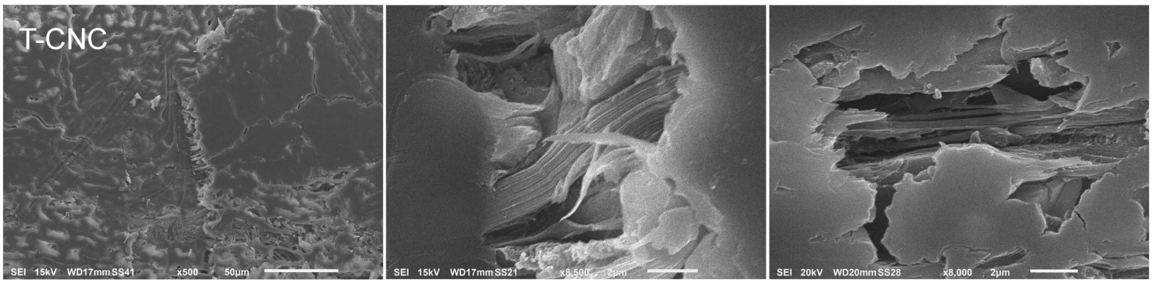

Figure 7: Creeps inside the glue-line of sample P (T-CNC, left). Bundles of cellulose nanocrystals inside the glue-line (center and right).

Table 4: Glue-line thickness of the tested adhesive formulations.

Sample label	Sample ID	Glue-line thickness [μm]
A	(PVA)	92.4
B	(PVA-CNC)	64.1
C	(PVA-PU-CNC)	80.9
D	(PVA-CNC-T)	101.8
E	(MUF)	140.0
F	(MUF-CNC)	82.8
G	**(T-CNC)**	**92.4**

3.2. Mechanical properties of laminated veneer lumber samples

Errore. L'origine riferimento non è stata trovata. shows the average shear strength of the lap joint test specimen prepared using seven different adhesive formulations, after the respective treatments A1, A2 and A3 (**Errore. L'origine riferimento non è stata trovata.**). The obtained values were also compared with their respective minimum and maximum shear strength results, their variability and the percentage of wood failure reported in the table 4. The results will be discussed in the following according to the respective treatments.

3.3. Dry conditions

In formulation 2 (PVAc-CNC), relative to its control (PVAc), the added CNC affected positively the resistance after treatment A1 in agreement with the results of (Jiang *et al*. 2018), who supposed an interlocking effect due to increased cross-linking of the methylene groups from PVAc with hydroxyl groups from CNC as well as cellulose from wood. Accordingly, the UVF photographs (Figure 5, A) revealed presence of glue on both sides of the lap joints and wood failure was indicated by brown spots. The partial delamination of the glue line from the wood surfaces however

, as assessed by SEM (Figure 1 B), was supported by the respective UV photograph which showed adhesive only on one side of the lap joint, due to a weakly developed interphase adhesive-wood (Figure 5, B). In Figure 5 B particles of aggregated CNC are visible confirming a strong agglomeration tendency reported elsewhere for CNC (Veigel *et al*. 2012).

For adhesive formulation 4, containing both CNC and tannin, the determined shear strength in the dry state A1 was not significantly higher compared to pure PVAc. Shear strength results showed rather high variability, however, when excluding the values below the threshold of 2 N/mm^2, minimum shear strength values were evidently increased reaching 9.25 N/mm^2 compared to 2 N/mm^2 in the control sample.

In conclusion, CNC and CNC-tannin as additives could increase the performance of PVAc adhesive, but glue handling during application onto the wood panels was identified as a crucial point. Further positive evidence was the percentage of wood failure which was higher compared to its control, both considering minimum and maximum values (Table 4).

The highest average lap joint tensile shear strength was observed for the adhesive formulations 5 (MUF-CNC) and 6 (MUF), reaching almost 12 N/mm^2. Compared to its control, the CNC-enriched formulation demonstrated very similar values after all three treatments. Considering the polymerization mechanism of MUF resins, where methylol groups and primary amines from urea and melamine react in a condensation reaction (Gonçalves *et al*. 2019), the high presence of side-chain methylol groups in cellulose was expected to promote cross-linking of CNC with amine groups of urea and melamine during the gluing process, leading to profound integration of CNC into the structure of the MUF resin. Since for methylolation of urea and melamine the use of formaldehyde is essential, CNC could present a promising substitute for formaldehyde moieties in MUF resin formulations offering their already present methylol side-chains for the addition of urea or melamin via condensation reactions creating methylene or methylene-ether bridges. The comparable performance of wood panels glued with MUF and MUF-CNC, was confirmed by their similar wood failure results. Furthermore, UV photographs revealed a homogeneous distribution of both adhesive formulations MUF and MUF-CNC on both contact sides of the lap joint (Fig. 5 D and E). When using the glue formulations MUF and MUF-CNC, shear strength values showed the lowest standard deviations, demonstrating highly homogeneous glue-lines along the length of the glued panels. Although CNC-addition to a MUF adhesive system did not result in higher shear strength under dry conditions, substitution of a part of the applied synthetic adhesive system by a renewable compound must be highlighted when aiming for more eco-friendly adhesive systems.

3.4. Wetting (A2) and wetting-reconditioning (A3)

In the wet-state, shear strength was substantially reduced (both after A2 and A3). Exceptionally, after treatment A3, adhesive formulation 3 (PVAc-PU-CNC) showed shear strength values higher than after A1 and A2 and almost in the range of the MUF adhesives (5 and 6), which fulfill requirements for the utilization for structural purposes (Table 1). Furthermore, a higher percentage of wood failure after shear strength testing was observed for formulation 3 (Table 4).Considering the results for formulation 2, where solely CNC was added to PVAc and shear strength after A3 was lower than for formulation 1, the reason for the higher shear strength of formulation 3 after treatment A3 however must be attributed to the addition of the PU component.

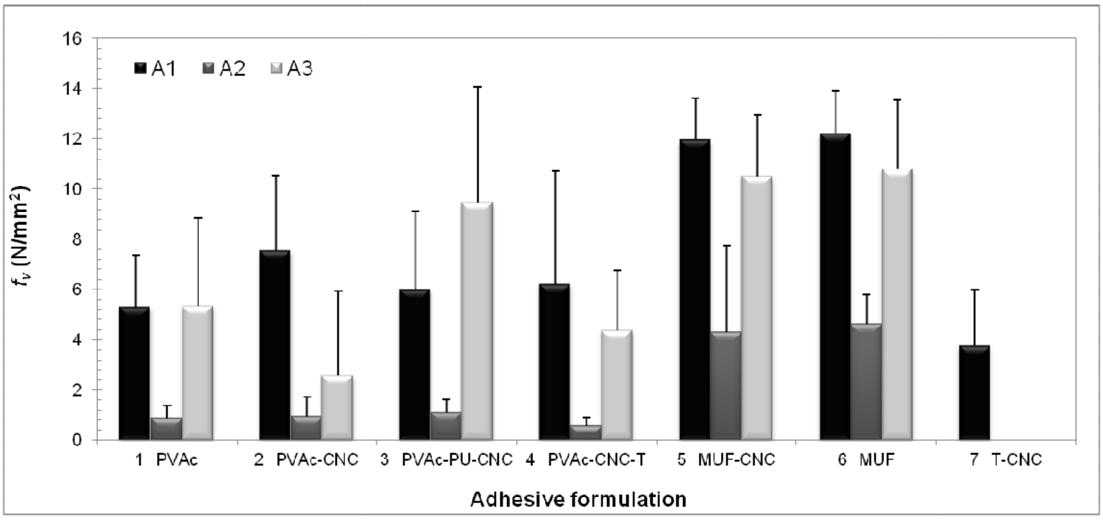

Figure 8: Average tensile shear strength (fv) of chestnut wood lap-joint specimens, according to EN 302:1-2013, glued with different adhesive formulations.

Table 5: Mean shear strength with standard deviation (SD), coefficient of variation (CV), minimum and maximum shear strength, number (#) of samples with a shear strength under 2 N/mm^2, invalid shear strength test samples, mean wood failure (WF) percentage with standard deviation, minimum and maximum wood failure.

Treatment type	Sample name	# samples	Mean Shear strength ± SD [N/mm^2]	CV [%]	Shear strength Min	Shear strength Max	# samples under threshold 2 N/mm^2	Invalid test samples	Mean WF ± SD [%]	WF Min [%]	WF Max [%]
A1	PVAc	8	5.32±2.06	38.72	2	7.82	0	0	50±25.0	10	60
	PVAc-CNC	5	7.54±3.02	40.05	2.82	11.24	0	0	40±19.2	20	80
	PVAc-PU-CNC	7	6.01±3.12	51.91	2.79	11.14	1	1	20±18.3	0	50
	PVAc-CNC-T	5	6.22±4.52	72.66	9.25	9.99	2	0	40±30.3	0	80
	MUF-CNC	8	11.95±1.67	13.97	9.83	13.73	0	0	90±9.1	70	100
	MUF	8	12.19±1.71	14.02	9.96	14.34	0	0	90±7.5	80	100
	T-CNC	6	5.04±2.22	44.04	4.84	5.24	1	3	8.3±7.5	0	20
A2	PVAc	4	0.85±0.54	63.52	0.38	1.61	0	0	20±5.7	20	30
	PVAc-CNC	5	0.92±0.8	86.95	0.23	1.79	0	2	10±5.4	10	20
	PVAc-PU-CNC	5	1.1±0.5	45.45	0.49	1.7	0	0	10±5.4	10	20
	PVAc-CNC-T	5	0.56±0.34	60.71	0.17	0.95	0	1	30±8.9	20	40
	MUF-CNC	5	4.31±3.46	80.27	0.83	9.01	2	0	80±5.4	80	90
	MUF	5	4.62±1.17	25.32	3	6.01	1	0	70±8.9	60	80
	T-CNC	3	INVALID	-	-	-	-	3	-	-	-
A3	PVAc	2	5.33±3.53	66.22	2.82	7.82	0	0	70±21.2	60	90
	PVAc-CNC	6	2.58±3.33	129.0	0.15	8.98	2	0	30±16.4	20	60
	PVAc-PU-CNC	5	9.48±4.6	48.52	2.14	14.09	1	0	70±19.2	40	90
	PVAc-CNC-T	5	4.39±2.35	53.53	1.23	6.74	1	0	60±28.2	20	80
	MUF-CNC	5	10.51±2.45	23.31	8.25	12.95	0	0	90±17.8	60	100
	MUF	4	10.8±2.77	25.64	7.56	13.94	1	0	80±12.2	60	90
	T-CNC	6	INVALID	-	-	-	-	6	-	-	-

After treatment A2, the addition of CNC to PVAc resulted in a slight shear strength increase, but in contrast gave much lower shear strength after wetting and re-conditioning (A3). Future investigations could additionally investigate other benefits of CNC-reinforced PVAc glues such as superior heat resistance that were reported by other authors (López-Suevos *et al*. 2010; Veigel *et al*. 2011). Using additional tannin reinforcement (PVAc-CNC-T), a slightly better performance was observed compared to the addition of only CNC to PVAc, leading to an increase of shear strength after treatment A3 as well as a moderate increase of wood failure after both treatments A2 and A3. The effect of tannin as an efficient glue additive capacity has been already proved elsewhere (Spina *et al*. 2013; Zanetti *et al*. 2014).

Adding CNC to the MUF adhesive system, no evident effect on the measured shear strength in the wet-state was observed. Nevertheless, a higher percentage of wood failure was noted which could indicate better performance in outdoor conditions, supported by a low variance of the different samples glued with formulation 5 (Table 4, CV). Analysis of the UV photographs further showed rather homogenous distribution of CNC (blue absorption) within the glue line (Figure 5, G). Good dispersability of cellulose nanofibrils in UF resins was also reported by (Veigel *et al*. 2011).

Adhesive formulation 7, which contained solely tannin and CNC, demonstrated lower shear strength and the glued samples completely delaminated during treatments A2 and A3, supposedly due to tannin solubility in water, which made tensile shear strength measurements impossible. In sample H (PVAc-CNC-T after treatment A2, Figure 5), the strong coloring of tannin, even in low percentages as here (5 wt%), got evident and the coloration of the contact sides further indicates that part of the glue was washed out during treatment A2.

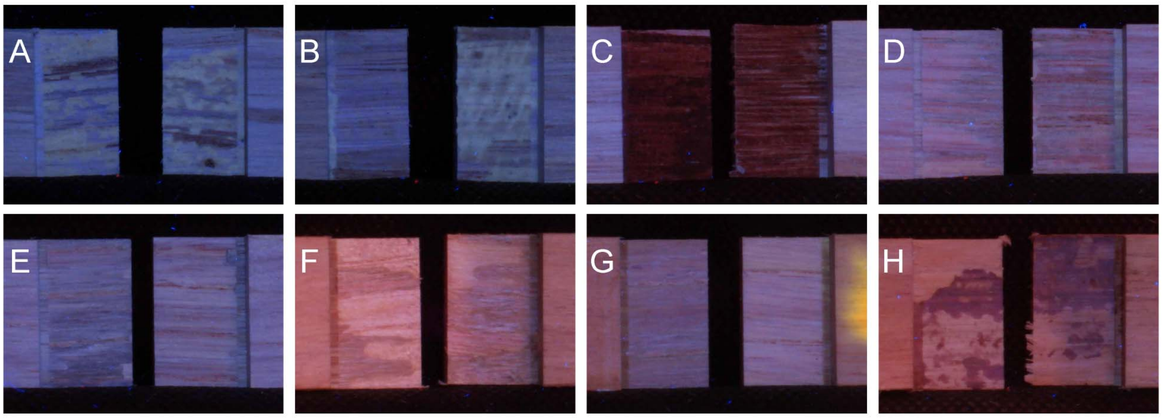

Figure 9: PVAc after treatment A1 (A), PVAc/CNC (B) after treatment A1, CNC-T after treatment A1 (C), MUF after treatment A1 (D), MUF-CNC (E) after treatment A1, MUF-CNC after treatment A2 (F), MUF-CNC after treatmentA3 (G), CNC-T after treatment A2 (H).

Conclusions

Many wood resources can be exploited more than they actually are, like small logs of chestnut wood that should be considered as a promising resource for a growing market of biocomposite materials. Lignocellulosic resources therefore can become a pillar in developing new value chains following basic concepts of a bio-circular economy. However, the exploitation of the latter, as well as their implementation within operative processes, should be evidence-based (Corona 2018). High abundance of cellulose in nature and the need for more ecofriendly adhesives qualify CNC as a reasonable additive. In our research work, CNC-addition to the synthetic adhesive PVAc resulted in increased mechanical performance as assessed by lap joint tensile shear strength tests under dry conditions. Addition of both CNC and tannin together to PVAc glue also increased shear strength of the prepared lap joint test specimen compared to the use of pure PVAc glue. In wet and in reconditioned samples, tannin successfully mitigated the negative effect of solely CNC-addition to PVAc. Furthermore, CNC proofed to be very compatible with MUF resin, and it could be a promising additive for the reduction of formaldehyde utilization in MUF adhesive systems via offering already present methylol groups.

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Conclusion and future perspectives

Sweet chestnut (*Castanea sativa* Mill.) plays an important role in Italian forestry, both due to its extension in the national territory and for its very central productive value.

The European research based on chestnut is abundant but on some specific subject (i.e. ring shake, structural properties of solid panels), and mainly in Italian context, lack of data excludes the current real awareness of true economic value of the species. In the recent past, for many Italians regions, sweet chestnut represented the only driver of sawmill economy, and there was a need of an active management on coppice stands to obtain constant wood product.

Active forest management, especially thinning during rotation age which has proved to be important in order to reduce stand competition, wood quality defect like ring shake, are not anymore so much performed because not convenient by the economic point of view and the final product from thinning has little or demand in the current market. Starting from the aim of this doctoral thesis research project to exploit wood from thinning and to find alternative and innovative use of these, several option were proposed that could be reactivate silviculture adding value to young shoots in coppice stand. The first issue that is to be addressed is the resilience of the species to climatic changes, according to a coppice forest management.

In this work it was considered, for the first time, the ecophysiological response of chestnut trees respect to actual climate conditions using stable isotopes $\delta^{18}O$ and $\delta^{13}C$. It was observed that climate is not particularly limiting for growth in the Monte Amiata area, although an increasing trend in minimum temperature was observed. This study highlighted that chestnut tree-ring growth is not particularly influenced by climate, while minimum temperature showed a positive relation with both stable isotopes studied, WUEi and $\delta^{18}O$, demonstrating that chestnut was sensitive to high minimum temperature in March and April, with a negative relationship with TRW and positive relationship with WUEi. Stand competition (indicated by shoots/stool and stools/ha) positively influenced both WUEi and $\delta^{18}O$. The stand with the highest competition between shoots and among stools was the most sensitive to climate parameters, testified by an increase in WUEi in the latter years of the study, and for this reason thinning could play an important role of intracompetition regulation under changing climatic conditions, even at sites currently not experiencing strong climatic stress.

The importance of thinning, on regulation of the number of stools/ha and shoot height, as well as for stress conditions, is the most promising characteristics related to the wood characteristics too.

A moderately positive correlation between the number of stools per hectare and wood density, indicates that is considerable the active forest management operating on number on stools and shoots per hectar to drive both stress resilience and wood quality in sweet chestnut.

Chestnut wood is naturally characterized by high durability, attractive aesthetics, and mechanical resistance, and in this project innovative applications were focused on the production of biocomposite materials with utilization of wood eco-friendly adhesives, developing a circular economy concept applied in forest-wood-chain. Thanks to this applications also small logs could be processed into a final product with satisfying mechanical properties. In this study, the influence of tannin and cellulose nanocrystals (CNC) as additives in PVAc and MUF adhesives on the mechanical properties of laminated veneer lumber made from young chestnut shoots from coppice stands was investigated with encouraging results in dry ambience, while for their utilization in wet ambience, i.e. outdoor, there is still a lot of work to do because results were not satisfying according to the delamination test in wet conditions.

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List of paper submitted or under review papers of Marini Francesco collaboration with

Giovando S, Koch G, Romagnoli M, Paul D, Vinciguerra V, Tamantini S, Marini F, Zikeli F, Scarascia Mugnozza G (2019) Spectro-topochemical investigation of the location of polyphenolic extractives (tannins) in chestnut wood structure and ultrastructure. Ind Crops Prod 141:111767 . doi: 10.1016/j.indcrop.2019.111767

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