

**Enhancement of the wood quality in the forest-woody supply chain among the  
“Aspromonte National Park”**

**Scientific Sector - AGR/05**

**Doctor’s dissertation**



**Department of AGRARIA**

**Mediterranean University of Reggio Calabria**

**Reggio Calabria**

**Italy**

**Ph.D candidate**

**Dr. Diego Russo**

**Supervisor**

**Prof. Fabio Lombardi**

**Ph.D Coordinator**

**Prof. Marco Poiana**

**Co-Tutotr**

**Prof. Pasquale Marziliano**

**A.A. 2018/2019**

# Contents

<b>Abstract</b> .....	1
<b>Riassunto</b> .....	3
<b>Chapter 1</b> .....	6
<b>1. GENERAL INTRODUCTION</b> .....	6
<b>1.1 Ecology and management of the species studied</b> .....	11
<b>1.2 History of the forest management</b> .....	14
<b>1.3 Woody Supply-Chain</b> .....	18
<b>1.4 Wood Quality – Non-destructive testing and evaluation techniques (NDT/NDE)</b> .....	20
<b>2. ORGANISATION</b> .....	23
<b>2.1 List of papers</b> .....	24
<b>Chapter 2</b> .....	25
<b>Does Thinning Intensity Affect Wood Quality? An Analysis of Calabrian Pine in Southern Italy Using a Non-Destructive Acoustic Method</b> .....	25
<b>1. Introduction</b> .....	25
<b>2. Materials and Methods</b> .....	29
<i>2.1. Study Area and Experimental Design</i> .....	29
<i>2.2. Field and Laboratory Activity</i> .....	30
<i>2.3. Statistical Analysis</i> .....	32
<b>3. Results</b> .....	33
<b>4. Discussion</b> .....	38
<b>5. Conclusions</b> .....	42
<b>Chapter 3</b> .....	43
<b>Tree growth and wood quality in pure vs. mixed-species stands of European beech and Calabrian pine in Mediterranean mountain forests</b> .....	43
<b>1. Introduction</b> .....	43
<b>2. Materials and Methods</b> .....	46
<i>2.1. Study Area</i> .....	46
<i>2.2. Tree sampling and BAI analyses</i> .....	47
<i>2.3. Wood quality</i> .....	48
<i>2.4. Relationship between Wood Quality and Tree Growth</i> .....	50
<i>2.5. Statistical analysis</i> .....	50
<b>3. Results</b> .....	51
<b>4. Discussion</b> .....	57
<b>5. Conclusions</b> .....	62

<b>Chapter 4</b> .....	63
<b>Relationships between tree age, growth, yield and wood quality: a chronosequence in a chestnut coppice of Southern Italy.</b> .....	63
<b>1. Introduction</b> .....	63
<b>2. Materials and Methods</b> .....	66
<i>2.1 Study area</i> .....	66
<i>2.2 Data collection and analysis</i> .....	66
<b>3. Results and Discussion</b> .....	69
<b>4. Conclusions</b> .....	76
<b>Chapter 5</b> .....	77
<b>5.1 Conclusions and Future Perspectives</b> .....	77
<b>5.2 Factors affecting the research performance</b> .....	78
<b>Acknowledgments</b> .....	81
<b>References</b> .....	82
<b>Appendix 1</b> .....	144
<b>Appendix 2</b> .....	145

## **Abstract**

The thesis aimed to implement the wood supply chain among the “Aspromonte” National Park in the Calabria Region (Italy), through the study of the more representative forest species occurring in the Park: chestnut, calabrian pine and beech. Tree growth and wood quality were studied through dendrochronological approaches and non-destructive technologies. Different forest types were tested: (i) pure plantation of calabrian pine; (ii) mixed-species stands of beech and calabrian pine; (iii) coppices of chestnut.

A more accurate assessment of the wood quality is needed and it is possible with modern technologies nowadays available, e.g. the acoustic technologies.

Firstly, it was hypothesized that the tree stand density could influence the dynamic modulus of elasticity (MOEd) and, therefore, the future wood quality in plantation of calabrian pine. It was tested if different management options, when applied, could influence the timber quality. The MOEd values were derived from field data obtained measuring the acoustic velocity through the TreeSonic™ timer. Calabrian pine trees were selected in stands where different intensities of thinning were applied eleven years before this study began (no thinning, thinning 25%, thinning 50%, and thinning 75%) and growing in similar ecological conditions. Results showed that, for the calabrian pine pure stand, a strong positive correlation occurred between the acoustic velocity, the thinning intensity and the tree diameters. The thinning realized at 25% induced the better tree wood quality, also uniform across the diameter classes.

The best predictors for MOEd estimation were evaluated using variables easily measurable in the field. Specifically, in high forests of pure and mixed-species stands of beech and calabrian pine (3 dominated by European beech, 3 dominated by Calabrian pine and 3 mixed-species plots), nine plots grouped into three triplets were analysed. Tree growth and wood quality were analysed through dendrochronological approaches and non-destructive technologies, respectively, hypothesizing that

the mixture might improve the wood quality. A linear mixed model was applied to test the effects of exogenous influences on the basal area index (BAI) and on the MOEd. The Recruitment period (Rp) was also studied to verify if the wood quality was independent from the radial growth.

Results showed that the tree mixing effect influenced both the wood quality and the BAI. In the mixed stand, for each species, MOEd values were significantly higher than in the corresponding pure stands. The mixture effect aligned MOEd values, making wood quality uniform across the different diameter classes. In the mixed stand, a significant positive relationship between MOEd and Rp, but also significantly higher BAI values than in the pure stand, were found for beech, but not for calabrian pine.

Results provided a useful tool for predicting the wood stiffness in relation to stand parameters easily measurable in forests. Furthermore, it could be useful to promote the mixture of European beech and Calabrian pine in this harsh environment, since it can improve both the tree growth and the wood quality.

Finally, this thesis focused on stands of chestnut coppices growing in similar environmental conditions in the "Aspromonte" National Park. A growth model was developed in order to verify if the wood quality at different ages of the coppice can vary if the cutting cycles are modified. The wood quality and tree productivity were analysed, using a chronosequence approach, in stands characterized by four cutting cycles (15, 25, 30 and 50 years). The results suggested that the culmination of the mean annual increment occurs at 28 years, while the current annual increment culminates 10 years earlier. The values of the MOEd, even if revealed a negative trend as tree age increases, however suggested the occurrence of an overall good wood quality across all the life cycles.

## Riassunto

Questo lavoro di tesi è stato finalizzato all'implementazione della filiera del legno nel Parco Nazionale dell'Aspromonte, in Calabria (Italia), attraverso lo studio delle specie forestali più rappresentative presenti nel Parco stesso, come il castagno, il pino laricio ed il faggio.

Gli accrescimenti arborei e la qualità del legno sono stati studiati attraverso approcci dendrocronologici e tecnologie non distruttive, focalizzandosi su diverse tipologie di boschi, rappresentative del territorio forestale aspromontano: (i) piantagioni di pino laricio; (ii) boschi misti e puri di faggio e pino laricio; (iii) cedui di castagno.

Con le moderne tecnologie disponibili per valutare la qualità del legno è possibile effettuare una valutazione accurata, utile ad ottimizzare il valore dei diversi usi finali del legno. In questo studio, è stato ipotizzato che la densità dei popolamenti possa influenzare il modulo dinamico di elasticità (MOEd) e, quindi, la futura qualità del legno. E' stato verificato se le diverse opzioni di gestione, quando applicate, possano influenzare la qualità del legname di pino laricio che cresce in condizioni ambientali simili. Sono stati quindi derivati i valori del MOEd attraverso la misurazione della velocità acustica tramite il TreeSonic <sup>TM</sup>. Sono state analizzate pinete calabresi in cui sono state applicate diverse intensità di diradamento (non-diradato, diradamento del 25%, diradamento del 50% e diradamento del 75%), undici anni prima dell'inizio di questo studio. I risultati ottenuti hanno evidenziato una forte correlazione positiva tra la velocità acustica, le diverse intensità di diradamento e il diametro degli individui studiati (DBH). Nel diradamento al 25% è stata riscontrata una migliore qualità del legno, a prescindere dalla classe diametrica di riferimento. Dai risultati ottenuti è stato quindi realizzato un modello per la stima del MOEd, utilizzando variabili facilmente misurabili sul campo, come il DBH e l'altezza.

Lo studio è quindi proseguito nell'ambito di fustaie miste e seminaturali, a dominanza di faggio e pino laricio. Si è ipotizzato che la crescita degli alberi e la qualità del legno possano essere favorite dalla presenza di più specie, rispetto a situazioni in cui esse crescono monospecifiche.

Si è quindi lavorato, attraverso approcci dendrocronologici e tecnologie non distruttive, su una tripletta caratterizzata da due popolamenti monospecifici di faggio e pino laricio, ed un bosco misto con presenza di entrambe le specie. È stato applicato un modello misto lineare per testare gli effetti delle influenze esogene sull'ampiezza delle cerchie annuali (espressa come BAI) e sul modulo dinamico di elasticità (MOEd). Il tempo di passaggio ( $R_p$ ) è stato studiato per verificare se la qualità del legno era indipendente dai modelli di crescita radiale del tronco.

I risultati hanno mostrato che l'effetto della coesistenza (faggio e pino laricio) ha influenzato sia la qualità del legno che il BAI. Nel bosco misto, per ogni specie, i valori MOEd sono risultati significativamente più alti rispetto ai rispettivi boschi monospecifici. L'effetto della coesistenza ha allineato i valori MOEd, uniformando la qualità del legno tra le diverse classi di diametro. I risultati ottenuti confermano gli effetti positivi indotti dalla diversificazione specifica sulla produttività legnosa e sulla qualità del legno, laddove la gestione favorisca la mescolanza tra specie.

Infine, in cedui di castagno caratterizzati da una densità omogenea, si è cercato di comprendere la durata del turno più idonea per avere una buona produzione caratterizzata dalla migliore qualità del legno. Attraverso lo studio di una cronosequenza costituita da popolamenti di età diverse afferenti a condizioni ambientali simili, sono stati quindi analizzati: i parametri dendrometrici, la qualità del legno e la produttività a diverse età. È stato sviluppato e implementato un modello di crescita specifico per i boschi di castagni situati nel Parco Nazionale dell'Aspromonte, al fine di verificare se la qualità dei materiali legnosi ottenibili a diverse età del bosco ceduo può variare se i cicli di taglio vengono modificati. Si è quindi analizzata la qualità e la produttività del legno, in una cronosequenza, nei cedui di castagno caratterizzati da quattro diversi cicli di taglio (15, 25, 30 e 50 anni). Le analisi qui svolte hanno consentito l'implementazione di un modello di crescita utile per simulare lo sviluppo temporale dei principali tratti strutturali. I risultati hanno mostrato che il culmine dell'incremento annuale medio si verifica a 28 anni, mentre l'incremento annuale culmina circa 10 anni prima. I valori del MOEd, anche se hanno rivelato una tendenza negativa all'aumentare

dell'età degli alberi, hanno dimostrato che durante tutto il ciclo di vita si ha una buona qualità del legno.

**Keywords:** *Forest management; Mediterranean mountain forests; Forest productivity; Treasonic; Dendrochronology; Recruitment period; modulus of elasticity;*



# Chapter 1

## 1. GENERAL INTRODUCTION

Forests provide a wide variety of goods, services and processes needed by society, including wood and fiber, non-timber products, clean water and air, habitats for wildlife, recreation, esthetics and preservation of biodiversity. The economic and social well-being of modern society depends, largely, on the presence of abundant and healthy forests. In the last centuries, huge changes in the distribution and nature of forests, caused by natural phenomena (disease and pests, storms, fire, drought and other climatic stresses) or human intervention, or by the interaction of human impacts and natural causes (European Environment Agency <http://www.eea.europa.eu/publications/92-826-5409-5/page034new.html>) were observed. Appropriate measures should be adopted to protect forests in order to maintain their full multiple values. Incorrect silvicultural practices are the main causes of timber productivity decrease and poor quality material production. The sustainable management of natural resources is, therefore, a guiding principle of a proactive approach for maintaining forest productivity, contrasting the forest degradation in a global changing scenario. Therefore, sustainable forest management is fundamental for the protection of the cultural identity and the physical integrity of the agro-forest landscape. In fact, it not only preserves the animal and vegetable biodiversity, but it is also an important historical, architectural and cultural heritage that valorizes the natural resources. In our case, the context of the “Aspromonte” National park has a high number of endemisms that strongly characterize the landscape, such as the presence of different forest tree species (pine, chestnut and beech), considerable very useful for the local economy.

In Southern Italy, Calabrian pine forests are strongly related to the complex geological history, lithological and climatic characteristics, but also to the long history of human exploitation of the related forest stands (Ciancio *et al.*, 2006).

This species is common also in Sicily and Sardinia, but it is mainly widespread in the “Sila” and “Aspromonte” National Parks, in Calabria Region. Calabrian pine covers an area of approximately

114,000 ha, mostly characterized by pure stands, both of natural origin and plantations. The latter originated from extensive reforestation projects carried out between 1950 and 1970, based on specific Italian state law (Nicolaci et al., 2014). These plantations were realized with the aim of reducing the hydrological risk in mountainous areas, but also for facilitating the natural succession toward mixed forests with a significant component of deciduous species (Cantiani et al., 2010). Together with soil and watershed protection, Calabrian pine has an important role in the local forest economy. In order to increase the economic value of these forests, the best silvicultural options should be selected and adopted at stand level, to achieve specific objectives. Therefore, different management practices and related intensities can change the tree species composition and richness and, also, the stand density and tree age distribution (Duncker et al., 2012). Species combinations show complementary resource use, with positive consequences for productivity (Pretzsch and Schütze 2009; Pretzsch and Forrester 2017), (higher) carbon storage capacity (He et al. 2013), ecosystem health and vitality (Balvanera et al. 2006; Jactel et al., 2009), resistance and resilience (Griess et al. 2012), reducing economic risks (Griess and Knoke 2013) and for providing insurance against environmental fluctuations (Metz et al. 2016; Jactel et al. 2017). In the face of climate change (IPCC 2014), fostering mixed-species forests, with species adapted to various climatic conditions, is considered as one of the most important measures to use in climate-adapted forest management of many forests in Europe (Bolte et al. 2009; Brang et al. 2014). In spite of the lack of the common forest policy in the EU (Dobšínská et al. 2015), diversity of tree species was one of the quantitative indicators of sustainable forest management in Europe adopted by 7<sup>th</sup> Ministerial Conference in Madrid (SFM 2015).

Moreover, in mountainous forest ecosystems of Southern Italy, extended mixed-stands formed by European beech (*Fagus sylvatica* L.) and Calabrian pine (*Pinus nigra* Arnold subsp. *calabrica*) also occur. European beech is a late-successional broadleaved tree species, here occurring in its southernmost ecological limit, whereas Calabrian pine is an early-successional conifer, providing timber of high quality. Heterogeneity of species composition belongs to ecological attributes, which make forests a complex adaptive system (Puettmann et al. 2013; Bauhus et al. 2013). In Europe,

many forest areas abandoned from any active management approach (Marziliano et al., 2017) are evolving in mixed deciduous forests.

Moreover, the chestnut (*Castanea sativa* Miller) is another broadleaves species widespread in southern Europe; in fact, it covers an area of more than 2.5 million hectares. Most of the area (89%) is concentrated in few countries (France, Italy, followed by Spain, Portugal, and Switzerland) with a long tradition of cultivation. In the wide ecological and geographical range where chestnut has been used, many different silvicultural treatments have been proposed and developed in order to improve its profitability.

Forest management and utilization have a considerable influence on the stability and sustainability of forest ecosystems (Swanson and Franklin, 1992; Larsen, 1995).

In this sense, chestnut stands have been intensively managed both for production (timber and edible nuts) and for encouraging the natural regeneration of mixed broadleaved species (Cucchi, 1990; Everard and Christie, 1995). The scientific literature often reports that the most profitable management of chestnut coppice is the conversion to high forests, in a long-term perspective; this approach can favour a gradual increase of the economical benefits, in the short- and medium-term (Ciancio and Eccher, 1983). Due to its high resprouting capacity, chestnut coppices represent the main type of forest management observable in the Italian landscape, with about the 80% of cover; they supply principally fire wood, charcoal, poles (fence, pit-props, etc.) and wood for small products (barrels, shingles, sleepers, etc.). Pure chestnut high forests are rare, representing only the 10% of the total chestnut forest cover, and producing timber wood for construction, furniture or long poles. Traditional chestnut management approaches (i.e. coppices, high forests, orchards) requires continuous cultural inputs.

Forest management is aimed to create a vigorous stand, increasing tree growth and developing structural characteristics useful for timber production. Furthermore, thinning activities can also favour the creation of new habitats for wildlife, favouring the occurrence of healthy and vigorous forests (Demers et al., 2013).

Thinning activities control the forest stand density, improving the growth of the remaining trees (Grant *et al.*, 2007) based on sustainable approaches (Zeide *et al.*, 2004), and decreasing, also, the tree mortality rates from a long-term perspective (Brissette *et al.*, 1999).

Furthermore, forest management can determine variation in the physical and mechanical properties of the harvested wood, both at stand and tree level (Machado, *et al.*, 2014). For this reason, the identification of certain wood properties, that can increase timber quality, is essential, as it is important to select the best forest management options to improve the wood quality.

Wood quality can be described as a set of characteristics that make woody materials economically valuable for their end uses (Jozsa, *et al.*, 1994). Briggs and Smith (1986) defined wood quality as “a measure of the aptness of wood for a given use”. These properties can include, for example, the wood density, the uniformity in tree ring size, the percent of knot-free wood, and the proportion between early wood and late wood.

The objective evaluation of the wood quality and quantity is then critical for quantifying the productive value of a forest (Marziliano, *et al.*, 2012; Proto, *et al.*, 2017). For this purpose, several non-destructive technologies (NDTs) have been developed in the past years to evaluate the quality of woody materials. For example, at belowground level, (mini) rhizotrons and ground-penetrating radar allows for evaluating tree rooting distribution and growth (Sanesi, *et al.*, 2013; Marziliano, *et al.*, 2015). Moreover, at aboveground level, NDT measures allow for evaluation of the mechanical and technological properties of standing trees (Škorpik, *et al.*, 2018; Krajnc, *et al.*, 2019). More specifically, stress wave-based non-destructive acoustic techniques have been extensively investigated during the past few decades (Guntekin, *et al.*, 2013), resulting in very useful methods for predicting the mechanical properties of woody materials.

The use of stress wave-based non-destructive tests is relatively common in the forest-to-mill woody supply chain in Australia (Tsehaye, *et al.*, 2000) and in North America (Wang and Ross, 2000; Wang, *et al.*, 2004), while it is less common in Europe. Specifically, research developments (Mora *et al.*, 2009) in acoustic sensing technology can, nowadays, permit the estimation of wood quality and

intrinsic woody properties for standing trees, stems, and logs. The information derived from NDT measures could be used to sort and grade trees and logs according to their suitability for different end uses, such as structural products, advanced composites, pulp, and paper, and for bioenergetics purposes.

Among the parameters measurable by acoustic methods, one of the most important is the modulus of elasticity of wood (MOE). The MOE, also known as wood stiffness, is essentially one of the fundamental wood quality parameters and measures the resistance to deflection (Wessels, et al., 2011). For example, it is important since some woody products, such as laminated veneer and dimension lumber, require stiff and strong woody properties (Tenorio, et al., 2011).

The recent literature has focused on determining whether stress wave techniques could be used to determine wood quality (Brashaw et al., 2009). Several studies shown a good relationship between the stress wave-based modulus of elasticity (MOE) and the static MOE of lumber cut from logs (Aratake and Arima, 1994). This methodological approach is also applied to determine the relationships between the environmental conditions, silvicultural practices, and wood fiber properties (Wang, 2012). The modulus of elasticity and the density of the woody materials strongly affect the acoustic properties of wood (Teder, 2011). One of the most important mechanical properties, measurable by NDT methods, is Young's modulus, i.e., the modulus of elasticity (MOEd), which describes the material's stiffness.

Many portable instruments have been developed to measure the wood stiffness of standing trees, logs, and sawn timber using acoustic technology (Legg and Bradley, 2016). These instruments are able to measure the speed at which an induced sound (stress) wave propagates through a woody sample, which is proportional to its stiffness (Mochan, et al., 2009). When the stress is applied to the wood surface, the generated disturbance propagates through the wood as stress wave. Several studies have hypothesized that the characteristics of the resulting wave are related to the mechanical properties of the wood (Wang, 2011; Wang, 2013).

Stress wave propagation in wood is a dynamic process correlated to several factors, such as the stand developmental stage (Vanninen, et *al.*, 1996), genetic characteristics (Vargashernandez and Adams, 1994; Rozenberg et *al.*, 2001) and also the silvicultural activities and their intensities (Zobel, B.J. and van Buijtenen, 1989).

### **1.1 Ecology and management of the species studied**

In mountainous forest ecosystems of Southern Italy, the more important tree species are: calabrian pine, european beech and chestnut.

- Calabrian pine, is a fast-growing conifer with a wide but fragmented distribution across Europe and Asia Minor, predominantly in mountain areas. It has also become naturalised in some areas in North America. It is subdivided into several distinct subspecies and its taxonomic status is still a subject of debate among specialists (Enescu et *al.*, 2016). In Central Europe, Balkans, and Mediterranean countries, calabrian pine was commonly planted for protection purposes (Bussotti, 2002).

In Italy, Calabrian pine occurs mostly in pure stands of even-aged forests (50 years old, on average) and covers an area of around 240.000 hectares (Gasparini and Tabacchi, 2011). The different ecological conditions in which calabrian pine occurs determine differences in its productivity and regeneration capacity; this aspect should be taken into account when the forest management is defined in a long-term perspective.

However, in the context of the sustainable forest management, it is recommended to find a compromise between production objectives and conservation needs, trying to reach in some areas a similar status to that found in natural forests, whose dynamics depends mainly on natural disturbances. A proper management of calabrian pine should try to maintain irregular structures with trees of different ages (MATT, 2004), including very old individuals, in order to ensure the kind of broad genetic variability that allows the forest to survive the various natural disturbances and environmental stresses. Suitable management should also promote a closed structure with a well-developed canopy, which offer suitable microclimatic conditions (shade and humidity) for

regeneration. It is also recommended to maintain a number of old trees, as well as an appropriate amount of deadwood, which play an important role in the conservation of biodiversity.

In general, forest regeneration composed by long-lived species can be reached with clear cuttings, which mimic the natural disturbances to the ecosystem (e.g. fires) (De Dios, 2006; Zaghi, 2008).

The most common silvicultural treatments in Europe currently aim at maximizing the stand stability, facilitating the transition from pure stands to mixed stands with a stronger presence of native tree species (Heitz and Hasenauer, 2000; Malcolm *et al.*, 2001; Kint *et al.*, 2006).

- European beech is the most abundant broadleaved forest tree in central and southern Europe; due to its physiological characteristics, it can form forest communities that dominate in a wide range of habitats, soil types and climatic conditions (Peters, 1997; Ellenberg, 1988).

In Italy, beech-woods are widespread and constitute around 12% of the national coverage of high-trunk forests, extending from the Alps to the southernmost sites in Sicily, with the exception of Sardinia and the smaller islands (Jalas and Suominen, 1972-1999). On the Apennines, it is the uppermost forest species, showing a pronounced attitude for expansion in different environmental conditions, including those moderately altered by human activities.

Beech is a hardy species. It tolerates very shady situations, so that natural regeneration is possible in silvicultural systems with continuous crown coverage as the seedlings are able to survive and grow below the canopy of established trees. Currently, the management of beech forests in Italy is, much diversified. Beech forests have been abandoned in many areas. In general, these forests can be classified in the following management types: coppices and high forests. Beech coppices were generally clear felled leaving 60-80 standards per hectare. Traditional forest management has had an important impact on the current European beech stands resulting in the creation and maintenance of a wide spectrum of structural forms (Bengtsson *et al.*, 2000), especially in Mediterranean areas (Nocentini 2009; Lombardi *et al.*, 2012).

Today there is a renewed scientific and operational interest in this management system because it can produce relatively high quantities of firewood in mountain areas where modern and

efficient wood burning stoves are gradually gaining importance while guaranteeing continuous cover and adequate soil protection (Ciancio and Nocentini 2004, Coppini and Hermanin 2007).

In general, results show that in coppices, which have passed the normal rotation age, thinning increases stand stability, reduces shoot mortality, maintains a “regular” stand structure, increases growth of both individual shoots and total stand volume.

Beech high forests was conducted well into the twentieth century, when it became customary to utilize beech stands with a very intensive cut leaving few seed trees (circa 50 per hectare). Resulting stands today show different structures, ranging from even aged pure beech stands with sparse old big trees, to stands with a light cover of big trees from the old cycle and with a lower plane formed by beech regeneration, originating both from seed or stool, to multistratified stands where felling of some of the big old seed trees has opened up space for new regeneration (Iovino and Menguzzato 2004, Ciancio et al., 2008). Instead, the traditional treatment for beech stands on private, and, rarely, on some public properties, was and still is a selection cut applied without precise written rules, but according to the needs of the owner and to the particular situation of each stand. Susmel (1957) reported on various areas between Campania and Basilicata where beech stands, from at least 1850, had been managed successfully with a “selection cut” and where wood production quality was very good. Fellings were carried out approximately every 14 years in the same stand. This type of management created an “irregular” small group structure.

According to Susmel, the final aim of this management model was to favour the transformation of pure beech stands into mixed stands.

- The distribution area of Chestnut ranges from Southern Europe (Iberian Peninsula, Italy, Balkans, Mediterranean Islands) and North Africa (Morocco), to North-Western Europe (England, Belgium) and eastward to Western Asia (North East Turkey, Armenia, Georgia, Azerbaijan, Syria), with an altitudinal range between 200 and 800 m, depending on the latitude (Avanzato, 2009; Schütt, et al., 2006). In Europe, the chestnut covers an area of more than 2.5 million hectares. Most of the area (89 %) is concentrated in just a few countries (France, Italy, followed



by Spain, Portugal, and Switzerland) with a long tradition of chestnut cultivation (Conedera et al., 2004). The broad diffusion and active management by man have resulted in the establishment of the species at the limits of its fundamental niche, which makes it nowadays difficult to trace its original range (Tinner, et al., 2000) and its ecology (Rubio, et al., 2002). The increasing demand for high-quality wood production has fostered a discussion about identifying appropriate management techniques to assure sustainable forest management for saw log production (Amorini et al., 1997, Manetti et al., 2009). As a result, the production of high-value chestnut timber is now being enhanced in some parts of Europe where growing conditions are appropriate (Conedera et al. 2001).

At present, the largest part of chestnut forests extending on the Italian surface is under two main management regimes: high forests and coppices, specialized in timber production.

Coppice represents the main type of forest management (Giannini et al., 2014) with about 80 % in cover of the chestnut forests, supplying principally fire wood, charcoal, poles (fence, pit-props, etc.), and wood for small products (barrels, shingles, sleepers, etc.). Pure chestnut high forests are rare with a cover of about 10 %, producing timber wood for construction, furniture or long poles.

Coppice stands often characterised by a low silvicultural management and short rotation periods (Fioravanti 1997), in south Italy cutting periods of 10-15 years are commonly adopted, nevertheless shortcutting periods of 6-8 years and long cutting periods of 18–24 years are found also (Aviolo 1987). Traditional chestnut management approaches (i.e. coppices, high forests, orchards) requires continuous cultural inputs. In the absence of management, chestnut stands tend to be invaded by other species and to evolve towards mixed deciduous forests.

## **1.2 History of the forest management**

The forest management has evolved over time according to the interests and needs of human population with respect to the use of natural resources.

During the whole of the middle Ages, forests were very much exploited, as a wood reserve, since wood was used as firewood or to build different items, such as barrels, tools, hurdles for enclosures, fencing, boats and ships. Forests were also seen as potential arable land, after being cleared of trees and shrubs (Paletto et al., 2008). Across the centuries these unplanned and more-and- more intensive activities seriously endangered the survival of forests and forced local communities to elaborate specific laws to limit pasture rights, tree-cutting, and land clearance (Naso, 1988).

In the Modern age (the late 15<sup>th</sup> century and 16<sup>th</sup>, 17<sup>th</sup> centuries), the multi-products forest (silvopastoral economics) came to be replaced with the traditional agricultural forest. Medieval forest management, based on selective cutting and uneven-aged stands, (Agnoletti, 2006) was replaced by tillage and the intensification of clearcutting (Thomas, 1983).

During the Modern age, particularly in the plain areas of Europe, a progressive increase of the agriculture to damage of the other land uses was observed. Specifically, in those years, a reduction of the extent of forests was observed (Le Master and Schmithüsen, 2006). These events, important for the development of the agricultural economies, created limitation for the silvopastoral ones, typical of the collective communities of the Middle ages (limitation in the rights of hunting and product collection). As a consequence, the hydrogeological instability (the protection function of forest) in mountain areas increased, but also flooding events in the plain zones (Paletto, 2008).

In conclusion, man bends nature to his own wishes, and consequently, the management of forests has been decided only on the basis on the human needs (Thomas, 1983). The end of Modern Age coincides with the advent of the Industrial Revolution, during this period new social needs and demands arose and, as consequence, the management of natural resources changed radically. The industrial revolution modified deeply the economy of European society, production increased considerably and the technological efficiency improved significantly. These factors caused an increase in the demand not only of raw materials (wood, cotton, iron, coal) but also of round wood for construction, fuelwood for domestic use, pole wood, charcoal and tannin (Paletto, 2008).

In this context, the work of Georg Ludwig Hartig and Heinrich von Cotta developed the concept of “modern” silviculture. The old mixed forests were replaced with monospecific forests managed with new techniques (fertilisation, selected exotic species, artificial regeneration), and harvested by clear cutting (Vos, 1996). In the Mediterranean regions coppice using short rotations of 3 to 10 years replaced the high forest (Agnoletti, 2002). The economic approach to forest management was imperative, the need to achieve maximum forest revenue has concurred to the affirmation of timber market, industrial silviculture and different forestry branches (wood technology, forest economics, forest mensuration and assessment (Agnoletti, 2006). After the industrial revolution, the social perception of the forest resource changed. In the new cultural context, two main principles in forest management emerged: multifunctionality and sustainability. The concept of forest multifunctionality borns in Germany in 1953 with the elaboration of the “Theory of Forestry Function”, published in the “Forstwirtschaftspolitik” by the Professor Viktor Dieterich of the University of Munich. In this theory, the concept of multiple-use, widespread in North America (Canada and United States), was developed and widened through a less anthropocentric vision where the functions had an intrinsic importance (vitality and health of ecosystem).

The modern formulation of the concept of sustainability was elaborated in the report of the World Commission on Environment and Development (WCED, 1987), better known as the Brundtland Report (1987). In this report, sustainability was defined as: “Meeting the needs of the present generation without compromising the ability of future generations to meet their needs”. This definition represents the conceptual basis of a new forest management paradigm that changed radically the traditional forest management in Sustainable Forest Management (SFM). Sustainable Forest Management (SFM) is currently widely accepted as the overriding objective for forest policy and practice. SFM is a concept developed over time, for the increasing needs to find new strategies and methods for a rational management of forest resources (Paletto, 2008).

The first international definition of SFM appeared in the early 1990s in a number of important documents: Agenda 21, the Rio de Janeiro Declaration on Environment and Development and the

Statement of Principles for the Sustainable Management of Forests. This was adopted by many Governments at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro (Brazil, 3-14 June 1992). The term, sustainable forest management, asserts that: “Forest resources and forest lands should be sustainably managed to meet the social, economic, ecological, cultural and spiritual human needs of present and future generations. These needs are for forest products and services, such as wood and wood products, water, soil, food, fodder, medicine, fuel, shelter, employment, recreation, habitats for wildlife, landscape diversity, carbon sinks and reservoirs, and for other forest products”. In Europe, the first definition of SFM was worked out during the second Ministerial Conference on the Protection of Forests in Europe (MCPFE) in Helsinki (1993): “sustainable management means the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems” (Resolution H1 point D, MCPFE 2000). The final evolution of forest management doctrine is Ecosystem Management (EM). EM “integrates scientific knowledge of ecological relationships within a complex socio-political and values framework toward the general goal of protecting native ecosystem integrity over the long- term” (Grumbine, 1994; Paletto, 2008).

The best management had to maintain a good level of health and vitality of the forest ecosystem (Wolynski, 1998). In order to achieve these objectives, managers must avoid traumatic actions against the forest ecosystem (for examples: clear cutting on wide surface, artificial regeneration with exotic species, etc.). The four major criteria for the sustainability of a forest ecosystem are: the maintenance of biological diversity, sustainment of the ecological processes, productivity of soil, water and air and the ability to provide for sustained human use (Georgia Forestry Commission, 2000). Contemporary, sustainable forest management aims to ensure that goods and services derived from forests meet present-day needs while at the same time securing the forests' continued viability and contributions to long-term development. Furthermore, forest management itself requires prudent management in

order to maintain essential ecosystem services such as soil fertility, water quality, but also carbon sequestration, maintenance of biodiversity and recreational uses. One of the most important questions for the future is how to manage forests for timber production however preserving or improving the other important ecosystem services. (Paletto, 2008; Duncker et al., 2012).

### **1.3 Woody Supply-Chain**

The supply chain can be defined as: “the manufacturer and its suppliers, vendors, and customers- that is, all links in the extended enterprise- working together to provide a common product and service to the marketplace that the customer is willing to pay for. This multi-company group, functioning as one extended enterprise, makes optimum use of shared resources (people, processes, technology, and performance measurements) to achieve operating synergy. The result is a product and service that are high-quality, low cost, and delivered quickly to the marketplace” (Kuglin, 1998).

Schonsleben (2004) defines supply chain management as coordination of strategic and long-term cooperation in logistics networks. In order to better monitor and manage the flow of goods and information, and to work towards efficient use of enterprise resources in the supply network, managers have started to introduce supply chain management systems (SCMS) (Davenport and Brooks, 2004). Schonsleben (2004) notes that “SCMS” just like logistic software in general – portrays products, actors, and processes of orders, and supports administration activities and accounting”. Shared databases are integral parts of SCMS as they provide network members with detailed and timely information (Symon, 2000). Forest-wood supply chain (FWSC) applies the concepts of logistics and supply chain management to the field of forestry, and in particular to the area of logging and transport operations. FWCs can be seen as a set of processes by which forest resources are converted into products and services. FWSC deals with all processes within this chain, starting from the management of a new forest to the valorization of the wood product; covering forest organization, logging and transport, and forest industry to end-use (Vötter 2009). Processes in FWSC are not separated and single processes but are linked together and interact with each others, creating entire and full system to supply wood from forest to sawmill in an expected way. Depending on a number

of factors such as the level of harvesting and transport industry development in a country, forest and terrain condition, and the investment capacity of the harvesting contractor, the methods used in the processes of a wood supply chain are not the same. This means that the level of integration and dependency of the processes with each other also varies within the chain. The forestry wood supply chain is a complex process. In fact, each provider involved in the wood supply chain can take independent decisions. Forestry operations, the wood processing industry and other actors involved in the process chain have organized their activities according to their own, usually functional criteria and spheres of responsibility (e.g. buying, logistics, marketing). Moreover, the fragmented structure of the timber supply chain makes it extremely difficult to optimize timber value added from supply in the forest through processing in a factory. For instance, no suitable procedures or tools exist to forecast the revenue from the sale of intermediate and finished products of the processed lumber (veneer wood, sawn and barked wood, lumber, industrial lumber, wood chips, etc.). There is also no procedure available to project the costs of transportation logistics, influenced by a multitude of parameters (timber assortment, lot sizes, transport distance, truck utilization, etc.), along the entire supply chain and beyond. The market for timber products has changed from a sellers' market (push system) into a buyers' market (pull system); Gunter (2006) states that "it is not possible anymore to produce timber for an anonymous market". Timber production has to take market requirements into account (Heinimann, 2000). Companies have to be able to react quickly and flexibly to customer's demands.

In response to these changes and needs, supply networks and supply chain management systems (SCMS) have been introduced in forestry and many other industries (Heinimann, 1999). A supply chain can be considered as a complex system of processes and related materials, in the case of wood fuel processes such as harvesting, extraction and transport and wood in different states of processing. Entrepreneurs often have to decide which type of supply chain to employ for a certain operation. Therefore, machinery has to be selected and its operations coordinated and balanced. In recent years, novel technologies and methods for the utilization of wood have been introduced to enhance the wood

supply chain. Basically, innovations have been grouped into two main classes: radical innovations that change the operating principle of a system and lead to a technology leap, and further innovations that improve the existing systems by enhancing their resource efficiency or reducing their costs in gradual steps. In wood harvesting, radical innovations have been the introduction of the bow saw in wood felling and cross cutting in the 1930s, the chain saw in the 1950s and 1960s and mechanization of the felling, delimiting and cross cutting by using the single grip harvester principle in the 1980s. Once introduced, these technologies have been gradually improved so that their performance levels have risen and e.g. fuel consumption has been reduced markedly. Moreover, wood characteristics and some specific measurements collected at each step of the wood chain process are diverse.

#### **1.4 Wood Quality – Non-destructive testing and evaluation techniques (NDT/NDE)**

Wood "quality" means different things for different people. While foresters think of tree size and form, and lumber manufacturers see large, straight and clear logs, customers associate wood quality with other attributes. The building industry, for example, is mainly interested in strength, stiffness and dimensional stability, but it cares very little about basic wood properties (Kliger *et al.* 1994). In many cases, the term was used as a synonym to wood density.

Many attempts have been made to define wood quality (Keith 1985), but the definition proposed by Mitchell (1961) appears to be the most widely cited: "Wood quality is the resultant of physical and chemical characteristics possessed by a tree or a part of a tree that enable it to meet the property requirements for different end products". Almost everybody agrees that wood quality must consider specific end uses, and this definition duly emphasizes their significance, but it fails to consider other aspects that are of importance to manufacturers, foresters or customers.

In addition, the definition needs to include serviceability, and cover attributes of interest to end-users, which may or may not have a direct impact on manufacturing, but will continue to matter long after the product has been sold and installed.

For centuries, wood has been assessed for quality, but with limited technologies; this was largely reliant on a visual inspection. Hence, wood quality assessment has long influenced its preferred use

and optimal value. This may have even led to the rise of the is aesthetic preference for wood that is free of knots because it is also structurally superior. In fact, many desirable attributes of wood quality are correlated, allowing for relatively simple field measurements of desired attributes.

With the modern technologies available to assess wood quality, a more accurate assessment of quality is possible and needed to optimize value for the different wood end uses.

The field of non-destructive testing (NDT) and non-destructive evaluation (NDE) of materials is constantly evolving. This is especially true in the area of wood and fiber based materials. The NDT techniques, equipment, and evaluation procedures that resulted from those efforts are now in widespread use. Currently, world-wide research and development efforts are underway to examine the potential use of a wide range of NDT technologies for evaluating wood and wood based materials.

The original impetus for research in NDT/NDE of wood was the need to provide methodologies for assessing wood based materials and products so that more accurate decisions could be made about proper use. Moreover, there is an increased emphasis around the world to address forest and ecosystem health issues. The utilization of woody biomass from widely varying growing conditions will play a key role in providing economical options for managing the health of these forests and ecosystems. Furthermore, the marketplace has become increasingly global and interconnected. Shipments of raw materials and products between countries on different continents is now really common. Both of these challenges will require accurate and cost-effective NDT/NDE technologies.

The international forest products research community is responding to these driving forces by conducting NDT/NDE research to provide the technologies needed to address these challenges.

The assessment of the quality of raw wood materials has become a crucial issue in the operational value chain as forestry and the wood processing industry are increasingly under economic pressure to maximize extracted value. A significant effort has been devoted toward developing robust NDE technologies capable of predicting the intrinsic wood properties of individual trees and stems and assessing the value of stands and forests. A typical approach for assessing wood quality of standing trees is to measure the acoustic velocity on the lower part of a tree stem. The testing procedure



involves inserting two sensor probes into the sapwood and introducing acoustic energy into the tree through a hammer impact. The standing tree acoustic tool measures time-of-flight (TOF) for a single pulse wave to pass through the tree trunk from the transmit probe to the receive probe. For tree quality assessment, going from velocity measurement to wood property prediction is a critical step. Until recently, post-harvest NDE methods such as E-rating, machine stress rating (MSR), and ultrasound veneer grading have been the standard procedures for evaluating wood stiffness and strength. The timber owner does not have a reliable way to assess the value of the final products prior to harvest. Recent wood quality research has shown that a range of wood and fiber properties can be predicted through a simple acoustic measurement in standing trees (Wang *et al.*, 2007). This will facilitate the use of acoustic NDT technology at a number of stages in the operational value chain, from timberlands through to the processing site.

## 2. ORGANISATION

This study was mainly aimed to select the best silvicultural practices and the tree species combination useful to improve the tree wood quality, in a long-term perspective, in the context of the “Aspromonte” National Park.

Different silvicultural systems were here investigated. In detail, coppice and high forests were studied, focusing on the more representative forest species occurring in the National Park: chestnut, pine and beech.

In detail, all the papers are connected each other following the relationships between the tree wood quality and other forest parameters and management options, such as the influence of the intensity of thinning, the effect of the species mixture, but also the variation of the cutting cycles in coppice stands.

The specific aims of the papers included in this dissertation are reported below.

- Develop a predictive model of MOEd estimation, and then of the wood quality, on calabrian pine plantations subjected to different intensities of thinning (Chapter I);
- Find the best intensity of thinning for calabrian pine plantations, useful for obtaining woody materials of good quality, regardless the tree size from which the assortments are obtained (Chapter I);
- Demonstrate a potential relationships between wood quality and tree growth, in mixture vs. monocultures stands of beech and calabrian pine (Chapter II);
- Analyse the tree growth patterns through the study of the basal area index (BAI) for beech and calabrian pine (Chapter II);
- Test whether (i) the mean wood quality in mixed species and corresponding pure stands are equal; (ii) the mean BAI in pure and mixed-species stands are equal; (iii) the wood quality and tree growth patterns are independent (Chapter II);
- Verify whether in the chestnut coppice are potential relationships between wood quality, at different tree ages and wood assortments (Chapter III);

- Verify if the effect of the silvicultural practices on wood quality can be identified by the measurement of MOEd (Chapter I, II and III);
- Offer a strategic key to integrate multiple information of forest components, developing a predictive method useful to assess the wood quality (Chapter I, II and III).

## **2.1 List of papers**

This dissertation is based on the following three articles, detailed in the chapters 2, 3 and 4.

### **Paper I - Chapter 2**

**Diego Russo**, Pasquale A. Marziliano, Giorgio Macri, Andrea R. Proto, Giuseppe Zimbalatti and Fabio Lombardi. Does Thinning Intensity Affect Wood Quality? An Analysis of Calabrian Pine in Southern Italy Using a Non-Destructive Acoustic Method. *Forests* 2020, 11, 6; doi:10.3390/f11010006.

### **Paper II - Chapter 3**

**Diego Russo**, Pasquale A. Marziliano, Giorgio Macri, Giuseppe Zimbalatti, Roberto Tognetti and Fabio Lombardi. Tree growth and wood quality in pure vs. mixed-species stands of European beech and Calabrian pine in Mediterranean mountain forests. *Forests* 2019, 10, 303; doi:10.3390/f10040303.

### **Paper III - Chapter 4**

**Diego Russo**, Pasquale A. Marziliano and Fabio Lombardi. Relationships between tree age, growth, yield and wood quality: a chronosequence in a chestnut coppice of Southern Italy. *Draft*.

## Chapter 2

### **Does Thinning Intensity Affect Wood Quality? An Analysis of Calabrian Pine in Southern Italy Using a Non-Destructive Acoustic Method**

#### **1. Introduction**

In Southern Europe, the Calabrian pine occurs mainly in Italy (Calabria and Sicilia) and in France (Corsica). In Southern Italy, Calabrian pine forests are strongly related to the complex geological history, lithological and climatic characteristics, and to the long history of human exploitation of the related forest stands (Ciancio *et al.*, 2006). In the past, calabrian pine has provided valuable timber useful for building houses and vessels, as well as offering resinous substances (pitch) employed for a variety of purposes (Bonavita *et al.*, 2015).

This species is particularly common in Sicily and on the Etna Volcano, but is mainly found in the Sila and Aspromonte National Parks in Calabria Region. Calabrian pine covers an area of approximately 114,000 ha, mostly characterized by pure stands of natural origin and plantations. The latter originated from extensive reforestation projects carried out between 1950 and 1970 on the basis of a specific Italian state law (Nicolaci *et al.*, 2014). These plantations were realized with the aim of reducing the hydrological risk in mountainous areas, but also for facilitating the natural succession toward mixed forests with a significant component of deciduous species (Cantiani *et al.*, 2010). Together with soil and watershed protection, Calabrian pine has an important role in the local forest economy. In order to increase the economic value of these forests, the best silvicultural options should be selected and adopted at stand level in order to achieve specific objectives. Therefore, different management practices and related intensities can change the tree species composition and richness and, also, the stand density and tree age distribution (Duncker *et al.*, 2012). Moreover, management practices can increase the quality and quantity of merchantable timber, reducing also the risks derived from diseases and forest fires (Skov *et al.*, 2004, Ostaff *et al.*, 2006). Forest management is aimed to create a vigorous stand, increasing tree growth and developing structural characteristics useful for

timber production. Furthermore, thinning activities can also favor the creation of new habitats for wildlife, favoring the occurrence of healthy and vigorous forests (Demers *et al.*, 2013).

Thinning activities control the forest stand density, improving the growth of the remaining trees (Grant *et al.*, 2007) based on sustainable approaches (Zeide, 2004), and decreasing, also, the tree mortality rates from a long-term perspective (Brissette *et al.*, 1999). Thus, selective thinning should be encouraged for proper and sustainable forest management, supporting the forest stability, productivity, and quality.

Furthermore, forest management can determine variation in the physical and mechanical properties of harvested wood, both at stand and tree level (Machado *et al.*, 2014). For this reason, the identification of certain wood properties that can increase timber quality is essential, as it is important to select the best forest management options to improve wood quality.

Wood quality can be described as a set of characteristics that make woody materials economically valuable for their end uses (Jozsa and Middleton, 1994). Briggs and Smith (1986) defined wood quality as “a measure of the aptness of wood for a given use”. These properties can include, for example, the wood density, the uniformity in tree ring size, the percent of knot-free wood, and the proportion between early wood and late wood.

The objective evaluation of the wood quality and quantity is then critical for quantifying the productive value of a forest (Marziliano *et al.*, 2012, Proto *et al.*, 2017). For this purpose, several non-destructive technologies (NDTs) have been developed in the past years to evaluate the quality of woody materials. For example, at belowground level, (mini) rhizotrons and ground-penetrating radar allows for evaluating tree rooting distribution and growth (Sanesi *et al.*, 2013, Marziliano *et al.*, 2015). Moreover, at aboveground level, NDT measures allow for evaluation of the mechanical and technological properties of standing trees (Škorpik *et al.*, 2018, Carter *et al.*, 2005, Wang *et al.*, 2007). More specifically, stress wave-based non-destructive acoustic techniques have been extensively investigated during the past few decades (Guntekin *et al.*, 2013), resulting in very useful methods for predicting the mechanical properties of woody materials.

The use of stress wave-based non-destructive tests is relatively common in the forest-to-mill woody supply chain in Australia (Tsehaye *et al.*, 2000) and in North America (Wang *et al.*, 2000, 2004), while it is less common in Europe. Specifically, research developments (Mora *et al.*, 2019) in acoustic sensing technology can, nowadays, permit the estimation of wood quality and intrinsic woody properties for standing trees, stems, and logs. The information derived from NDT measures could be used to sort and grade trees and logs according to their suitability for different end uses, such as structural products, advanced composites, pulp, and paper, but also for bioenergetics purposes.

Among the parameters measurable by acoustic methods, one of the most important is the modulus of elasticity of wood (MOE). The MOE, also known as wood stiffness, is essentially one of the fundamental wood quality parameters and measures the resistance to deflection (Wessels *et al.*, 2011). For example, it is important since some woody products, such as laminated veneer and dimension lumber, require stiff and strong woody properties (Tenorio *et al.*, 2011).

The recent literature has focused on determining whether stress wave techniques could be used to determine wood quality (Brashaw *et al.*, 2009). Several studies shown a good relationship between the stress wave-based modulus of elasticity (MOE) and the static MOE of lumber cut from logs (Aratake *et al.*, 1994, Ross *et al.*, 1997). This methodological approach is also applied to determine the relationships between the environmental conditions, silvicultural practices, and wood fiber properties (Wang *et al.*, 2012). The modulus of elasticity and the density of the woody materials strongly affect the acoustic properties of wood (Teder *et al.*, 2011). One of the most important mechanical properties, measurable by NDT methods, is Young's modulus, i.e., the modulus of elasticity (MOEd), which describes the material's stiffness.

Many portable instruments have been developed to measure the wood stiffness of standing trees, logs, and sawn timber using acoustic technology (Legg and Bradley, 2016). These instruments are able to measure the speed at which an induced sound (stress) wave propagates through a woody sample, which is proportional to its stiffness (Mochan *et al.*, 2009). When the stress is applied to the wood surface, the generated disturbance propagates through the wood as stress wave. Several studies have

hypothesized that the characteristics of the resulting wave are related to the mechanical properties of the wood (Wang, 2011, 2013).

Stress wave propagation in wood is a dynamic process correlated to several factors, such as the stand developmental stage (Vanninen *et al.*, 1996), genetic characteristics (Vargas-hernandez and Adams, 1994, Rozenberg *et al.*, 2001), and also the silvicultural activities and their intensities (Zobel and van Buijtenen, 1989). More specifically, the quality and properties of wood are generally affected by silvicultural practices, especially the anthropic control of stand density. Silvicultural practices might not only increase the biomass production of trees, but also improve the quality and the related physical and mechanical characteristics of the wood in trees (Todaro and Macchioni, 2011, Todaro *et al.*, 2002).

Furthermore, some authors have reported how high thinning intensities adversely influence the patterns of tree ring width and the tree competitive position within a forest stand (Schweingruber, 1998, Wang *et al.*, 2005, Peltola *et al.*, 2007).

Wang (1999), examining the effect of thinning treatments on the wood quality of radiata pine, found that trees were characterized by higher acoustic velocity and stiffness mostly occurred in uncut stands and in forests characterized by light and medium intensities of thinning, whereas the lowest values occurred in stands that received the most intensive thinning approaches.

In Southern Italy, Todaro and Macchioni (2011) and Proto *et al.* (2017) showed a significant improvement of wood properties induced by a medium thinning operation for Douglas fir and Calabrian pine trees, respectively. Moreover, Cown *et al.* (1974) and Barbour *et al.* (1994) reported that heavy thinning approaches caused a slight decrease in wood density for radiata pine and Douglas fir. Finally, Wang *et al.* (2001) indicated that heavy thinning induced the creation of more woody knots and larger-diameter knots than the medium thinning, or where no thinning had been applied.

The general objective of this study was the evaluation of the wood mechanical properties for Calabrian pine trees occurring in a forest stand located in the “Aspromonte” National Park (Calabria, Southern Italy) using innovative non-destructive methods (stress wave techniques). In detail, the

evaluation of wood quality was carried out through acoustic measurements useful for assessing the MOE. Specifically, we hypothesized that different intensities of thinning can influence the wood quality of Calabrian pine trees. Three areas characterized by different management options as well as a no-thinning area, as control, were assessed. They were characterized by similar environmental conditions, such that the only discriminating parameter was the applied silviculture.

Furthermore, we also verified if the MOEd values may be predicted by easily recordable variables such as tree diameter (D), height (H), H/D ratio, or their transformations (number of trees per hectare, basal area per hectare).

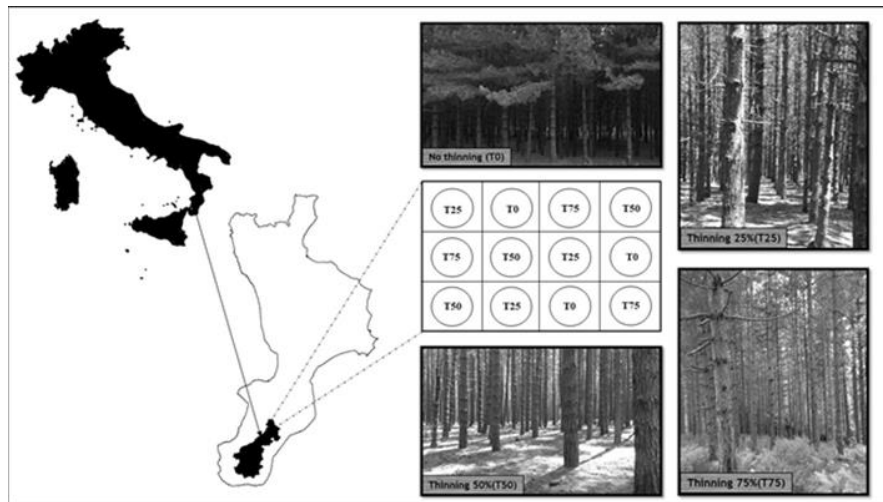
## **2. Materials and Methods**

### *2.1. Study Area and Experimental Design*

The study area was located in Zervò (Municipality of Santa Cristina d'Aspromonte), in the context of the Aspromonte National Park (Calabria Region—38°14'30" N; 16°01'09" E), at an elevation of 1100 m a.s.l. The climate is temperate, with an annual mean temperature of around 10 °C and minimum monthly means of 3 °C (coldest month) and 17 °C (warmest month), respectively. The annual rainfall is 1508 mm, with minimum precipitation occurring in summer, but is, however, unevenly distributed over the year (Meteorological station of Santa Cristina d'Aspromonte—980 m a.s.l.). According to Pavari's phytoclimatic classification (1959) the study area belongs to the Castanetum/Fagetum zone. The whole area is characterized by gently undulating slopes with northeast exposure and soils developed from high-rank metamorphic rocks, such as schist and biotitic gneisses, and classified according to the IUSS WRB (2014).

The investigated forest stands are plantations of Calabrian pine which were established in 1968, with a planting density of 2000 trees per hectare (2.0 m × 2.5 m). In 2007, at the age of 39 years, the whole plantation has been subject to different intensities of thinning, following a randomized block experimental design with three intensities of thinning repeated three times. Moreover, a portion of the stand was not characterized by cutting and considered as control. Then, twelve plots in total were considered in the field measurements. Each block had an extension of 5 hectares (Figure 1).





**Figure 1.** Location of the study area in Southern Italy (Calabrian Region) and the applied experimental design.

The treatments (intensity of thinning) can be described as follows: (1) No thinning (T0—Control); (2) Thinning where the 25% of the occurring trees were cut (T25); (3) Thinning where the 50% of the occurring trees were cut (T50); (4) Thinning where the 75% of the occurring trees were cut (T75).

## 2.2. Field and Laboratory Activity

In 2018, eleven years after the thinning operation (age of the plantation: 50 years), 804 trees were selected in total. Particular care was taken to select trees in good vegetative conditions, with canopies well separated from each other and referring to the dominant tree layer. The 804 trees were distributed between three blocks containing the four treatments, containing 201 trees for each treatment (67 trees for each replicate).

The diameter at breast height (DBH) and height of trees were measured. Moreover, for each tree, the acoustic wave tests were conducted at breast height. The measurements were conducted from June to July 2018, in order to reduce the effect of air humidity which could affect the obtained results (Yang *et al.*, 2015). More specifically, the relative air humidity was measured in the study area during the sampling period 1 m above the ground, using a HOBO1 Pro RH/Temp Data Logger (Onset Computer Corporation, Pocasset, MA, USA).

The system used for measuring acoustic velocity was the TreeSonic™ (Fakopp Enterprise, Agfalva, Hungary), a tool which has already applied in other studies (Divos, 2010). This tool is characterized by an handheld hammer and two probes, a transmitting accelerometer, and a receiving accelerometer.

The operation consists in the insertion of two sensor probes (a transmit probe and a receiver probe) into the sapwood, introducing, then, the acoustic energy into the tree through a hammer impact. The probes were aligned within a vertical plane on the same face. In our study, a 1.00 m testing span was roughly centered at breast height. The lower probes were placed about 60 – 70 cm above the forest floor. Three measurements were realized for each selected tree and the average of the three recordings was used as the final transit time. In order to measure the acoustic velocity wave, the start and stop sensors were driven at a 45° angle through the bark and into the wood of the standing tree (Eckard *et al.*, 2010). Indeed, the TreeSonic™ was developed to operate in the longitudinal direction of the tree. The acoustic velocity was then calculated from the span between the two sensor probes and the time-of-flight (TOF) data using the following formula (Equation 1):

$$CT = S/TOF, \quad (1)$$

where CT = tree acoustic velocity (m/s), S = distance between the two probes (sensors) (m), TOF = time of flight (s).

For determination of the MOEd, it was necessary to determine the wood density. A subsample of trees was selected, considering trees where the TOF was also measured. In detail, woody cores were extracted, bark to bark, at breast height (1.30 m) with a Pressler borer from trees, referring to each of the diameter classes occurring in the different treatments (three cores for each treatment and diameter class). The fresh weight and volume of the tree cores were measured in the laboratory. Samples were then weighed to the nearest 0.01 gram with an electronic scale. Oven drying of all samples was done at 105 °C to constant weight. Density ( $\text{kg m}^{-3}$ ) was calculated by dividing the dry weight with the fresh sample volume.

Afterwards, it was possible to calculate the modulus of elasticity (MOE), according to the following equation (Equation 2):

$$MOEd = WD_{ij} \cdot CT^2, \quad (2)$$

where  $WD_{ij}$  = tree wood density ( $\text{kg m}^{-3}$ ), shared by diameter class (*i*) and treatment (*j*); and CT = velocity ( $\text{m s}^{-1}$ ).

The MOE estimated using the above cited formula (Lasserre *et al.*, 2007) is called the dynamic modulus of elasticity (MOEd) [58], since the stress wave propagation in wood is a dynamic process and internally related to the physical and mechanical properties of the wood (Wang *et al.*, 2001).

### 2.3. Statistical Analysis

The preliminary shape indexes (skewness and kurtosis) were calculated, and the Shapiro-Wilk test was performed to evaluate the distribution of the acquired data. Afterwards, the analysis of variance (ANOVA), based on a scheme of randomized blocks (four treatments repeated three times), was carried out to test the differences in MOEd values obtained among the four treatments and in relation to the occurring diameter classes. The significance level of the differences was tested using Tukey's method. When the significance level (p-value) was  $\leq 0.05$ , the null hypothesis was rejected and significant differences in the means were accepted.

For the estimation of the MOEd, the following parameters (easily measurable in the field) were considered as predictors: diameter at breast height (DBH), height (H), height/diameter ratio (H/DBH), basal area (BA), stand density (number of trees per hectare) and their mutual interactions.

As a preliminary analysis, the correlations between these variables and the MOEd were analyzed using the Spearman correlation coefficient ( $r$ ). Subsequently, the analysis was carried out by comparing different transformations and combinations of the variables correlated with the MOEd, suitable for expressing the relationship between MOEd and the above cited variables. The process involved regression analysis with a stepwise procedure (in each step, a variable was considered for addition to or subtraction from the set of explanatory variables based on F-tests). We then evaluated the fit of the final model using and analyzing the value of root mean square error (RMSE) and the coefficient of determination ( $R^2$ ) value. Finally, the Shapiro-Wilk test was used to verify the normality of the error distribution.

Data analysis were carried out using the statistical software R version 3.2.5 (R Core Team, 2016).

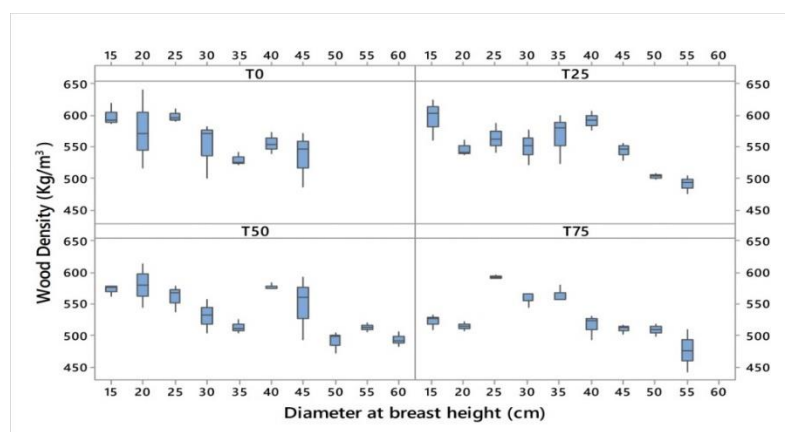
### 3. Results

The relative air humidity measured in the study area during the sampling period ranged from 39% to 56%. For each treatment, the main measured structural parameters and the derived values of stand density and basal area are reported in Table 1. The skewness and kurtosis values, as well as the Shapiro-Wilk test (SWT), revealed that all the attributes were characterized by normal distribution. Tree diameters varied from about 25 to 32 cm, while tree heights showed similar values (19–20 m).

**Table 1.** The main parameters measured and the related structural characteristics for the four treatments analyzed (DBH: diameter at breast height; H; total tree height; N ha<sup>-1</sup>: number of trees per hectare; SD: standard deviation; SWTsig: *p*-values of the Shapiro–Wilk Test).

Treatments	Parameters	Mean	SD	Skewness	Kurtosis	SWTsig
T0	DBH (cm)	24.9	6.07	0.228	-0.408	0.106
	H (m)	18.84	2.83	0.447	0.483	0.112
	Stand density (N ha <sup>-1</sup> )	1977	134	0.468	-0.62	0.125
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	95.9	7.16	-0.873	0.024	0.095
T25	DBH (cm)	26.7	8.19	0.352	0.242	0.053
	H (m)	20.03	2.76	0.298	0.237	0.131
	Stand density (N ha <sup>-1</sup> )	1548	77	0.045	-0.938	0.096
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	86.88	11	0.049	-0.965	0.364
T50	DBH (cm)	26.4	8.73	0.646	1.001	0.064
	H (m)	20.05	3.65	-0.326	0.042	0.055
	Stand density (N ha <sup>-1</sup> )	939	49	0.676	1.055	0.118
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	51.45	4.28	-0.451	-0.579	0.247
T75	DBH (cm)	32.5	9.96	0.444	-0.46	0.217
	H (m)	21.1	3.68	-0.503	0.399	0.146
	Stand density (N ha <sup>-1</sup> )	514	29	-0.281	-0.684	0.214
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	42.67	3.05	0.194	-0.544	0.079

Figure 2 reports the variability and the distribution of the wood density in relation to the type of treatment and the different diameter classes.



**Figure 2.** Variability of the tree wood density for each treatment as shared by diameter classes.

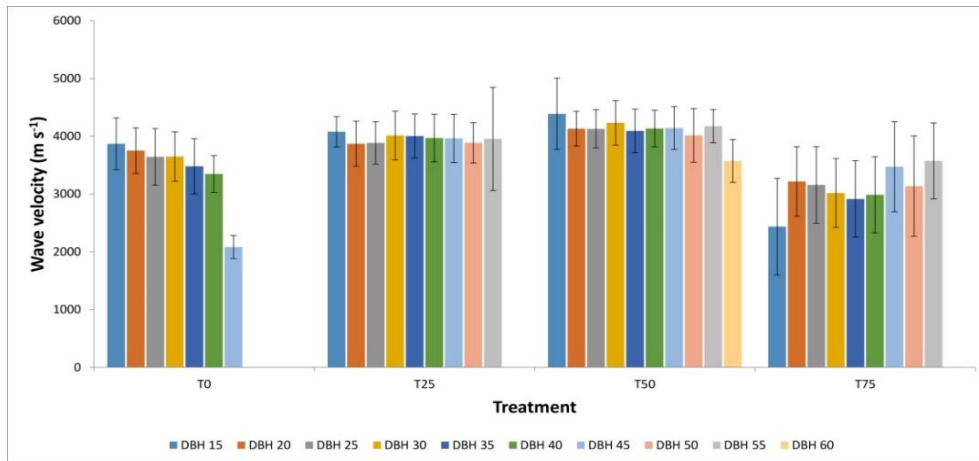
Table 2 shows the stress wave times and the related mechanical properties (wave velocity and MOEd) for the sampled trees in relation to the different silvicultural treatments. Moreover, the tree wood density (on average) is also shown.

**Table 2.** Tree wood density, stress wave time, and mechanical properties for the sampled trees among the different treatments considered (SD: standard deviation; MOEd: dynamic modulus of elasticity). Means in the same column followed by the same letter are not statistically different at  $p \leq 0.05$  (Tukey test).

Treatments	Tree wood density (kg/m <sup>3</sup> )		Stress wave time (μs)		Wave Velocity (m s <sup>-1</sup> )		MOEd (MPa)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T0	563	30.2	282.5 <sup>b</sup>	48.0	3637.9 <sup>d</sup>	465	7206.2 <sup>c</sup>	1699.9
T25	550	35.5	257.0 <sup>c</sup>	27.0	3959.7 <sup>ab</sup>	397	8487.5 <sup>b</sup>	1695.4
T50	538	28.2	245.2 <sup>cd</sup>	22.0	4141.6 <sup>a</sup>	371	9275.8 <sup>a</sup>	1717.5
T75	529	27.4	344.5 <sup>a</sup>	90.8	3090.1 <sup>c</sup>	681	5371.9 <sup>d</sup>	2242.2

With reference to the stress wave time, significant differences were recorded among the different intensities of thinning ( $F_{3;794} = 134.24$ ;  $p \leq 0.001$ ), while no difference between blocks ( $F_{2;794} = 2.012$ ;  $p = 0.134$ ) were observed. The treatment characterized by the higher thinning intensity (T75) revealed a longer stress wave time (344.5 μs), also differing significantly with respect to all other conditions: T75 was about 22% and 40% higher than T0 and T50, respectively. Moreover, each treatment differs significantly in stress wave time from all the others, except T25 and T50, which had similar values. The wave velocity is positively correlated to the thinning intensities, up to the T50 treatment (Table 2); afterwards, it significantly decreased for the higher thinning intensity (T75) ( $F_{3;794} = 174.55$ ;  $p \leq 0.001$ ). No differences between blocks ( $F_{2;794} = 1.579$ ;  $p = 0.207$ ) were observed.

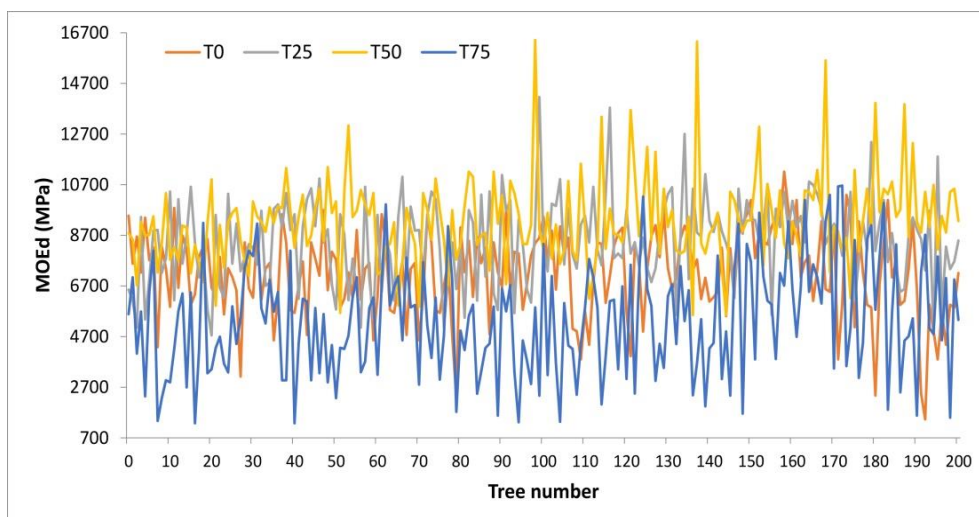
In Figure 3, the variation of the wave velocity in relation to the tree diameter classes is reported for each treatment.



**Figure 3.** Wave velocity in relation to the diameter classes for each intensity of thinning. DBH: diameter at breast height. For Control,  $F_{6;191} = 3.371$ ;  $p = 0.006$ ; for T25,  $F_{8;189} = 0.658$ ;  $p = 0.728$ ; for T50,  $F_{9;188} = 1.600$ ;  $p = 0.118$ ; for T75,  $F_{8;189} = 2.330$ ;  $p = 0.021$ .

In the control plots, the wave velocity tends to decrease as the tree diameters increase; more specifically, the 45 cm diameter class had significant lower values when compared to all other diameter classes. No significant differences were observed between diameter classes for T25 and T50. On the contrary, the wave velocity values were the lowest for the T75 treatment, revealing significant differences also between diameter classes.

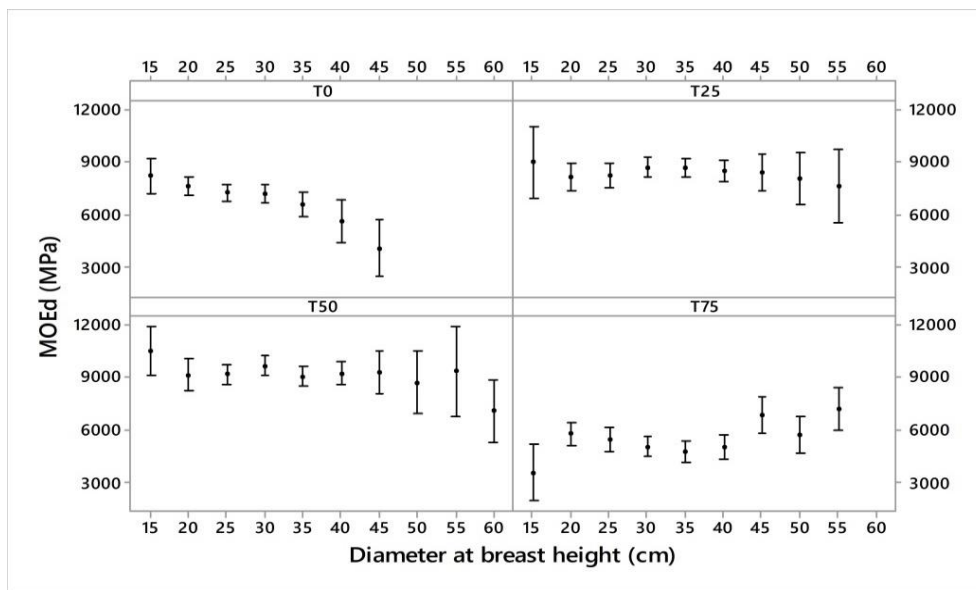
Furthermore, Figure 4 shows the MOEd values obtained for all the sampled trees in each intensity of thinning.



**Figure 4.** MOEd values obtained for all the sampled trees. Different colors refer to the four intensities of thinning.

Generally, for each tree, lower values always occurred in T75, while higher values occurred in T25 and T50. The analysis of variance (ANOVA) showed a significant effect of the thinning intensity on

MOEd values ( $F_{3;794} = 170.82$ ;  $p \leq 0.001$ ). Table 2 shows that the MOEd was significantly higher in T25 (on average, equal to 8487 MPa) and T50 (on average, 9275 MPa) than in T0 (on average, 7206 MPa) and T75 (on average 5371 MPa). Furthermore, the MOEd values for treatment T75 were always lower than in the T0 (Table 2). No difference between blocks was observed ( $F_{2;794} = 1.574$ ;  $p = 0.208$ ). Furthermore, the analysis of variance showed a significant effect of the diameter classes on MOEd values for the thinning intensities T0 and T75, while no significant effects were observed in treatments T25 and T50 (Figure 5).



**Figure 5.** Dynamic modulus of elasticity (MOEd) in relation to the diameter classes for each intensity of thinning. For Control,  $F_{6;191} = 3.371$ ;  $p = 0.006$ ; for T25,  $F_{8;189} = 0.658$ ;  $p = 0.728$ ; for T50,  $F_{9;188} = 1.600$ ;  $p = 0.118$ ; for T75,  $F_{8;189} = 2.330$ ;  $p = 0.021$ .

The MOEd values decrease as the diameters for T0 increase, with significant differences observed between the smallest and largest diameter classes. On the contrary, for the T25 and T50 treatments, the MOEd values were not significantly different when the diameter increased (Figure 5). The thinning, especially in the T25 treatment and, to a lesser extent, in the T50 treatment, had the effect of aligning the MOEd values, making the wood quality uniform in each diameter class. On the contrary, for the T75 treatment, the MOEd values not only were significantly lower than the T0, T25, and T50 treatments, but they also varied significantly with the increase of diameters.

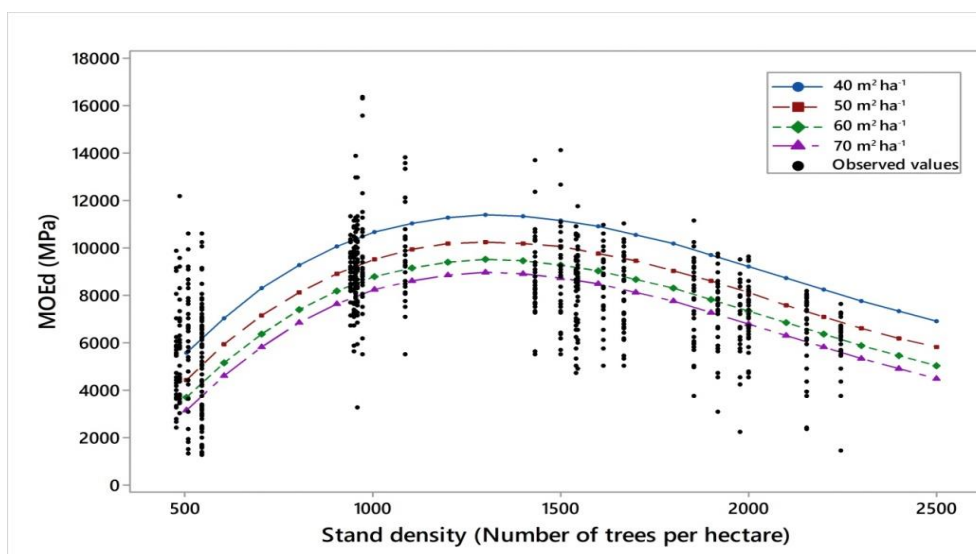
In analyzing the best predictors for the estimation of MOEd, the applied analysis showed correlations between MOEd and DBH ( $r = 0.011$ ), between MOEd and H ( $r = 0.040$ ) and between MOEd and H/D ( $r = 0.033$ ) that were not considered significant. On the contrary, significant correlations emerged between the MOEd and the stand density ( $r = 0.474$ ) and basal area ( $r = 0.217$ ).

Therefore, a model that allows for computing the MOEd as a function of the stand density (number of trees per hectare) and basal area ( $\text{m}^2$  per hectare) was applied. According to the stepwise regression procedure, the variables were combined in the following model (Equation 3):

$$MOEd = \beta_0 + \beta_1 \cdot \frac{1}{BA} + \beta_2 \cdot SD + \beta_3 \cdot SD^2 + \beta_4 \cdot SD^3, \quad (3)$$

where BA = basal area per hectare; SD = number of trees per hectare.

Figure 6 shows the variation of the MOEd in relation to the number of trees per hectare for different basal areas. The analysis covered a basal area lapse ranging from 40 to 70  $\text{m}^2 \text{ha}^{-1}$ . The MOEd curve is lower for high values of basal area (70  $\text{m}^2 \text{ha}^{-1}$ ) and higher when basal area values decrease (40  $\text{m}^2 \text{ha}^{-1}$ ). The root mean square error (RMSE) was 1850.69 MPa and  $R^2$  was 0.368. Moreover, the Shapiro–Wilk normality test ( $W = 0.9614$ ;  $p = 0.096$ ) confirmed the absence of deviation from normality. Furthermore, Table 3 reports the statistical values obtained by the application of the Equation 3.



**Figure 6.** MOEd values in relation to the stand density and to the basal area.



**Table 3.** Statistical parameters obtained in the model and their significance (BA: basal area; SD: number of trees per hectare; T: results of the Student t-test).

Model	Coefficients	Standard error of coefficients	T	Significance
(Constant)	-11895.537	1349.925	-8.782	$p < 0.0001$
1/BA	227408.509	44672.651	5.068	$p < 0.0001$
SD	31.669	2.538	12.458	$p < 0.0001$
SD <sup>2</sup>	-0.018	0.002	-7.941	$p < 0.0001$
SD <sup>3</sup>	0.00000281	0.000	5.371	$p < 0.0001$

#### 4. Discussion

The obtained results demonstrate how the effect of silvicultural practices on wood quality can be successfully identified by measurement of MOEd. The MOEd values recorded in standing trees were significantly influenced by thinning intensities, since they determined significant variations in MOEd values with respect to the control. Specifically, the T25 and T50 treatments produced significant benefits in terms of wood quality, while a higher thinning intensity (T75) induced a significant decrease of the MOEd, even lower than the control. The strong diametric increment induced by the intensive thinning probably resulted in a less-stiff mature wood, resulting in a significant loss of wood quality.

On other hand, many authors confirmed that wood quality and intrinsic wood properties are generally affected by thinning (Proto *et al.*, 2017, Candel-Pérez *et al.*, 2016, Mitchell, 2000), especially by stand density (Todaro, 2011, Macdonald and Hubert, 2002). In this study, density values were measured on a subsample, rather than all, of the trees. This could lead to slight variations in MOEd values, but should not compromise the obtained results. In Southern Italy, Todaro and Macchioni (2001) also found a significant variation of wood properties caused by thinning operations in a Douglas fir forest.

Generally, in the management of forest stands, it is common to apply a strong intensity of thinning in order to obtain a high assortment of diameters (Štefančík *et al.*, 2018). However, our results show that these assortments are of a lower quality compared to those derived from moderate intensities of thinning.

It is also interesting that the increase in the MOEd values from T0 to T25 is more sustained than the increase in MOEd from T25 to T50. This indicates that light thinning has a significant and positive effect on the wood quality, while increasing thinning intensities are always less significant. On the other hand, the T25 treatment had a positive effect on MOEd, both at the stand level and at the diametric class level, making the MOEd values almost equal for each diameter class. On the contrary, in the T0 and T75 treatments, we observed a decrease in wood quality when diameters increased. Other studies conducted on trees of the same age for different conifers (Sitka spruce (*Picea sitchensis* Bongard, Carrière, 1855), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), jack pine (*Pinus banksiana* Lamb.), ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), and radiata pine (*Pinus radiata* D. Don) (Ikeda and Kino, 2000, Wang et al., 2003) reported that the stress wave velocity was higher for trees with a slower growth rate or narrower rings.

The results obtained here are interesting on the basis of their practical and scientific applications, since they can provide useful silvicultural indications: the application of moderate thinning can favor, at least for the Calabrian pine, the formation of woody materials of good quality, regardless of the tree size from which the assortments are obtained.

More specifically, the MOEd values increase as the number of trees rise, up to 1200–1500 trees per hectare: this tree density seems to be the optimal value for obtaining the best woody materials for Calabrian pine. Briggs (2007) showed that the tree acoustic velocity measured in Douglas fir increases as tree age rises, and decreases with increasing DBH; moreover, it is affected by the initial stand density.

Furthermore, higher values of basal area, when the number of trees and tree age are similar, determine lower values of the MOEd. We can then observe that a rapid diameter increment can negatively affect the wood quality.

In Douglas fir forests, Zhang (1995) and Todaro and Macchioni (2011) also reported that large trees deriving from higher growth rates would generally produce wood of lower stiffness. Furthermore, Chauhan and Walker (2006) showed how, in fast-growing trees of radiata pine, the increased diameter

with its larger second moment of inertia induced a lower tendency for high material stiffness; moreover, for trees of the same age, slow-growing trees tend to have a high stiffness, helping to sustain the trees under various environmental disturbances. Furthermore, Lasserre et al. (2004) have observed that outerwood stiffness increases dramatically with stocking (and so with smaller tree DBH).

The low values of MOEd therefore appeared to be associated to a higher growth rate in trees, which adversely affects the specific gravity as well as the wood's strength and stiffness. Younger wood is lower in specific gravity and stiffness, while fast-growing wood has a larger diameter core of juvenile wood (Clark and Daniels, 2002).

The moderate thinnings not only increase the biomass production of trees (Marziliano et al., 2015, Coletta et al., 2016, Marziliano et al., 2017), but also improve the wood quality in trees, as highlighted in this study. However, Nakamura (1996), using ultrasonically induced waves to assess the wood quality in larch trees, had already observed significant differences in the wave velocity and in MOEd values for forest stands characterized by different density some decades ago. In addition, Wang (1999), assessing the effect of thinning treatments on the technological properties of Sitka spruce trees in southeast Alaska, showed that trees with higher acoustic velocity and stiffness were mostly found in forest stands that were uncut and/or slightly thinned, while the lowest values were found in stands subjected to high intensity thinning.

These results are encouraging, and indicate that the time of flight in the acoustic technologies may be applied, in the future, to monitor the wood property changes in forest stands. The technology can also be used to determine how silvicultural treatments affect the wood and fiber properties; consequently, the most effective treatment can be selected for maximizing the wood value, improving the timber quality of future plantations (Krajnc et al., 2019). Finally, the precision of the acoustic technology has been strongly improved: nowadays, the tree quality, but also the intrinsic wood properties, can be predicted and correlated with the economic value of the final products (Wang, 2012).

In this study, the model developed can be used as a decision support system useful for the woody supply chain: the determination of the MOEd is fundamental for the final end uses of the woody products.

However, even if many studies have been carried out for estimating the MOEd through various non-destructive tests (Sandoz, 1996, Zhang *et al.*, 2002), few of them have, in any case, examined the relationships between MOEd and the stand structural features (e.g., stand density, DBH, total tree height, tree taper). Gorman *et al.* (2002) confirmed that the stress wave velocity is not affected by knots and other defects; nevertheless, it is important to underline that this method only measures the sound velocity within the outermost growth tree rings.

Furthermore, we identified, here, the most useful variables for predicting the MOEd, based on stand and tree characteristics in Calabrian pine.

In accordance with other studies (Proto *et al.*, 2017, Castera *et al.*, 1996, Lei *et al.*, 2005), significant relationships between the dendrometric parameters and MOEd values were found. However, the relationships between MOEd and stand density, which showed a decrease in MOEd at high stand density, have not been previously described. While the MOEd always decreased with higher basal area, MOEd only decreased from a certain number of trees per hectare. However, in addition to the stand density (number of trees per hectare and basal area), the tree diameter classes could be considered for explaining the MOEd values in trees, as also already highlighted by Lei *et al.* (2005). Finally, as some of these stand structural features are commonly measured in forest inventories we provide, here, a useful tool for predicting the wood stiffness in relation to the tree and stand characteristics measured in the field. This approach allows for determination of the wood quality directly from inventory data.

However, the model used is site- and species-specific since, in other silvicultural systems, the implemented equation can differ. In any case, a pioneer of forest modeling (Burkhart, 1997) confirmed that no single model can be expected to be the “best” for all the conditions which are common in forest prediction.

## 5. Conclusions

This study showed that silvicultural practices might not only increase biomass production, but also improve the wood quality in trees. We verified here, through innovative and non-destructive methods, that different intensities of thinning can influence the wood quality of Calabrian pine trees in Southern Italy. Our results demonstrated that the effect of silvicultural practices on the properties of wood can be successfully identified by stress wave MOEd. Furthermore, we proved that MOEd values may be predicted by easily recordable variables in the field.

More specifically, for Calabrian pine, different intensities of thinning can affect the wood quality and, therefore, the final obtainable woody products. We also demonstrated that using a low intensity of thinning could be the best option for obtaining woody materials of good quality, regardless of the tree size from which the assortments derive. The results obtained are encouraging, since they demonstrate the potential of the non-destructive acoustic technique to determine the influence of thinning treatments performed on Calabrian pine. However, it could be interesting to also test the same methodological approach on other tree species and in different ecological contexts.

Finally, we tested a useful tool for predicting the wood stiffness in relation to tree and stand characteristics commonly measured in the field. This approach allows for determination of the wood quality directly from inventory data, even if the model used is site- and species-specific and the implemented equation can differ in other silvicultural systems.

## Chapter 3

### Tree growth and wood quality in pure vs. mixed-species stands of European beech and Calabrian pine in Mediterranean mountain forests

#### 1. Introduction

Mixed-species forests may deliver forest functions and services more effectively than monocultures (Gamfeldt *et al.*, 2013, van der Plas *et al.*, 2016), particularly in threatened mountain environments (Cudlín *et al.*, 2017) and in man-made mixed-species forests. Therefore, their spread is an important option to adapt European mountain forests and forestry to future disturbances and extreme events (Pretzsch *et al.*, 2013). Mixed-species forests may show less temporal variation in growth and more stable productivity in comparison with pure stands, due to reduced tree species competition for resources (Yachi *et al.*, 2007, Piotta *et al.*, 2008, Morin *et al.*, 2011, Paquette *et al.*, 2011, Pretzsch *et al.*, 2013, Pretzsch and Schütze, 2015, Jucker *et al.*, 2014, Metz *et al.*, 2016, Liang *et al.*, 2016). Nevertheless, contradictory mixed-species effects on tree growth have been found under conditions favouring drought stress or in dry years (Grossiord *et al.*, 2014, Merlin *et al.*, 2015, Conte *et al.*, 2018). Gebauer *et al.* (2012) observed that stand-level canopy transpiration was not higher in mixed broad-leaved forests than in pure European beech stands and that the spatial complementarity in root water uptake of mixed-species stands could be masked by edaphic conditions preventing the vertical stratification of species-specific root systems. An increase in the frequency and severity of drought events, as predicted for the coming decades (IPCC, 2017, Hanewinkel *et al.*, 2013), will have dramatic implications for the resilience of Mediterranean mountain ecosystems, particularly in the case of forest stands with a simplified vertical structure (Altieri *et al.*, 2018). Indeed, species-specific functional traits and allometric relations can be more important for stand water use than tree species diversity *per se*. Therefore, more insight into species mixing, structural diversity and forest dynamics is essential for modeling risk assessment and forest functions aimed at fostering alternative silvicultural practices in harsh environments.

Although mixed-species stands can be more productive in comparison with monocultures (Zhang, et al., 2012, Kanowski et al., 2005, Petit and Montagnini, 2006, Richards et al., 2010) up to 30% (Bielak et al., 2014), site conditions, stand age, and tree species interactions affect these responses (Forrester, 2014, Petráš et al., 2016). Focusing on the causes of differences in tree growth and stand productivity between mixed-species and pure forests, most research addressed environmental settings and relationships with climatic conditions, species composition, mixture type, and stand age (Magin 1954, Kennel 1965, 1966, Hausser et al., 1967, Mitscherlich, 1967, Hink 1972, Mettin, 1985, Kramer, 1988, Pretzsch, 2010). Indeed, few studies exist on the quality and value of wood produced in mixed-species vs. corresponding pure stands (Saha et al., 2012). Information on how wood quality can be affected in relation to tree species composition is essential for decision making in adaptive forestry, especially where forest planning and thinning activities favour the occurrence of mixed-species stands (Petráš et al., 2016).

Liu et al. (2018) showed that spacing and thinning experiments in pure stands highlighted the strong effect of the surrounding spatial stand structure on tree growth and morphology and, ultimately, wood structure and timber quality. Chomel et al. (2014) demonstrated that, in mixed-species plantations, mixing hybrid poplar and white spruce might increase the wood production of poplar in comparison with monocultures of either poplar or white spruce. Battipaglia et al. (2017) showed a considerable increase in cumulative basal area and in intrinsic water use efficiency in mixed-species stands of pedunculate oak and Italian alder, largely resulting from an increase in N fixation, which levelled off, when natural mortality or management practices decreased the competitive ability of Italian alder. In addition to stand productivity and water use efficiency, species mixtures with structural stratification may also enhance individual-tree growth rates and stem quality of species in the upper canopies, minimizing the proportion of taller species that reach the highest production (Piotto, 2008, Kelty, 2006).

Forest management practices oriented to obtain mixed-species stands potentially determine variation in the physical and mechanical properties of the harvested wood, both at stand and tree level

(Machado *et al.*, 2014). Nevertheless, although mixed-species forestry is gaining popularity in Europe (Pretzsch and Schütze, 2009, 2015), a greater understanding of the differences in wood quality between mixed-species vs. corresponding pure stands is needed. In the last decades, the evaluation of wood quality has been preferentially based on non-destructive technologies (NDTs) (Russo *et al.*, 2019). More specifically, stress wave-based non-destructive acoustic techniques resulted in very useful methods for predicting the mechanical properties of woody materials (Guntekin *et al.*, 2013). Nowadays, acoustic sensing technology allows for the estimation of wood quality and intrinsic woody properties for standing trees, stems and logs. Among the parameters measurable by acoustic methods, the most important is the dynamic modulus of elasticity (MOEd), being related to wood anatomy and tree physiology. This parameter can be used for the evaluation of wood quality, providing information on the stiffness of material (Teder *et al.*, 2011, Wessels *et al.*, 2011).

In this study, the wood quality term refers to the use of wood in the field of construction. The wood properties that determine the structural requirements are defined by indicators, such as strength grades, that depend on knottiness, stiffness and density of the wood (Bacher and Krosek, 2014). These parameters are commonly used worldwide to define strength grades (Pretzsch and Rais, 2016). With reference to stiffness, the dynamic modulus of elasticity (MOEd) is considered a good predictor, so as to be used as a proxy variable for assessing the wood quality and, in particular, its stiffness (Rais and Van de Kuilen, 2015). As a matter of fact, profound implications for wood properties and utilization derive from the growth and ecophysiological responses of trees to environmental conditions.

We focused on two important tree species, European beech and Calabrian pine, widespread in mountainous forest ecosystems of Southern Italy; European beech is a late-successional broadleaved tree species, here occurring in its southernmost ecological limit, whereas Calabrian pine is an early-successional conifer, providing timber of high quality. In the Calabrian Apennines, these species occur in both pure and corresponding mixed-species stands, which may help test the effects of mixture on tree growth and wood quality in a drought-prone environment. Our study comprises nine plots



grouped into three triplets of pure and mixed-species stands of European beech and Calabrian pine (three dominated by European beech, BP, three dominated by Calabrian pine, PP, and three mixed-species plots, MBP), in the Aspromonte National Park. The three stands grow in the same environmental conditions and show similar structural traits. We hypothesized that the mixture effect may improve the physiological fitness of each species and, thus, the wood quality. The specific objectives of the study were to: (Q1) evaluate the wood quality (MOEd), (Q2) analyse tree growth patterns through the basal area index (BAI), and (Q3) highlight potential relationships between wood quality and tree growth, in mixture vs. monocultures. In particular, we tested whether (i) the mean wood quality in mixed-species and corresponding pure stands are equal, (ii) the mean BAI in pure and mixed-species stands are equal, and if (iii) the wood quality and tree growth patterns are independent.

## **2. Materials and Methods**

### *2.1. Study Area*

The study area is located in the Aspromonte National Park, Calabria (Southern Italy), near the village of Bagaladi (RC). The climate is temperate, with an annual mean temperature of around 8 °C and minimum and maximum monthly means of 0.5 °C (coldest month) and 16 °C (warmest month), respectively. Annual precipitation is 1611 mm unevenly distributed over the year (Meteorological station of Gambarie d'Aspromonte—1187 m above sea level (a.s.l.).

The study is based on nine plots (each with an extension of 5000 m<sup>2</sup> and square shape), grouped into three triplets of pure and mixed-species stands of European beech and Calabrian pine, using a randomized block design. Plots within each block were randomly assigned to the units. Each triplet, extended over 1.5 ha, contains two monospecific plots, dominated by European beech (BP) or Calabrian pine (PP), and one mixed-species European beech-Calabrian pine stand (MBP). The pure stands were selected if the target species represented ~90% of the stand basal area. The mixed-species stand was defined as the stand in which the two species together represented at least ~80% of the total stand basal area and the sum of the basal area of other species was lower than that of each of the two

studied species. In order to quantify the mixing effects, the pure stands were used as reference for the mixed-species stand.

Plots are located in similar environmental conditions in terms of environmental settings (topography, slope, substrate) and climatic conditions. Soils developed from igneous and metamorphic rocks and are classified as Umbrisols, Cambisols and Leptosols (FAO, 2014), with an udic soil regime moisture. Further details on the main environmental conditions characterizing the study site are reported in Table 1.

These forest stands are of natural origin, with a dominant age ranging from 70 to 120 years old. They evolved naturally in the last 70 years. However, these forests (approximately until the Second World War) were cut following a management approach based on the “selection cutting” criteria, in which few trees were cut approximately every 20 years in the same forest section (Ciancio *et al.*, 2016). This type of management has preserved the typical forest landscape by maintaining a continuous forest cover, determining a stand structure consisting of clusters of trees in different age classes. These clusters are the result of the natural regeneration occurring in the gaps opened by the selection cutting previously applied (Ciancio *et al.*, 2016).

**Table 1.** The main geographical features of the investigated triplets located nearby the village of Bagaladi, RC (Aspromonte National Park).

	Triplet 1	Triplet 2	Triplet 3
Latitude (N)	38°06'50.53''	38°05'54.59''	38°06'15.69''
Longitude (E)	15°51'53.25''	15°50'37.72''	15°51'23.37''
Exposure (°)	59	59	59
Altitude (m a.s.l.)	1521	1511	1497
Slope (°)	28	30	34

## 2.2. Tree sampling and BAI analyses

In 2017, in order to derive the dendrometric variables at the stand level, the nine plots were fully inventoried. The diameters at breast height (DBH) and the total heights (Ht) of all trees were measured. Tree volume was calculated using the equations derived for the prediction of the aboveground tree volume (Tabacchi *et al.*, 2011). Canopy dominant/co-dominant trees were targeted for sampling (coring and measuring MOEd) and were selected through a stratified random sampling, in relation to the frequency of the diameter classes at the plot level. In detail, in each monospecific

stand (BP and PP), 30 dominant trees per species were cored, while 60 dominant trees were cored (30 for European beech and 30 for Calabrian pine) in MBP. For each selected tree, two increment cores were collected at breast height and at an angle of 120° to each other. Particular care was taken to select trees with canopies well separated from each other. Moreover, to avoid the effect of wood alteration and exogenous disturbances on tree ring growth, only trees without abrasion scars or other visible evidence of injury were selected. Cores were then mounted on channeled wood, seasoned in a fresh-air dry store and sanded a few weeks later. Ring widths were measured with a resolution of 0.01 mm using the LINTAB measurement equipment (Frank Rinn, Heidelberg, Germany) fitted with a Leica MS5 stereoscope (Leica Microsystems, Wetzlar, Germany). Tree ring widths were then statistically cross-dated and verified with the software TSAP software package (version 4.81c) and COFECHA (version 6.06) (Holmes, 1983). Once all measurement series were validated, tree-ring chronologies were developed for each species. Subsequently, tree ring widths were converted into tree basal area increment (BAI), according to the following standard formula:

$$BAI = \pi(r_n^2 - r_{(n-1)}^2)$$

where  $r$  is the radius of the stem at breast height and  $n$  is the year of tree-ring formation. In order to examine the mean growth trend for the sampled trees, BAI for each year was averaged over all the individuals for removing the variation in radial growth attributable to the increasing tree circumference.

The latest fully built tree ring valid for our analysis was related to 2016. We considered only the tree-ring chronologies starting from 1900, because few trees had rings formed before the year 1900.

### 2.3. Wood quality

In order to evaluate the wood quality, acoustic wave tests were conducted at breast height on the same 120 trees from which the woody cores were collected. In order to reduce the effect of air humidity (Wang, 2013), the tests were carried out in the summer of 2017, from June to July.

TreeSonic (FAKOPP TreeSonic™ Fakopp Enterprise, Agfalva, Hungary) (Russo et al., 2019, Vanninen et al., 1996) was used for measuring the acoustic velocity. It is characterized by a hand-

held hammer and two probes, a transmitting accelerometer and a receiving accelerometer. The system consists in the insertion of two sensor probes (a transmitting probe and a receiving one) into the sapwood, applying acoustic energy into the tree stem through hammer impact. The probes were aligned within a vertical plane on the same face. In our study, a 1.00-m testing span was roughly centered at breast height. The lowest probe was placed about 60–70 cm above the forest floor. Three measurements were realized for each selected tree and the average of the three recordings was used as final transit time. In order to measure the acoustic velocity wave, the start and stop sensors were driven at a 45° angle through the bark into the wood of the standing tree (Vargas-Hernandez and Adams, 1994). Acoustic velocity was determined on the upstream side of the tree (according to standard procedure), the same side where the stem diameter was measured. The acoustic velocity (CT) was then calculated from the span between the two sensor probes and the time-of-flight (TOF) data, using the following formula:

$$CT = S/TOF \quad (1)$$

where CT = tree acoustic velocity (m/s), S = distance between the two probes (sensors) (m), TOF = time-of-flight (s).

The wood density of each measured tree was also determined on the woody cores. The fresh weight and volume of the tree cores were measured in the laboratory. Woody samples were weighed to the nearest 0.01 g with an electronic scale. After ring width measurements, the woody cores were dried in oven at 105 °C, to constant weight. Density ( $\text{kg m}^{-3}$ ) was calculated by dividing the dry weight by the fresh volume.

Afterwards, it was possible to calculate the modulus of elasticity (MOE), according to the following equation:

$$MOEd = WD_i \times CT^2 \quad (2)$$

where  $WD_i$  = tree wood density i ( $\text{kg m}^{-3}$ ) and CT = velocity ( $\text{km s}^{-1}$ ).

When MOE is estimated using the above formula, it is termed dynamic modulus of elasticity (MOEd) (Zhembo *et al.*, 2006), as the stress wave propagation in wood is a dynamic process, internally related to the physical and mechanical properties of wood (Todaro and Macchioni, 2011).

#### *2.4. Relationship between Wood Quality and Tree Growth*

In standing trees, the stress wave propagation is affected by tree stem diameter, wood travel distance and internal wood conditions (Zhang *et al.*, 2011). Furthermore, the mean tree values of timber grade-determining properties (elastic modulus, bending strength, and wood density) are related to the acoustic velocity and tree slenderness. Signals are transferred through the whole stem, depending on stem diameter: when smaller is the diameter, then the signal is more transferred inside the stem (Krajnc *et al.*, 2019). In this study, we used the tree final growth time to evaluate the relationship between wood quality and tree growth, in order to verify if the wood quality was independent from tree growth. In detail, the final growth time is given by the number of radial rings included in the outermost 2.5 cm of the sampled trees. This parameter is called “recruitment period” (RP), which indicates the number of years needed to pass from a diameter class  $x_i$  to the largest class  $x_i + 5$ , assuming classes of 5 cm (Marziliano *et al.*, 2012). Therefore, for each sampled tree, we counted the number of rings contained in the last 2.5 cm.

#### *2.5. Statistical analysis*

The data collected were characterized by a nested structure and they were not independent from each other: in detail, an inter-correlation among samples occurred, since they were referred to the same triplets, and the single tree ring chronologies belonged to one single tree. Therefore, an analysis based on a linear mixed model was used, including both fixed and random effects. We then set up the model functions to test the effect of mixing on tree ring width (expressed as BAI) and on the MOEd. The linear mixed models incorporated the triplet identifier as a random effect, thus considering both the mixing effect (expressed as percentage of basal area of the examined species of beech or pine, compared to the total area) and the nested structure of the data. The initial model included the following independent variables: basal area, stem DBH, tree height, tree age. A stepwise procedure

(in each step, a variable was considered for addition to or subtraction from the set of explanatory variables based on F-tests) eliminated all variables, except for the basal area, the only variable that had a significant effect on the dependent variable. Therefore, the below model, based only on mixing effect and the nested design of data, was applied to evaluate if significant differences on BAI between mixed-species and corresponding pure stands occurred:

$$BAI_{ij} = \beta_0 + \beta_1 \cdot Mix_{ij} + u_j + \varepsilon_{ij}$$

where  $BAI_{ij}$  is the mean of the basal area increment per tree  $i$  on triplet  $j$ ,  $\beta_0$  is the intercept,  $Mix_{ij}$  is the fixed effect describing the quantification of the mixing effect (expressed as % basal area) on tree BAI for tree  $i$  on triplet  $j$ ,  $u_j$  is the random effect for triplet  $j$  and  $\varepsilon_{ij}$  is the error term. Moreover, the following model was used to analyse the effect of both mixture and tree ring width (expressed as recruitment period) on wood quality (MOEd values), incorporating the triplet identifier as a random effect:

$$MOEd_{ij} = \beta_2 + \beta_3 \cdot Mix_{ij} + \beta_4 \cdot RP_{ij} + u_j + \varepsilon_{ij}$$

where  $MOEd_{ij}$  is the wood quality of tree  $i$  on triplet  $j$ ,  $RP_{ij}$  is the recruitment period of tree  $i$  on triplet  $j$ , examined as the main effect. For the linear mixed-effect model analysis, the nlme package for the R programming language (Team, 2016) was used. In addition to the linear mixed-effect models, the Mann-Whitney Test for independent-sample (U-Test) was also used to compare the average MOEd values and the average BAI values between mixed-species and pure stands. More specifically, the U-test is a non-parametric test and requires no assumptions.

### 3. Results

Table 2 shows the main structural and dendrometric characteristics of the studied stands, while in Table 3, the age, the wood density, the acoustic velocity and the MOEd for the sampled trees are reported. Forest structure did not differ markedly among the studied stands. Analysis of variance (ANOVA) showed no significant differences among plots in stand density ( $F_{3/6} = 1.020$ ;  $p = 0.447$ ), tree DBH ( $F_{3/6} = 0.329$ ;  $p = 0.805$ ), basal area ( $F_{3/6} = 2.104$ ;  $p = 0.201$ ) and stand volume ( $F_{3/6} = 2.208$ ;  $p = 0.188$ ). The number of trees per hectare varied from 743 in the pure European beech plots

to 873 in the mixed-species plots. The tree volume ranged between 773 m<sup>3</sup> ha<sup>-1</sup> in the pure European beech plots and 876 m<sup>3</sup> ha<sup>-1</sup> in the mixed-species plots.

**Table 2.** Structural traits obtained for the investigated triplets. Mean values and the related standard deviation (in bracket) are reported.

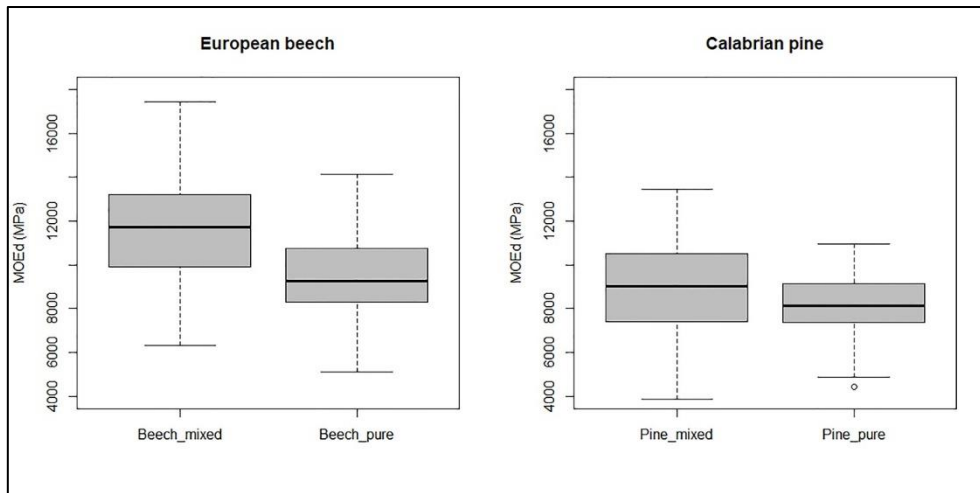
	Stand density (N. trees ha <sup>-1</sup> )	DBH (cm)	Tree height (m)	Basal area (m <sup>2</sup> h <sup>-1</sup> )	Volume (m <sup>3</sup> ha <sup>-1</sup> )
Beech pure	743 (155.7)	33.2 (2.8)	24.2 (2.2)	64.3 (4.6)	772.7 (41.5)
Pine pure	754 (96.3)	35.6 (4.4)	23.1 (0.8)	75.1 (10.4)	857.6 (160.9)
MBP-B	470 (75.9)	28.3 (2.3)	18.8 (1.3)	29.6 (6.3)	277.0 (31.1)
MBP-P	403 (74.1)	40.3 (9.6)	23.6 (5.1)	51.4 (14.1)	599.1 (90.7)

**Table 3.** Tree age, wood density, acoustic velocity, and MOEd values obtained for the two studied species in the pure and mixed-species stands (SD: standard deviation; MOEd: dynamic modulus of elasticity).

Stands	Tree Age (Years)		Wood Density (kg m <sup>-3</sup> )		Wave Velocity (m s <sup>-1</sup> )		MOEd (MPa)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Beech pure	69	41	658	28.4	3841.7	382.4	9523.2	1738.1
Pine pure	97	38	562	27.6	3823.4	427.5	8056.6	1358.2
MBP-B	127	33	653	30.1	4253.0	349.3	11583.0	2212.6
MBP-P	103	21	555	25.2	4066.4	370.6	8999.8	2132.6

Tree age differed between the pure European beech plots (on average 69 years) and the European beech trees sampled in the mixed-species plots (on average 127 years) (Table 3). By contrast, Calabrian pines occurring in the pure and mixed-species plots revealed no significant differences in tree age (on average 100 years).

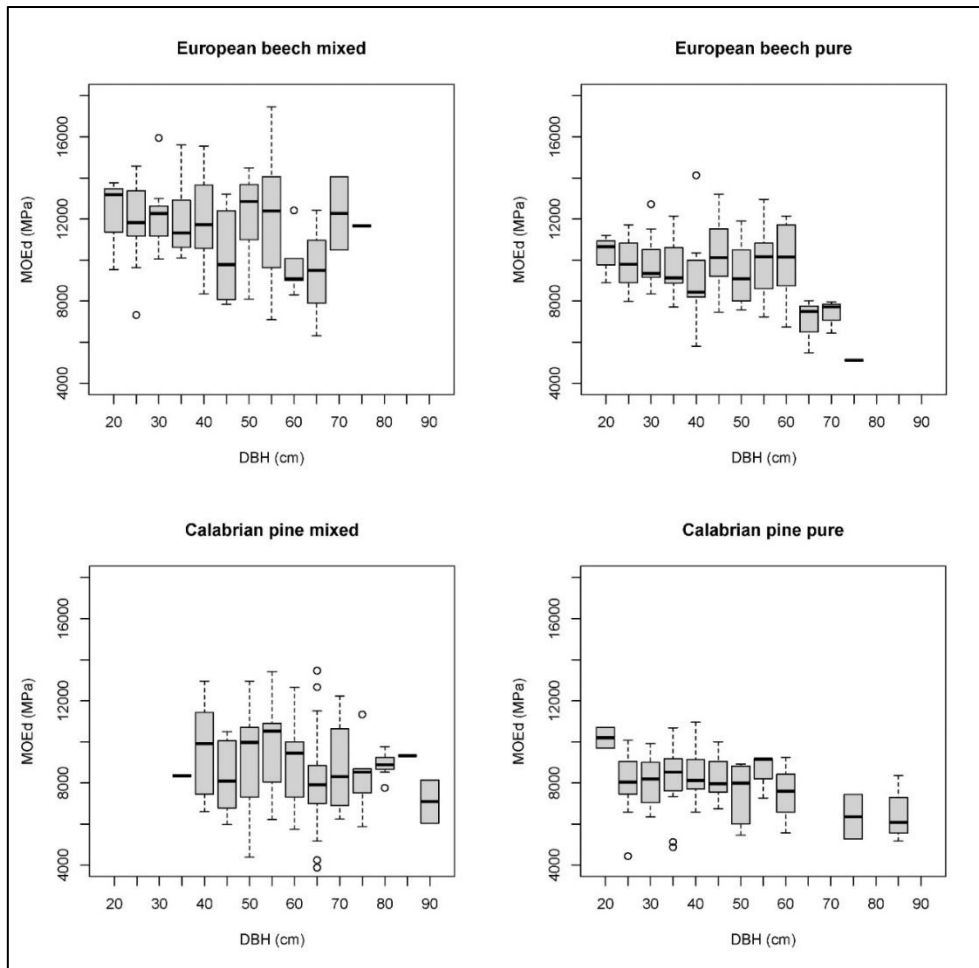
For both tree species, MOEd values were significantly higher in MBP than in BP and PP, as confirmed by the Mann-Whitney test applied for independent-samples (Figure 1). MOEd was 21.6% and 10.7% higher in MBP than in BP and PP, respectively. Further, considering the different diameter classes investigated, MOEd values were always higher in MBP than in BP and PP.



**Figure 1.** MOEd values in pure and mixed-species stands for European beech (Mann-Whitney Test,  $Z=-6.491$ ,  $p<0.001$ ) and Calabrian Pine (Mann-Whitney Test,  $Z=-3.134$ ,  $p<0.010$ ).

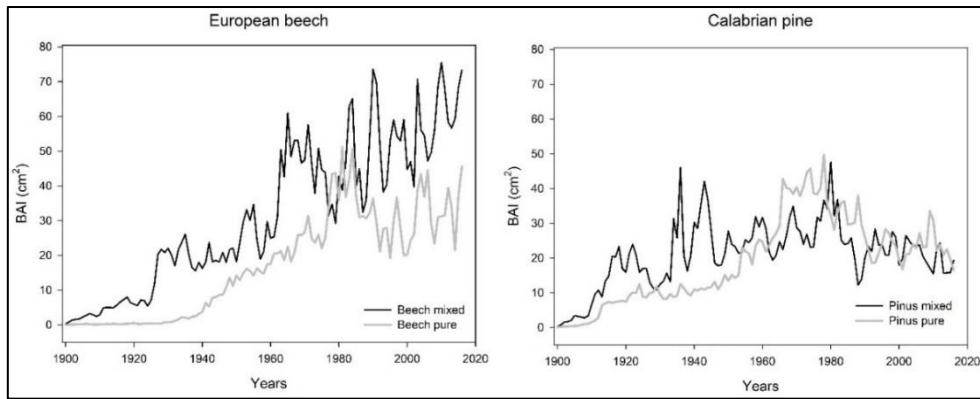
Analysis of variance (ANOVA) showed a significant effect of the diameter classes on MOEd for BP and PP. As the diameter classes are not independent, the Kruskal–Wallis test was also used (Zar, 1999), which confirmed the significant effect of the diameter classes on MOEd. MOEd decreased as tree DBH increased, with significant differences observed between the smallest and the largest diameter classes. On the contrary, no significant differences were observed in MBP (Figure 2). The mixture of species had the effect of aligning MOEd values, both for European beech and Calabrian pine, making wood quality more uniform for each diameter class. In contrast, in the pure stands, MOEd values were significantly lower than in MBP, also varying significantly as tree DBH increased.





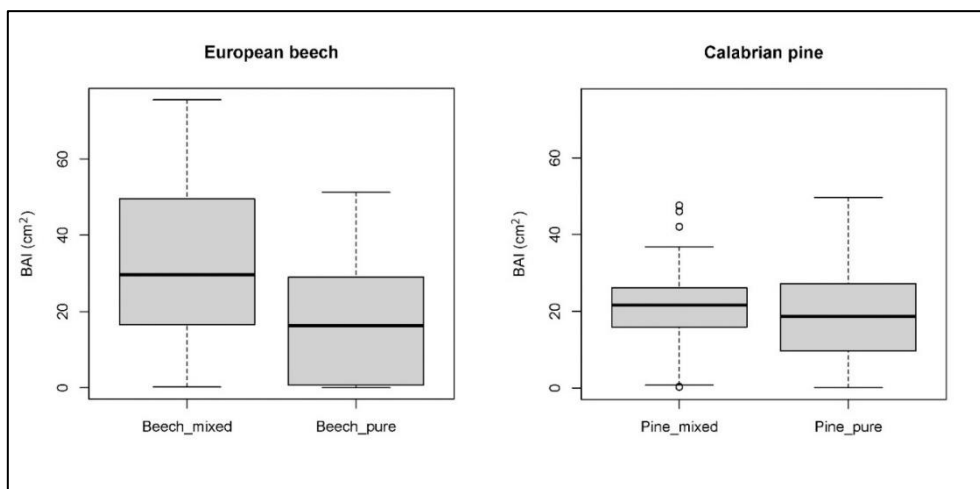
**Figure 2.** Dynamic modulus of elasticity (MOEd) in relation to the diameter classes for European beech and Calabrian pine growing in pure and mixed-species stands. European beech in the mixed-species stands:  $F_{12;18} = 1.255$ ,  $p < 0.322$ ; for European beech in the pure stands:  $F_{12;18} = 2.461$ ,  $p < 0.050$ ; Calabrian pine in the mixed-species stands:  $F_{12;18} = 0.774$ ,  $p < 0.669$ ; Calabrian pine in the pure stands:  $F_{11;19} = 2.621$ ,  $p < 0.050$ .

Figure 3 shows the BAI values obtained for European beech and Calabrian pine. In general, BAI increased over time (at least up to a determined year) in both species. Overall, trees revealed higher BAI in MBP than in BP and PP. However, until 1980, BAI values of European beech growing in mixture were always higher than in BP. Later, a similar trend was observed, until 1990. In the last period (1990-2016), BAI values were again higher in MBP. In the period 1900-2016, BAI always increased in MBP, while it gradually decreased in BP, from 1990. For Calabrian pine, BAI values were higher in MBP than in PP, considering the period 1900-1960. Later, for about 20 years (1960-1980), an opposite trend was observed, with higher BAI in PP. Furthermore, for 1980-2016, a consistent decrease of BAI values was observed for Calabrian pine both in MBP and PP.



**Figure 3.** BAI values for European beech and Calabria pine growing in pure and mixed-species stands. Values were considered starting from 1900.

Figure 4 reports both the variability and the average of BAI values for European beech and Calabrian pine growing in mixed-species and pure stands. For European beech, the BAI variability was higher in MBP, while for Calabrian pine in PP. European beech growing in mixture had a significantly higher BAI values than in BP (+65%, 30.6 vs. 18.5 cm<sup>2</sup>, on average,  $p$ -value < 0.001). Yet, Calabrian pine growing in mixture revealed higher BAI values than in PP, although not significantly (+11%, 21.1 vs. 19.1 cm<sup>2</sup>, on average,  $p$ -value = 0.0563).



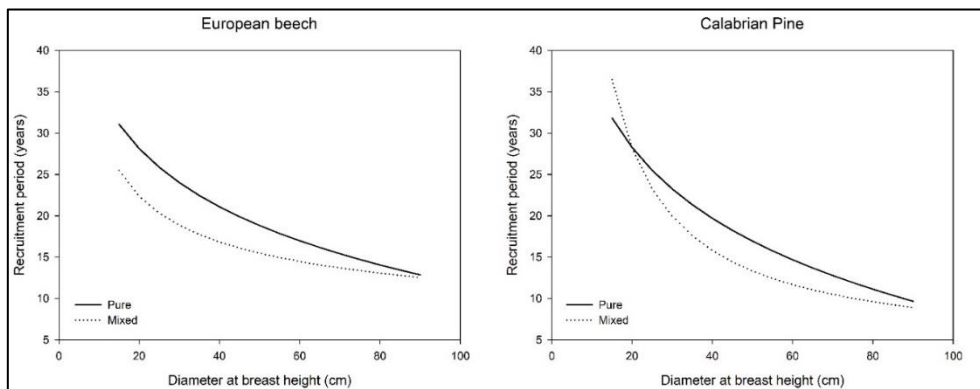
**Figure 4.** BAI values (mean values) in the pure and mixed-species stands for European beech (linear mixed-effect,  $p$  < 0.05,  $R^2$  = 0.437; Mann-Whitney Test,  $Z$ =-4.345,  $p$ <0.0001) and Calabrian pine (linear mixed-effect,  $p$  =0.271,  $R^2$  = 0.078; Mann-Whitney Test,  $Z$ =-1.928,  $p$ =0.0563).

In Table 4, results obtained through the application of the linear mixed model are shown; the site identifier was considered as random effect. The mixture significantly influenced European beech ( $p$ =0.015), but not Calabrian pine ( $p$ =0.601).

**Table 4.** Values achieved with the application of the linear mixed-effect model, considering the “Triplet” as random effect. The influences of the fixed effects (BA%, RP) on the response variables “basal area increment” (BAI) and “dynamic modulus of elasticity” (MOEd) were examined. Significant variables are reported in bold.

Model	Value	t-value	p-value	R <sup>2</sup>
European beech (BAI)				0.502
Intercept	17.623	7.720	<0.0001	
<b>Mix (BA)</b>	<b>0.358</b>	<b>4.047</b>	<b>0.0155</b>	
Calabrian pine (BAI)				0.015
Intercept	19.299	8.126	<0.0001	
Mix (BA)	0.028	0.567	0.6009	
European beech (MOEd)				0.278
Intercept	5114.401	4.191	0.0000	
<b>TP</b>	<b>210.252</b>	<b>4.119</b>	<b>0.0001</b>	
<b>Mix (BA)</b>	<b>76.434</b>	<b>3.353</b>	<b>0.0285</b>	
Calabrian pine (MOEd)				0.045
Intercept	6487.034	6.291	<0.0001	
TP	83.52	1.833	0.0684	
Mix (BA)	23.23	2.079	0.1061	

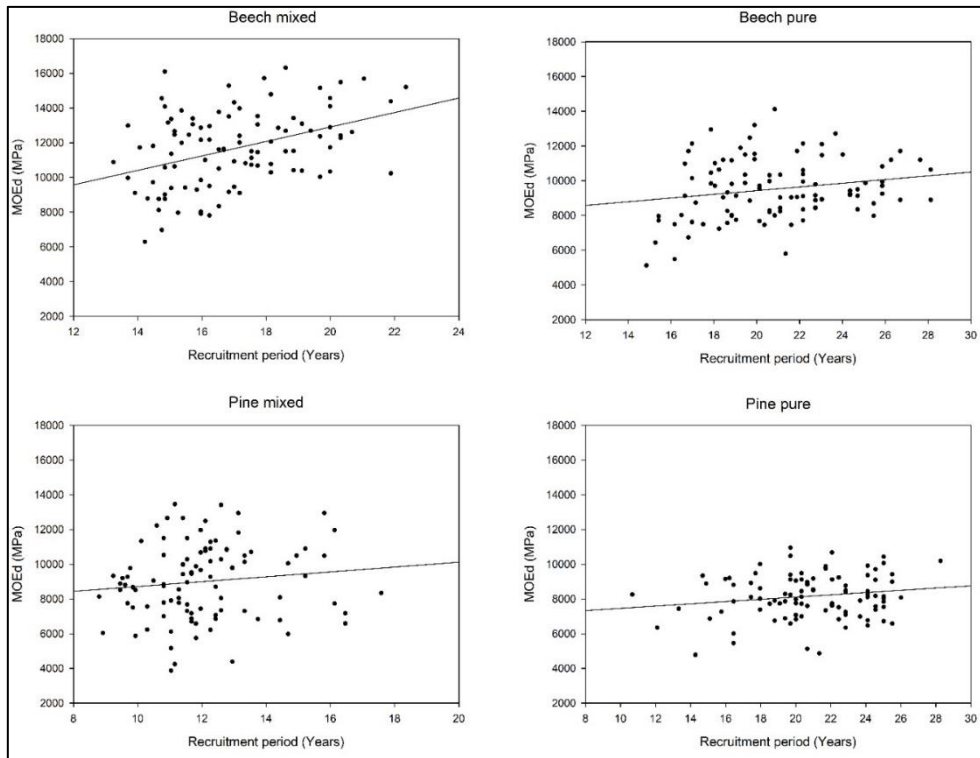
Figure 5 shows the values of the recruitment period (RP) for European beech and Calabrian pine, which invariably decreased as DBH increased. For European beech, RP was lower in MBP than in BP, though with lessening differences as DBH increased. Calabrian pine growing in PP had, for the first diameter classes, a slightly lower RP than in MBP, at least for the first diameter classes. Then, the trend was opposite and the differences tended to increase, though not for DBH of about 90 cm.



**Figure 5.** Recruitment period obtained for European beech and Calabrian pine growing in the pure and mixed-species stands. It indicates the number of years needed to pass from a diameter class  $x_i$  to the largest class  $x_i + 5$ cm.

Finally, in Figure 6, variations of MOEd as RP changes are shown. In each stand, MOEd tended to rise as RP increased, even if it revealed higher values in MBP than in BP and PP. In addition, the relationship between MOEd and RP was stronger in MBP, for both species. However, the analyses of the linear mixed-effects model underlined that only for European beech, RP ( $p < 0.0001$ ) and the

mixing effect ( $p=0.0285$ ) had a significant role, explaining the largest proportion of MOEd variation (Table 3). On the contrary, for Calabrian pine, RP ( $p=0.0684$ ) and the mixing effect ( $p=0.1061$ ) had marginal effects on MOEd.



**Figure 6.** Dynamic modulus of elasticity (MOEd) in relation to the recruitment period for European beech and Calabrian pine growing in pure and mixed-species stands.

#### 4. Discussion

Results demonstrated how the mixture effect influenced both wood quality and tree ring widths. In both the pure and mixed-species stands, MOEd values were above the minimum quality threshold ( $MOEd > 9000$  MPa) (Detters, et al., 2011). However, in the mixed-species plots, MOEd values were always higher than in the corresponding pure plots. This difference was more evident for European beech (11583 vs. 9523) than for Calabrian pine (8999 vs. 8056). Tree age differed between European beech trees sampled in the pure and mixed species plots, which might have played a role in determining differences in MOEd values. In the case of Calabrian pine, the differences in MOEd values are less evident, though significant.

As a matter of fact, tree age did not differ between trees sampled in the pure and mixed-species plots.

Eventually, effects on MOEd exerted by the other parameters related to the stand structure (stand density, basal area, stand volume) could be excluded, since the parameters did not differ significantly between the pure and mixed-species stands.

Several studies showed that, considering other variables being equal (stand density, stand volume, etc.), the mixture effect could have a role in improving the resistance and resilience of trees in comparison with the corresponding monocultures (Zhang *et al.*, 2012, Kanowski *et al.*, 2005, Petit and Montagnini, 2006, Richards *et al.*, 2010). Yet, the mixed-species stands could also be more productive than the corresponding monocultures (Forrester, 2014).

Therefore, even with some limitations, a mixture of European beech and Calabrian pine might have a positive effect on MOEd, not only at the stand level, but also considering the different diameter classes. In fact, in the mixed stands, the MOEd values were similar for all the diameter classes, in both species. On the contrary, in the pure stands, we observed a decrease in wood quality as the tree DBH increased. A combination of a light demanding tree species with one more shade tolerant was probably the foundation of these results. In other studies, mixed-species stands were found to show higher light interception and light-use efficiency in comparison with monocultures (Pretzsch and Schütze, 2015, Binkley *et al.*, 1992, Kelty, 1992, Forrester *et al.*, 2012).

Promoting the coexistence of these two species in the present environmental conditions might improve the quality of wood materials, regardless of the size of trees from which the assortments are obtained.

The MOEd values, strongly related to wood density and acoustic velocity, indicated an overall higher mechanical stability attained in the mixed-species stands. In fact, wood density is correlated with timber strength (Saranpää, 2003), hardness and abrasiveness (Bacher and Krosek, 2014).

Therefore, mixing these species might provide higher mechanical resistance to natural disturbances, such as windstorms, and higher carbon sequestration potential in these Mediterranean mountain forest ecosystems. It must be pointed out that Pretzsch and Rais (2016) observed that the wood strength and stiffness could be lower in complex forests than in homogeneous monocultures, where tree size and

shape development progress more continuously. Yet, Torquato et al. (2014), in black spruce forests in Canada, detected lower strength and stiffness properties in complex stands.

Growing in mixtures induced an increase in tree biomass production, particularly for European beech, while differences between the pure and mixed-species stands were not significant for Calabrian pine.

In European beech, although environmental conditions did not differ between stands, BAI was significantly higher in mixture than in monoculture. However, differences between the pure and mixed-species stands in tree age might also have affected BAI trends. The identification of growth trends and attribution of their drivers are not easy tasks, and require long-term and spatially-representative experiments to control the effect of tree size and age, avoiding sampling biases at the various scales. Indeed, heterogeneous crown structures and the tree size of mixed-species stands might facilitate the penetration of light into the lower canopy layers (Pretzsch and Schütze, 2015).

In the studied stands, European beech could take advantage of growing underneath the relatively transparent canopy of Calabrian pine. On the other hand, European beech in pure and dense stands develops homogeneous canopy cover, having high shade tolerance and large canopy expansion. Indeed, European beech growing in monocultures showed low self-tolerance (Metz et al., 2013, Pretzsch and Biber, 2005), resulting in severe intraspecific competition due to high lateral canopy expansion (Pretzsch, 2006). Moreover, other studies reported beneficial effects on European beech productivity from growing in mixture (Pretzsch et al., 2010, 2013). Condes et al. (2013) reported that the productivity of pine-beech admixtures was generally greater than in the corresponding pure stands. In light of this, admixture of European beech with Calabrian pine might, therefore, reduce competition or even increase facilitation processes in this Mediterranean mountain environment. Nevertheless, Conte et al. (2018) observed higher productivity in the pure than mixed-species stands of European beech and Scots pine, in Alpine environmental conditions. These discrepancies suggest caution in generalizing the positive effects on European beech productivity from growing admixed with pine species.

However, the complexity of the species interactions, which depends on stand development stage, stand density and site conditions (Forrester, 2014), suggests caution in generalizing these results, since other studies reported opposite patterns (Zeller *et al.*, 2017). Equal productivity at the stand level might not necessarily indicate a neutral behaviour of the two species co-occurring in the mixed-species stands. In fact, species-specific reactions, at individual or stand level, might counteract and cancel each other with respect to the stand level productivity (Pretzsch *et al.*, 2013). Behind overyielding or underyielding of mixed-species in comparison with nearby pure stands, as revealed in this study for Calabrian pine and European beech, there is always a modified supply and uptake, or different use-efficiency, of available resources (Richards *et al.*, 2010, Forrester, 2014, Binkley *et al.*, 2004). Zhang *et al.* (2012) reported that beneficial effects of admixing provided an overall 25% increase in productivity across forest types and a 12% increase at European scale in Scots pine—European beech mixtures (Pretzsch and Schütze, 2015). Nevertheless, the mechanisms that might promote complementarity effects, leading to increased productivity in pine-beech mixtures, are poorly understood, despite the frequent occurrence and economic importance of these forest types (Pretzsch and Schütze, 2015).

Values of BAI in Calabrian pine and European beech mixtures, of both species, were generally greater than in the corresponding pure stands, although significant only in the case of European beech. European beech, especially in the mixed-species stands, had a constantly increasing BAI in the investigated time-span, although alternating years of little stem radial growth and years of great stem radial growth.

On the contrary, Calabrian pine revealed a decrease in BAI values in the last 30–40 years.

Several studies reported that the inter-annual tree growth variability and its dependence on climatic conditions might be modulated by species composition (Pretzsch *et al.*, 2013, Lebourgeois *et al.*, 2013, Del Río *et al.*, 2014, 2017). A positive effect of species diversity on stand productivity, due to complementarity effects, might result in a greater size heterogeneity, with unknown consequences on the provision of goods and services in pure vs. mixed-species forests. A reduction in size asymmetry

and growth inequality for European beech in mixture with Scots pine was related to the complementary light ecology of the associated species (Pretzsch and Schütze, 2015). At the stand level, light absorption of admixed light demanding and shade tolerant species might benefit from light-related interactions, including canopy structure, stand density, tree size, crown architecture, and allometric relationships (Ellenberg and Leuschner, 2010, Pretzsch, 2019). Nevertheless, in the present Mediterranean environment, although light-related interactions might contribute to the mixing effect on tree growth for Calabrian pine, water- and/or nutrient-related interactions might dominate in the mixing effect on tree growth for European beech (Forrester, 2018). Especially for European beech, we showed that the variability of BAI was higher in the mixed-species vs. the pure stands. Although this variability might have a minor role in determining the strength and stiffness of structural timber (Pretzsch and Rais 2019), it might still affect wood properties, such as the dimensional stability. Nevertheless, we may confirm that (i) wood quality was higher in the mixed-species than pure stands, (ii) wood quality was dependent on tree growth patterns and that (iii) the longer a tree took to pass from one diameter class to the next, the better was the wood quality. However, Genet et al. (2012) stated that the way in which tree ring widths and ring wood density are related to each other would depend on whether the tree is a conifer, ring-porous hardwood, or diffuse-porous hardwood species. We found a positive relationship between final growth time and MOEd, in both species. However, while for European beech MOEd was significantly dependent on tree growth (expressed as recruitment period), this relationship was not significant for Calabrian pine. In these relationships, MOEd was higher in the mixed-species than pure stands, for both species. Again, this might depend on species-specific growth patterns, as well as on technological wood features. However, it must be pointed out that wood quality of coniferous trees, in comparison with broadleaved species, might be strongly influenced by forest management practices. In fact, several studies on conifers (Vanninen et. al., 1996, Grammel, 1990, Brazier and Mobbs, 1993, Larocque and Marshall, 1995, Zhang et. al., 2006, Moore et. al., 2015), including Calabrian pine (Russo et. al., 2019), showed a reduction in wood quality with increasing spacing and thinning.



Admixture of Calabrian pine and European beech might improve adaptation to rainy winters and dry summers of the Mediterranean climate, increasing both tree growth and wood quality, especially for European beech. Several studies showed that mixed-species forests might be more productive and resistant to disturbances, including drought, than corresponding pure stands (Pretzsch et. al., 2013, Lebourgeois et. al., 2003), though contrasting evidence was also reported (Grossiord et. al., 2014, Conte et. al., 2018). In particular, European beech populations from marginal ecological conditions were found more resistant to drought than those from the core of the distribution range (Tognetti et. al., 1995, Bolte et. al., 2016, Coccozza et. al., 2016), and their admixture with co-occurring drought-tolerant conifers might serve as benchmark for selecting resilient tree species combinations. Additional insight into the effect of tree species mixture on wood quality is required to support the entire wood supply chain, from the integration of wood quality in forest inventories to silvicultural guidelines for decision support tools. In fact, although structure and function of mixed-species stands are relevant for their role as supporting services in Mediterranean mountain forests, such as biodiversity conservation and soil protection, the consequence of structural heterogeneity in admixture on wood quality requires greater consideration in the future.

## **5. Conclusions**

In the present study, the admixture of Calabrian pine and European beech increased stand productivity, particularly for European beech, and improved wood quality. Nevertheless, caution is still needed in drawing general conclusions on the mixture effect on wood quality and stand productivity, in marginal environmental conditions. Nevertheless, European beech and Calabrian pine co-occurring in forest stands of Southern Italy should be managed with the aim of improving the overall quality of wood, which could be promoted by mixing these species. Although any generalization could be misleading, the admixture of tree species in these harsh environments might better maintain forest stability, ensuring also woody products of better quality. These results, though related to marginal environmental conditions, could be significant to implement and support climate-smart measures for managing Mediterranean mountain forests.

## Chapter 4

### **Relationships between tree age, growth, yield and wood quality: a chronosequence in a chestnut coppice of Southern Italy.**

#### **1. Introduction**

Forests in southern Italy are an important socio-economical context in terms of forest production (Scarascia-Mugnozza *et al.*, 2000; Pastorella *et al.*, 2016) and they cover a significant area, especially in the mountainous and inner areas. Particularly, forests managed as coppices widely occur in the Mediterranean basin (NFI, 2005), usually characterized by a mixture of different broadleaves species, but also as monospecific stands.

Furthermore, in Calabria Region (southern Italy), coppices dominated by chestnut are widespread. For this species, the cutting cycles are usually of 12-18 years. The silvicultural system dominated by coppices is an ancient forest management option in which stands are clear-felled at regular intervals of approximately 15-30 years (Ford and Newbould, 1970; Rackham, 1980, La Marca *et al.*, 1998). The stand regeneration after cut is obtained through the re-sprouting of the stumps thinned, rather than from the establishment of new trees from seeds. In order to maintain the re-sprouting capacity across the years, frequent cutting interventions are needed. Moreover, the application of the coppice management requires usually relatively short rotations time-span (Spinelli *et al.*, 2017). Coppice management is extremely efficient, since it offers the benefits of simplified care, prompt regeneration and short waiting time (Moscatelli *et al.*, 2007). Coppice woodlands were widespread all over the European continent until recent times, when the industrialization transformed both the economy and the landscape of many regions (Coppini and Hermanin, 2007). In the post-war years, traditional coppice systems have suffered from the competition of oil and plastic products, which have resulted in a decreasing interest towards the active management of traditional coppice stands (Hédli *et al.*, 2010).

Woody materials deriving from coppices are likely used for bio-energetic purposes, but also for providing firewood and pulpwood (Leonardi *et al.*, 1996; Lancho and Gonzales 2005; Patricio *et al.*, 2005). However, coppices are also a main source of posts, tool handles and fencing materials (Buckley, 1992). Furthermore, these silvicultural systems are very important for the economic incomes in the rural communities and inner areas, representing a further production support to the conventional agricultural systems.

Recently, a renewed interest in coppicing has developed in many European countries (Rydberg, 2000) for two major reasons: (1) the increasing importance of renewable energy sources as a substitute for fossil fuels (BMU 2011, European Parliament 2009: directive 2009/28/EG) and (2) the preservation of coppice forests as an historical landscape element (Buckley, 1992; Lanuv, 2007; Scherzinger, 1996). These reasons may lead to a new interest in managing the abandoned coppices occurring in many areas of southern Europe, especially for chestnut forests in the Mediterranean context.

Chestnut coppices were used and promoted for a variety of reasons, including: (a) the re-sprouting ability of stumps practically unlimited; (b) the fast early growth trends; (c) the multiplicity of assortments that can be derived; (d) the versatility of the chestnut wood, lending itself to many different uses, often also valuable; (e) the possibility to modify the cutting cycles in relation to the market requirements, without compromising the coppice vitality (Manetti *et al.*, 2006).

Furthermore, the effects of thinning on yield, tree diameter distribution and height, but also on tree diameter increment have been widely studied for chestnut coppices (Kneifl *et al.*, 2015). However, although studies have been recently carried out on the effect of coppicing on forest productivity (Manetti *et al.*, 2016; Esteban *et al.*, 2018), researches based on chronosequences are not as well documented, even if they are very useful for evaluating the biological responses to the applied silviculture.

In detail, several researchers tried to obtain information about temporal trends using chronosequences (space for time substitution) (Aide *et al.*, 2000; Hedde *et al.*, 2008; Pawson *et al.*, 2009). Even though this approach has been criticized because chronosequences are subject to errors if sites differ in

respects other than their age (Yanai *et al.*, 2003), there is not another way to collect field data about forest ecosystem development in the short term.

In forest sciences, a chronosequence is a set of forested sites that share similar attributes but are of different ages (Johnson and Miyanishi 2007) and can be considered a time sequence (Salisbury 1952, Pickett 1989). The key assumptions of chronosequences are that each of the sites representing different developmental stages had the same initial conditions and has traced the same sequence of changes. However, when there are demonstrable linkages between stages (i.e. the successional trajectory is predictable), chronosequences provide a useful approach to study temporal changes with time frames of 1-100 years (Walker *et al.*, 2010).

In the last decades, the evaluation of wood quality has been preferentially based on non-destructive technologies (NDTs) (Russo *et al.*, 2019). More specifically, stress wave-based non-destructive acoustic techniques resulted in very useful methods for predicting the mechanical properties of woody materials (Guntekin *et al.*, 2013). Nowadays, the acoustic sensing technology allows the estimation of wood quality and intrinsic woody properties for standing trees, stems and logs. Among the parameters measurable by acoustic methods, the most important are the modulus of elasticity of wood (MOE) and the dynamic modulus of elasticity (MOEd), being related to wood anatomy and tree physiology. These parameters are fundamental for the evaluation of wood quality, providing information on the resistance to deflection and the stiffness of material (Teder *et al.*, 2011, Wessels *et al.*, 2011).

Here we focused on coppices dominated by chestnut, widespread in mountainous forest ecosystems of Southern Italy.

A growth and yield model, specific for chestnut coppices located in the “Aspromonte” National Park, was developed and implemented in order to verify if the quality of the woody materials obtainable at different ages of the coppice can vary if the cutting cycles are modified.

We then analysed the wood quality and productivity deriving from stands characterized by four different cutting cycles (15, 25, 30 and 50 years) using a chronosequence approach.

Our study was aimed to answer to the following questions: (1) Could the increase of the cutting cycles duration in chestnut coppices induce a higher wood quality production? (2) If a greater wood production is hypothesized, due to the increase of the cutting cycle time-span, is the wood quality altered?

## **2. Materials and Methods**

### *2.1 Study area*

The study area is located near the village of Santo Stefano d'Aspromonte (Reggio Calabria, southern Italy), in the context of the "Aspromonte" National Park, (570304.25 E; 4226245.48 N) at an altitude of about 900 m a.s.l.. The site morphology is gently sloping with a northern exposure. The occurring soils developed from igneous and metamorphic rocks and are classified as Umbrisols, Cambisols and Leptosols (FAO, 2014), with an udic soil regime moisture. The average annual rainfall is 1.605 mm, with the lowest monthly average precipitation occurring in July (29.2 mm) and the highest in January (245.4 mm). The mean annual temperature is 10.6°C, with the lowest values in January (2.4°C).

The studied forest stands were characterized by monospecific coppices dominated by chestnut, extending on 228 ha. The analysed stands, growing in the same environmental conditions, represented a chronosequence, since their age varied from 5 to 50 years.

### *2.2 Data collection and analysis*

Data collection interested 44 plots, positioned through a systematic sampling design, proportionally positioned in the different coppice stands in relation to their extent and age. The area of each plot was also determined in relation to the stand age and density, extending between 530 and 1200 m<sup>2</sup>.

In each plot, the following parameters were recorded: (1) the number of stumps, (2) number of shoots per stump, (3) the diameter at breast height (DBH) of all the shoots and (4) the total height of the 20% of the occurring shoots, homogeneously distributed in the different diameter classes.

Furthermore, in the coppices stands characterized by an age of 15, 25, 35 and 50 years, the dynamic modulus of elasticity (MOEd) was also measured, recording its value for each shoot occurring in 4 plots per stand, for a total of 16 plots.

In order to measure the acoustic velocity, the TreeSonic™ (Fakopp Enterprise, Agfalva, Hungary) was used inserting two sensor probes (a transmit probe and a receiver probe) into the sapwood, then introducing the acoustic energy into the tree through a hammer impact (for further details, see the previous chapters of this thesis, but also Vanninen *et al.*, 1996, Divos 2010, Russo *et al.*, 2019).

Three measurements were realized for each selected tree and the average of the three recordings was used as the final transit time. The acoustic velocity was then calculated considering the span between the two sensor probes and the time-of-flight (TOF) data using the following formula (Equation (1)):

$$CT = S/TOF \quad (1)$$

where CT = tree acoustic velocity (m/s), S = distance between the two probes (sensors) (m), TOF = time of flight (s).

Afterwards, the dynamic modulus of elasticity (MOEd) was calculated, according to the following equation (Equation (2)):

$$MOEd = WD_{ij} * CT^2 \quad (2)$$

where  $WD_{ij}$  = tree wood density ( $\text{kg m}^{-3}$ ), shared by diameter class (i) and age (j); and CT = velocity ( $\text{m s}^{-1}$ ).

The wood density was determined on a subsample of trees, considering trees where the TOF was also measured. In detail, woody cores were extracted, bark to bark, at breast height (1.30 m) with a Pressler borer from trees, referring to each of the diameter classes occurring in the different ages. The fresh weight and volume of the tree cores were measured in the laboratory. Samples were then weighed to the nearest 0.01 gram with an electronic scale. Oven drying of all samples was done at 105 °C to constant weight. Density ( $\text{kg m}^{-3}$ ) was calculated by dividing the dry weight with the fresh sample volume.

Furthermore, the structural traits of each selected stand were then detailed. In detail, a growth and yield table, with a projection up to 50 years, was implemented. The table was modelled basing on the average number of shoots occurring per hectare, but also considering the relationship diameters-heights and the average values of the basal area.

Moreover, in order to estimate the number of shoots per hectare ( $NS$ ) in relation to the tree age ( $Age$ ), the following hyperbole function was used:

$$NS = \beta_0 \cdot AGE^{\beta_1}$$

The equation coefficients were determined analytically after a logarithmic linearization:

$$\ln(NS) = \beta_0 + \beta_1 \cdot \ln(AGE) \quad (3)$$

where  $NS$  is the number of shoots per hectare and  $AGE$  represents the stand age (years).

The diameter-height-age model, according to the approach already used by Clutter et al. (1983), was estimated using the following Equation (4):

$$\ln(Ht) = \beta_2 + \beta_3 \cdot NS + \beta_4 \cdot \frac{1}{Age} + \beta_5 \cdot \frac{1}{dbh} + \beta_6 \cdot \frac{1}{dbh \cdot Age} \quad (4)$$

where:  $Ht$  = total shoot height (m);  $NS$  = number of shoots per hectare;  $dbh$  = diameter at breast height (cm);  $AGE$  = Stand age (years).

In order to estimate the basal area development, we used the average basal area ( $g$ ) as dependent variable, since the number of shoots ( $NS$ ) (density expression) is structurally included in the stand basal area ( $G$ ). Considering several combinations of variables realized through stepwise procedures, the best model resulted the following (Equation (5)):

$$\ln(g) = \beta_7 + \beta_8 \cdot \frac{1}{Age^2} + \beta_9 \cdot NS \quad (5)$$

where:  $g$  = average basal area ( $m^2$ );  $Age$  = Age (years);  $NS$  = number of shoots per hectare.

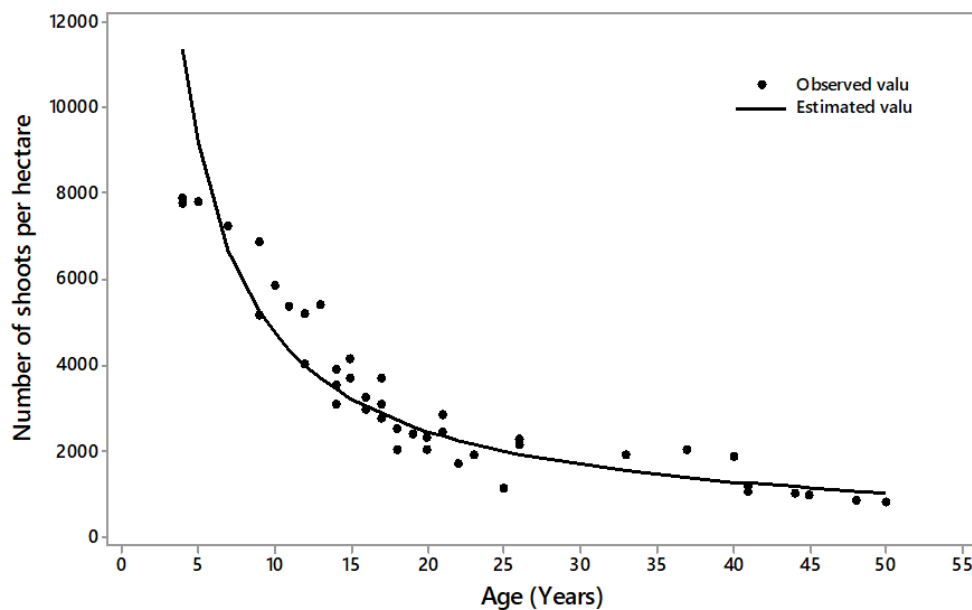
In the simulation of the growth and yield development, once identified the initial conditions of the stand ( $NS$ ,  $Age$ ,  $G$ ,  $H$ ), the stand volumes were estimated using the equations reported for chestnut coppices in the INFC 2005 (Tabacchi et al., 2011). Finally, the mean annual increment (MAI), the

current annual increment (CAI) and percentage of current annual increment (PCAI) were calculated basing on the estimates of tree volumes at the different ages. Finally, the basal area (G) per hectare was obtained multiplying the average basal area (g) estimated with the Equation (5) and the number of shoots occurring at each specific age.

### 3. Results and Discussion

The analyses here carried out allowed the implementation of a growth and yield model useful for simulating the temporal development of the main structural traits. These models, based on similar methodological approaches, were already applied by Marziliano *et al.* (2013 and 2019), even if in different silvicultural systems and forest types.

Figure 1 reports the occurrence of shoots (NS), both observed and estimated, in relation to the stand age.



**Figure 1.** Numbers of shoots per hectare, observed and estimated, in relation to the stand age.

The number of shoots decreases as tree age increases. More in detail, the amount of shoots is very high in the first years after coppicing, then significantly reducing due to the competition between shoots occurring on the same stumps. On average, from the occurrence of about 9.000 shoots per hectare estimated in the first years after coppicing, their number then significantly decrease, halving



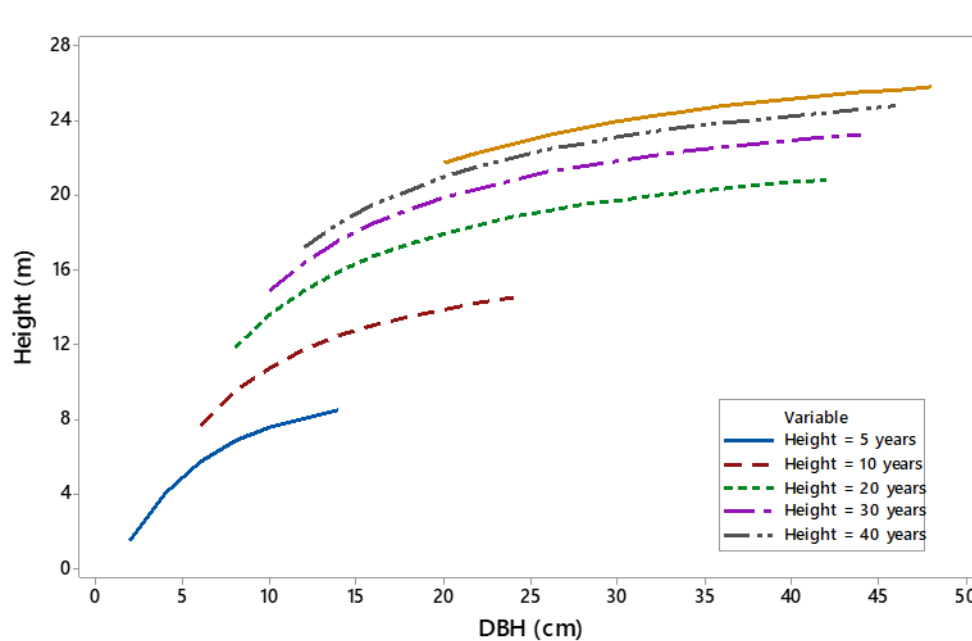
ten years after cutting. This trend is also confirmed in the following years, reaching less than 2000 shoots and 1000 shoots at 25 and 50 years after cutting, respectively.

Moreover, Table 1 shows the regression statistics, revealing all the significant parameters. The regression coefficients values and their standard errors expressed good levels of confidence.

**Table 1.** Estimation of each parameter used for the Equations 3, 4 and 5. The related statistics values for each equation are also reported. NS (number of shoots), HT (shoot height), g (average basal area).

Equations	Parameters	S.E. parameters	R <sup>2</sup>	RMSE	
$Ln(NS) = \beta_0 + \beta_1 \cdot \ln(AGE)$ (eq. 3)	$\beta_0$	10.6562	0.1579	0.8833	0.2217
	$\beta_1$	-0.9514	0.0534		
$\ln(Ht) = \beta_2 + \beta_3 \cdot NS + \beta_4 \cdot \frac{1}{Age} + \beta_5 \cdot \frac{1}{dbh} + \beta_6 \cdot \frac{1}{dbh \cdot Age}$ (eq. 4)	$\beta_2$	3.5479	0.0295	0.9601	0.1842
	$\beta_3$	0.0002	<0.00001		
	$\beta_4$	-22.7110	0.9744		
	$\beta_5$	-6.1284	0.3351		
	$\beta_6$	10.2808	0.5148		
	$\beta_7$	-2.2932	0.0930		
$\ln(g) = \beta_7 + \beta_8 \cdot \frac{1}{Age^2} + \beta_9 \cdot NS$ (eq. 5)	$\beta_8$	47.6108	2.4583	0.9833	0.1369
	$\beta_9$	-0.0007	<0.00001		

Furthermore, Figure 2 shows the tree height-diameter relationship (i.e. the hypsometric curve) at different ages.



**Figure 2.** Tree height-diameter relationship at different ages, estimated through the equation 4.

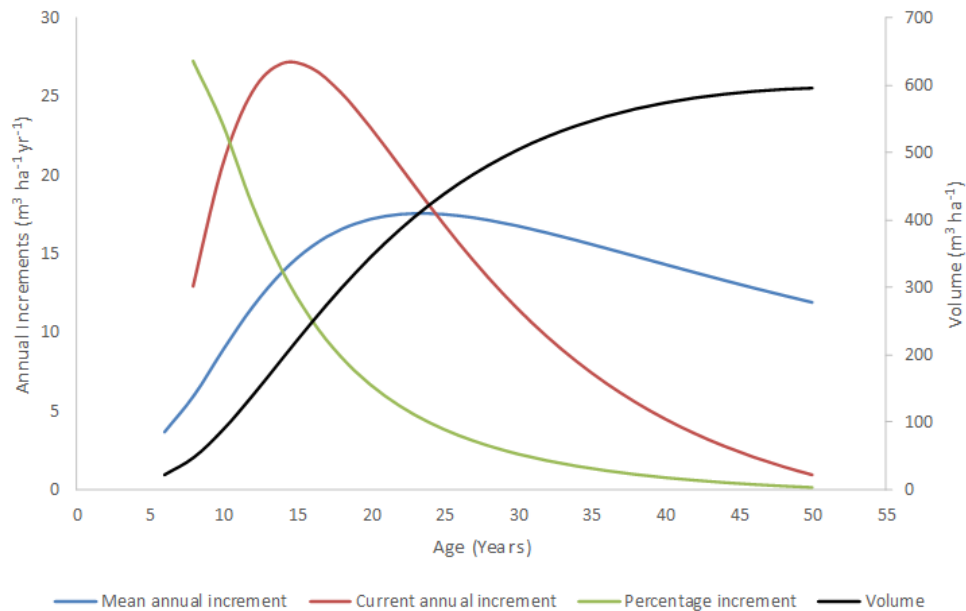
As expected, a different longitudinal growth of shoots was observed as tree ages vary: the hypsometric curve for young shoots (5 years old) appeared steeper than the other curves (e.g., from 20 to 50 years old). This result suggests that during the earlier stage after coppicing, the shoots are characterized by a considerable increase in height. At these stage, a relevant hypsometric differentiation occurs, probably due to the strong competition for light between individuals. When the coppice reaches an age higher than 10-15 years, the hypsometric curves became more flattened, thus indicating a high level of spatial competition between trees. At these ages, the competition is mainly affected by diametrical differentiation rather than hypsometric variation: trees grow more in diameter than in height.

Furthermore, Table 2 shows the growth and yield model obtained from the age of 5 years up to 50 years old.

**Table 2.** Main structural characteristics estimated for the investigated stands at different ages (BA: Basal Area; MAI: Mean Annual Increment; CAI: Current Annual Increment).

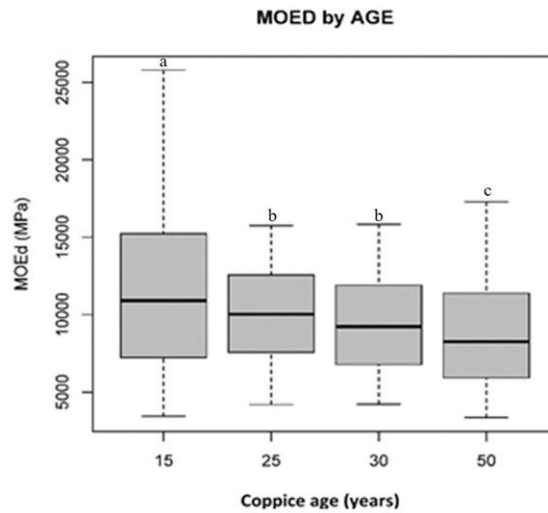
Ages (Years)	N <sup>r</sup> hoots (N <sup>r</sup> ha <sup>-1</sup> )	Diameters (cm)	Heights (m)	BA (m <sup>2</sup> ha <sup>-1</sup> )	Volumes (m <sup>3</sup> ha <sup>-1</sup> )	MAI (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	CAI (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )
6	7720	4.7	1.6	13.16	21.68	3.61	
8	5871	6.7	3.2	20.46	47.59	5.95	12.95
10	4748	8.6	5.1	27.79	88.92	8.89	20.67
12	3992	10.5	7.0	34.29	139.52	11.63	25.30
14	3448	12.1	8.8	39.72	193.76	13.84	27.12
16	3036	13.6	10.3	44.07	247.47	15.47	26.86
18	2715	14.9	11.7	47.46	298.10	16.56	25.31
20	2456	16.1	12.9	50.05	344.30	17.22	23.10
22	2243	17.2	13.9	51.97	385.56	17.53	20.63
24	2065	18.1	14.9	53.35	421.81	17.58	18.13
26	1913	19.0	15.7	54.30	453.29	17.43	15.74
28	1783	19.8	16.5	54.90	480.37	17.16	13.54
30	1670	20.5	17.2	55.22	503.45	16.78	11.54
32	1570	21.2	17.8	55.32	522.98	16.34	9.76
34	1482	21.8	18.3	55.24	539.35	15.86	8.18
36	1404	22.3	18.8	55.03	552.94	15.36	6.80
38	1333	22.9	19.3	54.70	564.11	14.84	5.58
40	1270	23.3	19.7	54.29	573.15	14.33	4.52
42	1212	23.8	20.1	53.81	580.34	13.82	3.60
44	1160	24.2	20.5	53.28	585.92	13.32	2.79
46	1112	24.6	20.8	52.71	590.10	12.83	2.09
48	1068	24.9	21.1	52.11	593.07	12.36	1.48
50	1027	25.3	21.4	51.49	594.97	11.90	0.95

Furthermore, in Figure 3 the values of the mean volumes, the current annual increments and the increments in percent are reported and related to the different tree ages. The culmination of the mean annual increment occurs at 28 years, while the current annual increment culminates about 10 years earlier.



**Figure 3.** Trends of the mean volumes, of the current annual increments and of the increment in percentages, in relation to the different tree ages.

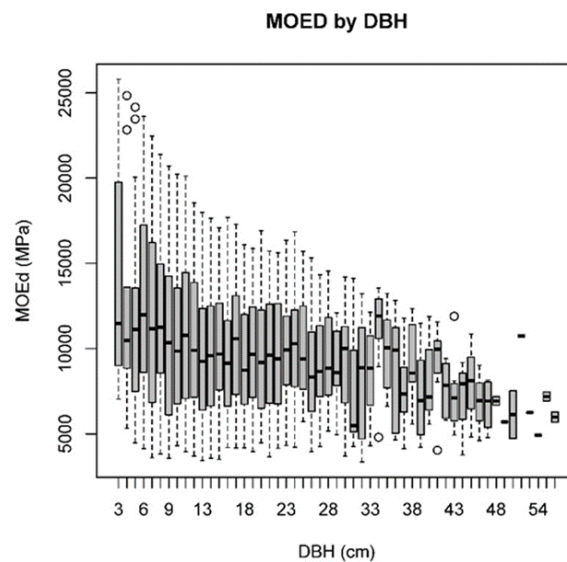
The results obtained for the MOEd along the chronosequences gave very interesting silvicultural indications. We observed how, for the youngest trees (15 years old), the MOEd values were significantly higher than in the oldest ones (e.g., 50 years old trees). On the contrary, for trees ranging between 25 and 50 years, the values of the MOEd were almost constant, then significantly decreasing at the age of 50 years (Figure 4).



**Figure 4.** Variation of the MOED in relation to the different stand ages. Error bars indicate  $\pm$  SE. The line through the box is the median value. Letters (a, b and c) on the columns refer to the significant difference within the different ages.

The values of the MOED, even if revealed a negative trend as tree age increases, however suggested the occurrence of an overall wood quality across all the life cycle. In fact, the MOED never fall below 7200 MPa, the lower threshold for considering the chestnut wood of the good quality (Detter *et al.*, 2008).

Furthermore, the MOED values obtained for all the sampled trees among the different diameter classes are reported.



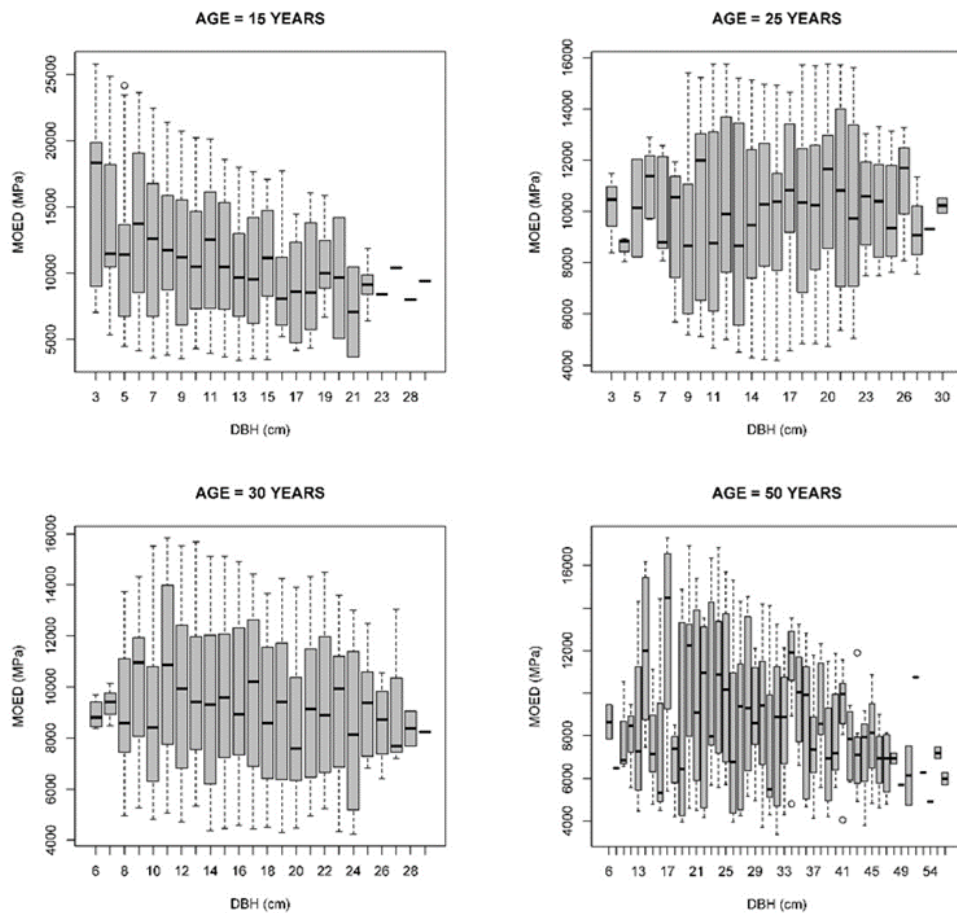
**Figure 5.** MOED values at different tree diameters. Error bars indicate  $\pm$  SE. The line through the box is the median value.

The MOEd values tends to decrease as the tree diameters increase; more specifically, with diameters over 38 cm, we observed significant lower values when compared to all the other trees with smaller diameters. These results demonstrated how the tree age and growth trends directly influenced the wood quality.

The strong diametric increments probably induced the production of a less-stiff mature wood, resulting in a significant loss of wood quality. However, there is very little information on the quality of wood deriving from chestnut stands managed as coppices (Fioravanti, 1999). Information on the influence of silvicultural practices on the technological quality of coppiced trees is also particularly sparse. However, for other hardwoods, e.g. *Eucalyptus*, Sharma et al. (2005) investigated non-coppiced and coppiced wood of *E. tereticornis*, concluding that the quality of wood deriving from both the management options is comparable. As a consequence, the derived wood can be used for the same purposes, however considering the different dimensions of the assortments. Most studies conducted on ring-porous hardwoods have shown frequent positive correlations between ring width and wood density (Zhang et al. 1993; Zobel and Van Bujten 1989; Guilley et al. 1999).

Generally, in chestnut stands where the management is not applied for decades, high tree densities and strong competition between trees are common, but also lower diametrical increments (Roces-Díaz et al., 2018).

Figure 6 reports the MOEd variability at different diameter classes and in relation to the stand age.



**Figure 6.** Variation of the MOEd as diameters increase for the stands at 15, 25, 30 and 50 years old. Error bars indicate  $\pm$  SE. The line through the box represents the median value.

In detail, at 15 and 50 years, the MOEd decrease significantly as the tree DBH increases. Generally, lower values of MOEd always occurred in trees characterized by larger diameters, while higher values occurred in the first years of growing up. Furthermore, at 25 years old, the maximum tree productivity was observed. Particularly, at the age of 15 years-old and for trees characterized by diameters higher than 15 cm, the velocity of the tree growth induced a significant decrease of the MOEd values. Moreover, the MOEd values decreased as the tree diameters increase: this trend is uniform at 15-years, with significant differences observed between the smallest and largest trees.

Similar results were obtained in the stand of 50-years, but without a uniform trend: the MOEd values decreased with significant differences in trees for diameters lower than 20 cm and higher than 35 cm. According to Romagnoli *et al.* (2014), a threshold was observed near the diameter 35 cm, where a decrease in the mechanical performance occurred if compared with trees of 25 to 30 years.

Our results demonstrated that in the stand of 25 years-old and, to a lesser extent, in the coppice of 30 years-old, the MOEd values aligned, making the wood quality almost uniform.

Furthermore, in this study has been shown that tree age plays an important role in ring-porous species such as chestnut, affecting the relationship between ring width and density, as already demonstrated by Adamopoulos *et al.*, (2010).

We can then underline that, even if chestnut coppices are harvested at a specific and fixed age, the tree diameters are often site-specific. Therefore, implications on the overall wood quality (i.e., density and mechanical properties) can be also significant. For this reason, the coppicing should be discussed and revised in order to maximize the wood quality, taking into account not only the tree age, but also the diameters at harvest (Genet *et al.*, 2013).

#### **4. Conclusions**

In chestnut coppices, the main aim of the silvicultural practices applied is linked to the improvement of the overall wood quality, obtaining materials in a reasonable time-span.

This study proved that the silvicultural practices applied to coppice stands can affect the wood quality of chestnut: higher tree age often mean less wood quality. We verified, through innovative and non-destructive methods, that different tree ages can affect the wood quality, demonstrating that the differences occurring across the years can be successfully identified by the MOEd.

The obtained results can give a valid decision support system for stakeholders, since they often require quick and effective predictors for assessing the wood quality. Therefore, postponing the cutting cycles with regards to the ongoing cycles prescribed by the law, would have benefits both in terms of productivity, wood quality and landscape conservation.

## Chapter 5

### 5.1 Conclusions and Future Perspectives

This study provided interesting information useful to highlight the importance of the non-destructive methods for the evaluation of the wood quality. Our results demonstrated that, for Calabrian pine stands, the effect of silvicultural practices on the properties of wood can be successfully identified by the stress wave techniques that give as output the MOEd values. Furthermore, here it was proved that MOEd values may be predicted by easily recordable variables in the field. More specifically, for Calabrian pine, different intensities of thinning can affect the wood quality and, therefore, the final obtainable woody products. Furthermore, it was found that mixed-species stands of Beech and Calabrian pine in Southern Italy might represent a positive example for improving the overall wood quality of both the species, at least in Mediterranean mountainous forest ecosystems. It could be interesting deeply verify if, in these harsh environments, the mixture could also increase the overall forest stand stability and the efficiency in the resources use.

Moreover, the dendrometric approaches, combined with the use of the acoustic measurements (wood quality), allowed also to verify if significant variations on the length of the cutting cycle could alter and / or modify the wood quality in chestnut forests, with significant consequences on the final market value. This approach was then implemented, also evaluating the final quality of the retractable assortments, in relation to the different size classes and the cutting cycle.

Finally, this study implemented a predictive model useful for determine the wood quality through dat sampling easily recordable in the field. In detail, it permitted to verify if the tree age classes and assortments could give the best possible quality to the final product.

Further investigation could be planned in the future, focusing also on other tree species, typical of the mountainous Mediterranean forest ecosystems. These approaches might permit the implementatation of more accurate models, useful to further improve the woody supply chain and the related economical incomes in the inner areas.



## 5.2 Factors affecting the research performance

This research, however, is subject to several limitations. The first is the experimental design, while, the second limitation concerns the instruments utilized and the characteristics of the tree sampled.

The research was conducted in a geographic area with omogenous characteristics (slope, esposition, altitudine and climate). The geographic location plays a role in the properties of wood. For example, Palmer et al. provide a map of the variation in density (related to stiffness) of radiata pine in New Zealand, where large differences can be observed with geographic location (Palmer at *al.*, 2013). This variation has been suggested to be related to factors such as mean air temperature, rainfall, and soil chemistry such as total soil phosphorus (Watt et *al.*, 2008).

This study was focused on the measure of wood stiffness on different forest species, by using the speed of sound based on time-of-flight (TOF) method. The speed of sound in wood is related to a number of factors including mechanical properties, moisture content, temperature, and variations in grain angle. It has been reported that TOF methods sometimes overestimate the stiffness when compared to bending and resonance techniques. Few studies have used the TOF technique to measure the stiffness on logs (Legg and Bradley, 2016). However, this technique is rarely used for measuring the stiffness of logs since it is considered to be less accurate than the acoustic resonance techniques, leading to an overestimation of stiffness (Legg and Bradley, 2016). TOF acoustic velocity tools have also been developed for measurements of the stiffness of seedlings and juvenile trees in breeding studies (Matheson et *al.*, 2008; Divos, 2010)

The longitudinal MOE and the density of a log, when dried, increases from pith outward toward the bark (Grabianowski et *al.*, 2006). However, this effect is offset to some degree by the higher moisture content at the core of the log than in the outerwood. The results in the longitudinal wave velocity increasing from pith to bark (Grabianowski et *al.*, 2006; Krauss and Kúdela, 2011), though not as much as might be expected from dry wood density alone (Andrews, 2000). The acoustic velocity is also reported to decrease with height up the tree stem (Chiu et *al.*, 2012; Wang et *al.*, 2013). However, some studies have reported that the longitudinal acoustic velocity in radiata pine initially increased

to a maximum a few meters up the tree and then decreased with height (Andrews, 2000; Waghorn et al., 2007).

Reaction wood within the tree stem can also cause variations in acoustic velocity measurements (Cown and McConchie, 1980). Moreover, variations in the occurrence of knots/branches and spiral grain, can also reduce the measured velocity in the sampled trees (Jones and Emms, 2010; Searles, 2012).

Gerhards (1982) showed that the wave front of an acoustic signal tends to follow the grain and flow around knots, potentially resulting in measurements of reduced acoustic velocity. The acoustic velocity has also been reported to have a negative correlation with diameter at breast height (DBH), when tree age is the same (Lasserre et al., 2004). Other studies showed that this correlation of DBH and stiffness, and hence velocity, can be inconsistent due to variations in growth rates between different locations (Legg and Bradley, 2016). Wind exposure appears to have an effect on the stiffness of trees (Grabianowski et al., 2004). Also, the acoustic velocity increases with tree age. Studies have shown that there is a good correlation of stiffness measurements made using the TOF technique and other methods, such as bending and resonance (Mahon et al., 2009). TOF velocity measurements, however, are considered less accurate than those obtained using the acoustic resonance technique (Chiu et al., 2012). TOF techniques produce stiffness measurements that are overestimated compared to those obtained using acoustic resonance and bending techniques. Furthermore, the fact that the signal used in the TOF technique propagated to a relatively short distance (about a meter) compared to that used for resonance (many reflections from the ends of log), has been attributed to TOF measurements being more sensitive to errors resulting from local inhomogeneousness in the wood properties and measurement errors (Legg and Bradley, 2016). Variations in results have also been reported with individual hammer hits. In this study, this limit is compensated for by averaging over multiple measurements, as reported by Wang, 2013.

Several studies provided data indicating that TOF velocity measurements are more closely correlated with outerwood MOE than that of the corewood. Grabianowski et al. (2006) made TOF

measurements of lumber at different positions in logs. They found that TOF acoustic velocity measurements had a higher correlation to resonance velocities in the outerwood than in the corewood. Studies have found that the TOF method provides measured values of MOE which are higher than those obtained using resonance for standing trees and logs (Grabianowski *et al.*, 2006; Gonçalves *et al.*, 2011; Chiu *et al.*, 2012). The overestimation of TOF, when compared to the resonance velocity, has also been reported to occur even if the TOF velocity measurements were made from pith to pith at each end of the measured log (Dickson *et al.*, 2004). Yin *et al.* (2010) and Chiu *et al.* (2012) reported that dynamic MOE values obtained using both TOF and resonance were higher than static MOE calculated using bending tests, though the resonance value was closer to the static values.

Several papers have stated that the presence of bark on a tree stem can cause the measured resonance velocity on a log to be lower than it would be without bark and thereby cause an underestimation of the MOE of a log. As example, Lasserre *et al.* (2007) showed that the values of MOE obtained using resonance measurements with and without bark were, respectively, on average 38% and 33% lower than MOE values obtained using TOF with the bark on the tree stem.

Legg and Bradley (2016) have reported that MOE values obtained using TOF techniques have higher correlation with outerwood MOE than that closer to the. However, other studies have reported that the overestimation also occurs in thin timber samples (Legg and Bradley, 2016).

Furthermore, silvicultural practices or environmental conditions could affect the wood stiffness (Lasserre *et al.*, 2004; Watson, 2013).

Several study mention the use of acoustic methods for stiffness measurements of tree stems; however, they do not focus in any great detail on this topic and may be in need of updating. Literature reviews have been published on the stiffness of wood (e.g. Bailleres *et al.*, 2009), but they have not specifically focused on the use of acoustics. Wang (2013) reviewed studies relating to differences in measured stiffness that were obtained for acoustic velocity measurements made on standing trees and logs. However, no papers and books are available to have a full/extensive review specifically on the use of acoustics for measuring the stiffness of wood: so that, many doubts still remain.

## **Acknowledgments**

I'm grateful to the "Aspromonte" National Park for the economic support given and fundamental to realize this study. The research is also linked to the activities conducted within the COST (European Cooperation in Science and Technology) Action CLIMO (Climate-Smart Forestry in Mountain Regions - CA15226) financially supported by the EU Framework Programme for Research and Innovation HORIZON 2020.

Furthermore, I would like to express my sincere gratitude to my advisors Prof. Fabio Lombardi, Prof. Pasquale Marziliano and Prof. Giuseppe Zimbalatti for the continuous support given during this study period, for their patience and motivations. They continuously supported me during the research activities and the thesis writing.

A special thanks goes to my family and my wife.

Last but not least, I would like to thank Giorgio, my best friend.

## References

- Adamopoulos S, Chavenetidou M, Passialis C, Voulgaridis E “Effect of cambium age and ring width on density and fiber length of black locust and chestnut wood,” Wood Research 2010, 55, 25-36.
- Agnoletti M Bosco ceduo e paesaggio: processi generali e fattori locali. In: Ciancio O, Nocentini S (Eds) Il bosco ceduo in Italia, Firenze: Accademia Italiana di Scienze Forestali 2002, 21-62.
- Agnoletti M Man, forestry, and forest landscapes. Trends and perspectives in the evolution of forestry and woodland history research. Schweizerische Zeitschrift für Forstwesen 2006, 9, 384-392.
- Vos W (1996) Changing forest functions in new Europe: from alienation to involvement. In: Glück P, Weiss G (Eds) Forestry in the context of rural development: future research needs, EFI Proceedings 15, 127-139.
- Aide TM, Zimmerman JK, Pascarella JB, Rivera L, Marcano-Vega H Forest regeneration in a chronosequence of tropical abandoned pastures: Implications for restoration ecology. Restoration Ecology, 2000, 8, 328-338.
- Altieri V, De Franco S, Lombardi F, Marziliano PA, Menguzzato G, Porto P The role of silvicultural systems and forest types in preventing soil erosion processes in mountain forests: a methodological approach using cesium-137 measurements. J of Soils Sedimen 2018, 1-10.
- Amorini E, Manetti MC Le ‘fustaie da legno’ di castagno del Monte Amiata. Ann. Ist. Sper. Selv., Arezzo 1997, 28, 53-61.
- Ansen JK, Jorgensen BB, Stoltze P, “Variation of Quality and Predicted Economic Returns between European beech (*Fagus sylvatica* L.) Provenances”, Silvae Genetica 2003, 52, 185-197.
- Aratake S, Arima T Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs. II. Possibility of application for sugi square lumber with pith. Mokuzai Gakkaishi 1994, 40, 1003-1007.
- Augusto L, Ranger J, Binkley D, Rothe A Impact of several tree species of European temperate forests on soil fertility. Ann For Sci 2002, 59, 233-253.

- Avanzato D, Following Chestnut Footprints (*Castanea* spp.) – Cultivation and Culture, Folklore and History, Tradition and Uses, 2009, 9 of Scripta Horticulturae (International Society for Horticultural Science).
- Aviolo S Il castagno in Italia meridionale (1. parte). Cellulosa e Carta, 1987, 3, 12-23.
- Bacher M, Krosek S Bending and tension strength classes in European standards. Annals of Warsaw University of Life Sciences - SGGW. For Wood Tech 2014, 88.
- Bagnaresi U, Giannini R La selvicoltura delle faggete: sintesi dello stato dell'arte. In: "Ecologia strutturale e funzionale di faggete italiane" (Scarascia Mugnozza G ed). Edagricole, Bologna, Italy, 1999, 187-199.
- Balvanera P, Pfister AB, Buchmann N, He JS, Nakashizuka T, Raffaelli D, Schmid B Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecol Lett 2006, 9:1146-1156.
- Barbour RJ, Foyle DC, Chauret G, Cook JA, Karsh MB, Ran S Breast height relative density and radial growth in mature Jack pine (*Pinus banksiana*) for 38 years after thinning. Can. J. For. Res. 1994, 24, 2439-2447.
- Battipaglia G, Pelleri F, Lombardi F, Altieri S, Vitone A, Conte E, Tognetti R Effects of associating *Quercus robur* L. and *Alnus cordata* Loisel. on plantation productivity and water use efficiency. Forest Ecol Manage 2017, 391, 106-114.
- Bauhus J, Puettmann KJ, Kühne C Close-to-nature forest management in Europe: does it support complexity and adaptability of forest ecosystems. In: Messier C, Puettmann KJ, Coates KD (eds) Managing forests as complex adaptive systems: building resilience to the challenge of global change. Routledge, New York 2013, 187-213.
- Bengtsson J, Nilsson SG, Franc A, Menozzi P Biodiversity, disturbances, ecosystem function and management of European forests. For Ecol Manag 2000, 132, 39-50.

- Bielak K, Dudzinska M, Pretzsch H Mixed stands of Scots pine (*Pinus sylvestris* L.) and Norway spruce [*Picea abies* (L.) Karst] can be more productive than monocultures. Evidence from over 100 years of observation of long-term experiments. *Forest Syst* 2014, 23, 573.
- Binkley D, Dunkin KA, DeBell D, Ryan MG Production and nutrient cycling in mixed plantations of eucalyptus and albizia in Hawaii. *For Sci* 1992, 38, 393-408.
- Binkley D, Stape JL, Ryan MG Thinking about efficiency of resource use in forests. *For Ecol Manage* 2004, 193, 5-16.
- Bolte A, Ammer C, Löf M, Madsen P, Nabuurs GJ, Schall P, Spathelf P, Rock J Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. *Scand J For Res* 2009, 24, 473-482.
- Bolte A, Czajkowski T, Coccozza C, Tognetti R, de Miguel M, Pšidová E, Ditmarová Ľ, Dinca L, Delzon S, Cochard H, Ræbild A, de Luis M, Cvjetkovic B, Heiri C, Müller J Desiccation and mortality dynamics in seedlings of different European beech (*Fagus sylvatica* L.) populations under extreme drought conditions. *Front Plant Sci* 2016, 7, 751.
- Bonavita S, Vendramin GG, Bernardini V, Avolio S, Regina TMR The first SSR-based assessment of genetic variation and structure among *Pinus laricio* Poiret populations within their native area. *Plant Biosyst.* 2015, 150, 1-20.
- Bourgoise C Améliorer les taillis de châtaignier [Improve chestnut coppice]. *Forêt Entreprise* 1987, 44, 8-15. [in French]
- Brang P, Spathelf P, Larsen JB, Bauhus J, Bončina A, Chauvin C, Drössler L, Carlos GarcíaGüemes C, Caroline Heiri C, Kerr G, Lexer MJ, Mason B, Mohren F, Mühlethaler U, Nocentini S, Svoboda M Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry* 2014, 87, 492-503.
- Brashaw BK, Bucur V, Divos F, Goncalves R, Lu JX, Meder R, Pellerin RF, Potter S, Ross RJ, Wang XP Non-destructive testing and evaluation of wood: A worldwide research update. *For. Prod. J.* 2009, 59, 7-14.

- Brazier JD, Mobbs ID The influence of planting distance on structural wood yields of unthinned Sitka spruce. *Forestry* 1993, 66, 333-352.
- Briggs DG, Smith WR Effects of Silvicultural Practices on Wood Properties of Conifers: A review. In Douglas-fir Stand Management for the Future; Oliver, C., Hanley, D., Johnson, J., Eds.; University of Washington Press: Seattle, WA, USA, 1986; 108-116.
- Briggs DG, Thienel G, Turnblom EC, Lowell E, Dykstra D, Ross R, Wang X, Carter P Influence of thinning on acoustic velocity of douglas-fir trees in western Washington and western Oregon. In Proceedings of the 15th International Symposium on Non-destructive Testing of Wood, Duluth, MN, USA, 10-12 September 2007; Forest Products Society: Madison, WI, USA, 2008; 113-123.
- Brissette JC, Frank RM, Stone TL, Skratt TA Precommercial thinning in a northern conifer stand: 18-year results. *For. Chron.* 1999, 75, 967-972.
- Brüchert F, Gardiner B The effect of wind exposure on the tree aerial architecture and biomechanics of Sitka spruce (*Picea sitchensis*, Pinaceae). *American Journal of Botany* 2006, 93, 1512-1521.
- Buckley GP Ecology and management of coppice woodlands. Chapman & Hall, London 1992.
- Burkhart HE Development of empirical growth and yield models. In Proceedings of the Empirical and Process-Based Models for Forest Tree and Stand Growth Simulation, A Workshop/Ph.D. Course Jointly Organized by Technical University of Lisbon and IUFRO 4.01, Oeiras, Portugal, 21-27 September 1997, 10.
- Bussotti F *Pinus nigra* Arnold. In Pines of silvicultural importance. Wallingford: CABI Publishing 2002, 266-286.
- Cameron AD Importance of early selective thinning in the development of long-term stand stability and improved log quality: a review. *Forestry* 2002, 75, 25-35.
- Candel-Pérez D, Lo YH, Blanco J, Chiu CM, Camarero J, González de Andrés E, Imbert J, Castillo F Drought-induced changes in wood density are not prevented by thinning in *Scots pine* stands. *Forests* 2018, 9, 4.



- Cantiani MG, Cantiani P Conversione ad alto fusto di un ceduo “composto” di faggio nell’Appennino toscano. *Cellulosa e Carta* 1994, 45, 36-46.
- Cantiani P, Plutino M, Amorini E Effects of silvicultural treatment on the stability of black pine plantations. *Ann. Silvic. Res.* 2010, 36, 49-58.
- Cantiani P, Plutino M, Amorini E Effects of silvicultural treatment on the stability of black pine plantations. *Annals of Silvicultural Research* 2010, 36, 49-58.
- Carter P, Briggs D, Ross RJ, Wang X Acoustic Testing to Enhance Western Forest Values and Meet Customer Wood Quality Needs; Department of Agriculture Forest Service, US Department of Agriculture (USDA): Madison, WI, USA, 2005; 121-129.
- Castera P, Faye C, Ouadrani AEI Prediction of the bending strength of timber with a multivariate statistical approach. *Ann. For. Sci.* 1996, 53, 885-898.
- Chauhan SS, Walker JCF Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. *For. Ecol. Manag.* 2006, 229, 388-394.
- Chomel M, DesRochers A, Baldy V, Larchevêque M, Gauquelin T Non-additive effects of mixing hybrid poplar and white spruce on aboveground and soil carbon storage in boreal plantations. *For. Ecol. Manage* 2014, 328, 292-299.
- Ciancio O, Eccher A La gestione dei cedui. *Italia Agricola* (eds) 1983, 120, 64-102.
- Ciancio O, Garfi V, Iovino F, Menguzzato G, Nicolaci A I cedui di castagno in Calabria: caratteristiche culturali, produttività e assortimenti ritraibili. *L’Italia forestale e montana rivista di politica economia e tecnica* 2004, FDC 222: 176.1 *Castanea sativa*: (450.78).
- Ciancio O, Iovino F, Mendicino V, Menguzzato G, Nicolaci A, Nocentini S Structure and management of Aleppo pine forests. *Options Méditerranéennes, series A*, 2008, 75, 61-72.
- Ciancio O, Iovino F, Menguzzato G, Nicolaci A Interventi selvicolturali in cedui di faggio che hanno superato il turno consuetudinario valutazione della biomassa legnosa ritraibile. *L’Italia Forestale e Montana* 2007, 62 (5/6), 339-353.

- Ciancio O, Iovino F, Menguzzato G, Nicolaci A, Nocentini S Structure and growth of a small group selection forest of calabrian pine in Southern Italy: A hypothesis for continuous cover forestry based on traditional silviculture. *For. Ecol. Manag.* 2006, 224, 229-234.
- Ciancio O, Iovino F, Menguzzato G, Nicolaci A, Nocentini S Structure and growth of a small group selection forest of Calabrian pine in Southern Italy: a hypothesis for continuous cover forestry based on traditional silviculture. *For Ecol Manag* 2006, 224, 229-234.
- Ciancio O, Nocentini S The coppice forest. Silviculture, regulation, management. In: "Il bosco ceduo. Selvicoltura, assestamento, gestione". Accademia Italiana di Scienze Forestali, Firenze, 2004, 679-701.
- Clark A, Daniels RF Modelling the effect of physiographic region on wood properties of planted loblolly pine in southeast United States. In *Proceedings of the Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software, Fourth Workshop IUFRO Working Party S5.01-04, Harrison Hot Springs, BC, Canada, 8-15 September, 2002*, 663.
- Clutter JL, Fortson JC, Pienaar LV, Brister GH, Bailey RL *Timber management: a quantitative approach*. New York: John Wiley and Sons, Inc.; 1983, 333.
- Cocozza C, de Miguel M, Pšidová E, Ditmarová L, Marino S, Maiuro L, Alvino A, Czajkowski T, Bolte A, Tognetti R Variation in ecophysiological traits and drought tolerance of beech (*Fagus sylvatica* L.) seedlings from different populations. *Front Plant Sci* 2016, 7, 886.
- Coletta V, Menguzzato G, Pellicone G, Veltri A, Marziliano P Effect of thinning on above-ground biomass accumulation in a Douglas-fir plantation in southern Italy. *J. For. Res.* 2016, 27, 1313-1320.
- Condés S, del Río M, Sterba H Mixing effect on volume growth of *Fagus sylvatica* and *Pinus sylvestris* is modulated by stand density. *For Ecol Manage* 2013, 292, 86-95.
- Conedera M, Krebs P, Tinner W, Pradella M, Torriani D The cultivation of *Castanea sativa* (Mill.) in Europe, from its origin to its diffusion on a continental scale. *Veget Hist Archaeobot* 2004, 13,161-179.

- Conedera M, Manetti MC, Giudici F, Amorini E Distribution and economic potential of the Sweet chestnut (*Castanea sativa* Mill.) in Europe. *Ecologia Mediterranea* 2004, 30, 179-193.
- Conedera M, Stanga P, Oester B, Bachmann P Different post-culture dynamics in abandoned chestnut orchards. *For. Snow Landsc. Res.*, 2001, 76, 487-492.
- Conedera M, Tinner W, Krebs P, de Rigo D, Caudullo *Castanea sativa* in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G. (Eds.), *European Atlas of Forest Tree Species* 2016. Publ. Off. EU, Luxembourg (pp. e0125e0+). G. Bounous, ed., *Il castagno* (Edagricole, Bologna, 2014). Edagricole-New Business Media. ISBN: 8850654154. Pagine: XII-420
- Conte E, Lombardi F, Battipaglia G, Palombo C, Altieri S, La Porta N, Marchetti M, Tognetti R Growth dynamics, climate sensitivity and water use efficiency in pure vs. mixed pine and beech stands in Trentino (Italy) *For Ecol Manage* 2018, 409, 707-718.
- Coppini M, Hermanin L Restoration of selective beech coppices: A case study in the Apennines (Italy). *Forest Ecology and Management* 2007, 249: 18-27.
- Coppini M, Hermanin L Restoration of selective beech coppices: a case study in the Apennines (Italy). *Forest Ecology and Management* 2007, 249, 18-27.
- Cown DJ Comparison of the effects of two thinning regimes on some wood properties of radiata pine. *NZ J. Forest Sci.* 1974, 4, 540-551.
- Cucchi CC Premesse alla selvicoltura di un acrocoro Appenninico. *Italia Forestale e Montana* 1990, 45, 29-54.
- Cudlín P, Klopčič M, Tognetti R, Máliš F, Alados CL, Bebi P, Grunewald K, Zhiyanski M, Andonowski V, La Porta N, Bratanova-Doncheva S, Kachaunova E, Edwards-Jonášová M, Ninot J M, Rigling A, Hofgaard A, Hlásny T, Skalák P Frans Emil Wielgolaski Drivers of treeline shift in different European mountains. *Clim Res* 2017, 73, 135-150.

- De Dios J Gestión para la diversidad forestal: una oportunidad. Jornadas Red Natura en la Comarca del Noroeste. Situación actual y perspectivas de futuro. Caravaca de la Cruz. Murcia, January 2006, 24-26.
- Del Río M, Pretzsch H, Ruíz-Peinado R, Ampoorter E, Annighöfer P, Barbeito I, Bielak K, Brazaitis G, Coll L, Drössler L Species interactions increase the temporal stability of community productivity in *Pinus sylvestris*-*Fagus sylvatica* mixtures across Europe. *J Ecol* 2017, 105, 1032-1043.
- Del Río MD, Schütze G, Pretzsch H Temporal variation of competition and facilitation in mixed species forests in Central Europe. *Plant Biol* 2014, 16, 166-176.
- Demers C, Andreu M, McGowan B Thinning Southern Pines-A Key to Greater Returns; Series of the School of Forest Resources and Conservation, SS FOR 24; Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida: Tallahassee, FL, USA 2013, 6.
- Detter A, Cowell C, McKeown L, Howard P Evaluation of current rigging and dismantling practices used in arboriculture. Research Report RR668): Health and Safety Executive (HSE) and Forestry Commission (FC), UK, 2008, 370.
- Divos F Acoustic Tools for Seedling, Tree and Log Selection. In Proceedings of the Final Conference of COST Action E53 The Future of Quality Control for Wood and Wood Products, Napier University, Edinburgh, UK, 4-7 May 2010, 5.
- Dobšínská Z, Rathke J, Weber N Synthesis report COST ACTION FP 1207, WG1 Forestrelated policy targets and measures. IUFRO occasional paper 2015, 29.
- Duncker PS, Barreiro SM, Hengeveld GM, Lind T, Mason WL, Ambrozy S, Spiecker H Classification of forest management approaches: A new conceptual framework and its applicability to European forestry. *Ecol. Soc.* 2012, 17, 51.
- Duncker PS, Raulund-Rasmussen K, Gundersen P, Katzensteiner K, De Jong J, Ravn HP, Smith M, Eckmüllner O, Spiecker H How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. *Ecology and Society* 2012, 17, 50.

- Eckard JT, Isik F, Bullock B, Li B, Gumpertz M Selection efficiency for solid wood traits in *Pinus taeda* using time-of-flight acoustic and micro-drill resistance methods. *For. Sci.* 2010, 56, 233-241.
- Ekö PM, Petterson N, Bjerregaard J “Pre-commercial Thinning in European Beech (*Fagus sylvatica* L.). Results from field trial.” *For. & Landsc. Res.* 1995, 1, 207-226.
- Ellenberg H The vegetation ecology of Europe. 4<sup>th</sup> Edition, Cambridge University Press, Cambridge, UK 1988, 731.
- Ellenberg H, Leuschner C Vegetation Mitteleuropas mit den Alpen in ökologischer, dynamischer und historischer Sicht. Eugen Ulmer, Stuttgart 2010.
- Enescu CM, de Rigo D, Caudullo G, Mauri A, Houston Durrant T *Pinus nigra* in Europe: distribution, habitat, usage and threats. In San-Miguel-Ayanz J, de Rigo D, Caudullo G, Houston Durrant T, Mauri A (Eds) European atlas of forest tree species. Publ. Off. EU, Luxembourg, 2016, 126-127.
- Esaro G, Colpi C Conversione a fustaia e “invecchiamento naturale”: il caso di un ceduo di faggio sulle Prealpi venete. In: “Il bosco ceduo in Italia” (Ciancio O, Nocentini S eds). Accademia Italiana di Scienze Forestali, Firenze, 2002, 305-324
- Esteban E, Spinelli R, Aminti G, Laina RL; Vicens I Productivity, Efficiency and Environmental Effects of Whole-Tree Harvesting in Spanish Coppice stands Using a Drive-to-Tree Disc Saw Feller-Buncher. *Croatian Journal of Forest Engineering* 2018, 39, 163-172.
- Everard J, Christie JM Sweet chestnut: Silviculture, timber quality and yield in the Forest of Dean. *Forestry* 1995, 68, 133-144.
- Fabbio G Coppice forests, or the changeable aspect of things, a review. *Annals of Silvicultural Research* 2016, 40, 108-132.
- FAO World Reference Base for Soil Resources; International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106; FAO: Roma, Italy 2014.

- Fioravanti M “Valutazione tecnologica dell’influenza delle pratiche selvicolturali sulla qualità del legno,” in: Il Legno di Castagno e di Douglasia della Toscana. Qualità del Legno e Selvicoltura, Classificazione e Valori Caratteristici del Legname Strutturale, Quaderno Arsia 1999, 9/99, 23-37.
- Fioravanti M The influence of juvenile wood and growthrate on the quality of Chestnut (*Castanea sativa* Mill.) wood. International Wood Quality Workshop in Québec City/Canada, August 18-22, 1997. Proceedings-Chapter VIII: Timber Management Toward Wood Quality and End-Product Value, p. VIII/31-VIII/3.
- Ford ED and Newbould PJ Stand structure and dry weight production through the sweet chestnut (*Castanea sativa*) coppice cycle. Journal ecology 1970, 58, 275-296.
- Forest Europe Resolution H1, general guidelines for the sustainable forest management of forests in Europe, 16-17 June 1993, Helsinki, Finland. Second Ministerial Conference on the Protection of Forests in Europe, Madrid, Spain.
- Forrester DI The spatial and temporal dynamics of species interactions in mixedspecies forests: from pattern to process. For Ecol Manage 2014, 312, 282-292.
- Forrester DI, Ammer C, Annighöfer PJ Effects of crown architecture and stand structure on light absorption in mixed and monospecific *Fagus sylvatica* and *Pinus sylvestris* forests along a productivity and climate gradient through Europe. J Ecol 2018, 106, 746-760.
- Forrester DI, Lancaster K, Collopy JJ, Warren CR, Tausz M Photosynthetic capacity of *Eucalyptus globulus* is higher when grown in mixture with *Acacia mearnsii*. Trees 2012, 26, 1203-1213.
- Gamfeldt L, Snäll T, Bagchi R, Jonsson M, Gustafsson L, Kjellander P, Ruiz-Jaen MC, Fröberg M, Stendahl J, Philipson CD, Mikusiński G, Andersson E, Westerlund B, Andrén H, Moberg F, Moen J, Bengtsson J Higher levels of multiple ecosystem services are found in forests with more tree species. Nat Commun 2013, 4,1340.
- Gasparini P, Tabacchi G L’Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio INFC 2005. Secondo inventario forestale nazionale italiano. Metodi e risultati [National Forest

- and Carbon sink Inventory INFC 2005. Second Italian national forest inventory. Methods and results]. Ministero delle Politiche Agricole, Alimentari e Forestali, Corpo Forestale dello Stato, Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di ricerca per il Monitoraggio e la Pianificazione Forestale, Edagricole- Il Sole 24 ore, Bologna, Italy, 2011, 653. [in Italian].
- Genet A, Auty D, Achim A, Bernier M, Pothier D, Cogliastro A Consequences of faster growth for wood density in northern red oak (*Quercus rubra* Liebl.). *Forestry* 2012, 86, 99-110.
- Giannini R, Maltoni A, Mariotti B, Paffetti D, Tani A, Travaglini D Valorizzazione della produzione legnosa dei boschi di castagno. *L'Italia Forestale e Montana*, 2014, 69, 307-317.
- Giannini R, Piusi P La conversion destailis en futaie: l'expérience italienne. *Proceed-ings of XVI IUFRO World Congress, Norway*, 1976, 388-396
- Gorman TM, Wagner FG, Wu SY Assessment of intensive stress-wave scanning of Douglas-fir trees for predicting lumber modulus of elasticity. In *Proceedings of the 13th International Symposium on Nondestructive Testing of Wood*, University of California: Richmond, BC, Canada, 19-21 August 2002, 143-148.
- Grammel R Zusammenhänge zwischen Wachstumsbedingungen und holztechnologischen Eigenschaften der Fichte. *Forst Central* 1990, 109, 119-129.
- Grant CD, Norman MA, Smith MA Fire and silvicultural management of restored bauxite mines in Western Australia. *Restor. Ecol.* 2007, 15, 127-136.
- Griess VC, Acevedo R, Härtl F, Staupendahl K, Knoke T Does mixing tree species enhance stand resistance against natural hazards? A case study for spruce. *For Ecol Manag* 2012, 267, 284-296.
- Griess VC, Knoke T Bioeconomic modelling of mixed Norway spruce – European beech stands. Economic consequences of considering ecological effects. *Eur J For Res* 2013, 132, 511-522.
- Grossiord C, Granier A, Gessler A, Jucker T, Bonal D Does drought influence the relationship between biodiversity and ecosystem functioning in boreal forests? *Ecosystems* 2014, 17, 394-404.

- Guilley É, Hervé JC, Huber F, Nepveu G “Modelling variability of within- ring density components in *Quercus petraea* Liebl. with mixed-effect models and simulating the influence of contrasting silvicultures on wood density,” *Annals of Forest Science* 1999, 56, 449-458.
- Guntekin G, Emiroglu ZG, Yolmaz T Prediction of bending properties for Turkish red pine (*Pinus brutia* Ten.) Lumber using stress wave method. *Bioresources* 2013, 8, 231-237.
- Gunter H, Grote G, Thees O Information technology in supply networks Does it lead to better collaborative planning? *Journal of Enterprise Information Management* 2006, 19, 540-550.
- Haartveit EY, Flate PO Mechanical properties of Norway spruce lumber from monocultures and mixed stand-modelling bending stiffness and strength using stand and tree characteristics. In *Proceedings of the Connection between Silviculture and Wood Quality: Modelling Approach and Simulation Software*, IUFRO WP S5.01-04 Workshop, BC, Canada, 8-15 September 2002, 2002.
- Hanewinkel M, Cullmann D, Schelhaas MJ, Nabuurs GJ, Zimmermann NE Climate change may cause severe loss in economic value of European forestland. *Nat Clim Chang* 2013, 3, 204-207.
- Hausser K, Troeger R Beitrag zur Frage der Massen und Wertleistung gepflanzter Weisstannen und Fichtenbestände auf gleichen Standorten. *Allg Forst- u J-Ztg* 1967, 138, 150-157.
- He Y, Qin L, Li Z, Liang X, Shao M, Tan L Carbon storage capacity of monoculture and mixed-species plantations in subtropical China. *For Ecol Manag* 2013, 295, 193-198.
- Hedde M, Aubert M, Decaëns T, Bureau F, Dynamics of soil carbon in a beechwood chronosequence forest, *Forest Ecology and Management*, 255, 193-202.
- Hédli R, Kopecky M, Komàrek J Half a century of succession in a temperate oakwood: from species-rich community to mesic forest. *Diversity and Distributions* 2010, 16, 267-276.
- Heinimann HR “Business process re-engineering – a framework for designing logistics systems for wood procurement”, *Proceedings of the 1st World Symposium on Logistics in the Forest Sector, Supply Chain Management for the Paper and Timber Industries* 2000.
- Heinimann HR “Logistics in timber production – state-of-the-art and perspectives”. *Forstwissenschaftliches Centralblatt* 1999, 118, 24-38.



- Heitz R, Hasenauer H Reconversion of Norway spruce (*Picea abies* (L.) Karst.) stands into mixed forests: effects on soil properties and nutrient fluxes. In: Proceedings of the International Conference “Forest ecosystem restoration: ecological and economical impacts of restoration processes in secondary coniferous forests”. Vienna (Austria) 10-12 Apr 2000. Institute of Forest Growth Research, Vienna, Austria 2000, 119-125.
- Hink V Das Wachstum von Fichte und Tanne auf den wichtigsten Standortseinheiten des Einzelwuchsbezirks “Flächenschwarzwald” (Südwestfalen-Lippe). Allgemeine Forst und Jagdzeitung 1972, 143, 80-85.
- Hofmann A Il faggio e le faggete in Italia. MAF CFS, Collana Verde 1991, 81, 140.
- Holmes RL Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull 1983, 43, 69-78.
- Ikeda K, Kino N Quality evaluation of standing trees by a stress-wave propagation method and its application I. Seasonal changes of moisture contents of sugi standing trees and evaluation with stress-wave propagation velocity. Mokuzai Gakkaishi 2000, 46, 181-188.
- Iovino F, Menguzzato G Gestione sostenibile dei boschi in ambiente mediterraneo, 2004. In: Atti del Convegno “Selvicoltura: a che punto siamo?”, Vallombrosa (Firenze) 23-24 ottobre 2003. Ed. Fondazione San Giovanni Gualberto-Osservatorio Foreste e Ambiente, pp. 143-151.
- IPCC. Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change (Core Writing Team, Pachauri RK, Meyer LA (eds)), IPCC, Geneva 2014, 151.
- IPCC. Meeting report of the intergovernmental panel on climate change expert meeting on mitigation, sustainability and climate stabilization scenarios. In: IPCC Working Group III Technical Support Unit, eds PRJ Shukla, R Skea, K van Diemen, Ø Calvin, F Christophersen, J Creutzig, et al. London: Imperial College London, 2017.

- IUSS Working Group WRB. World Reference Base for Soil Resources; International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106; FAO: Roma, Italy, 2014.
- Jactel H, Bauhus J, Boberg J, Bonal D, Castagnyrol B, Gardiner B, Gonzalez-Olabarria JR, Koricheva J, Meurisse N, Brockerhoff EG Tree Diversity Drives Forest Stand Resistance to Natural Disturbances. *Curr Forestry Rep* 2017, 3, 223.
- Jactel H, Nicoll BC, Branco M, Gonzalez-Olabarria JR, Grodzki W, Långström B, Moreira F, Netherer S, Orazio C, Piou D, Santos H, Schelhaas MJ, Tojic K, Vodde F The influences of forest stand management on biotic and abiotic risks of damage. *Ann For Sci* 2009, 66, 701.
- Johansson K “Effect of early competition on wood properties of Norway spruce”, *Acta Universitatis Agriculturae Sueciae, Silvestria* 1997, 19.
- Johnson EA and Miyanishi K Testing the assumptions of chronosequences in succession. *Ecology Letters* 2008, 11, 419-431.
- Jozsa L, Middleton G A Discussion of Wood Quality Attributes and Their Practical Implications; Special Publication No. SP-34; Forintek Canada Corp: Vancouver, BC, Canada, 1994.
- Jucker T, Bouriaud O, Avacaritei D, Coomes DA Stabilizing effects of diversity on aboveground wood production in forest ecosystems: linking patterns and processes. *Ecol Lett* 2014, 17, 1560-1569.
- Kanowski J, Catterall CP, Wardell-Johnson GW Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. *For Ecol Manage* 2005, 208, 359-372.
- Keith CT Defining wood quality: what's important? *Wood Quality Considerations in Tree Improvement Programs*. Workshop Forintek Canada Corp Quebec, Canada 1985, 21-25.
- Kelty MJ Comparative productivity of monocultures and mixed-species stands. In: *The Ecology and Silviculture of Mixed-Species Forests*. Springer, Netherlands, 1992, 125-141.
- Kelty MJ The role of species mixtures in plantation forestry. *For Ecol Manage* 2006, 233, 195-204.

- Kennel R Soziale Stellung, Nachbarschaft und Zuwachs. Forstwissenschaftliches Centralblatt 1966, 85, 193-204.
- Kennel R Untersuchungen über die Leistung von Fichte und Buche im Reinund Mischbestand. Allg Forst u Jagdztg 1965, 136, 149-161.
- Kint V, Geudens G, Mohren GMJ, Lust N Silvicultural interpretation of natural vegetation dynamics in ageing Scots pine stands for their conversion into mixed broadleaved stands. Forest Ecology and Management 2006, 223, 363-370.
- Klang F, "The influence of Silvicultural Practices on Tree Properties in Norway spruce". Doctoral thesis Swedish University of Agricultural Sciences, Alnarp 2000.
- Kliger IR, Johansson G, Perstorper M, Engström D Formulation of requirements for the quality of wood properties used by the construction industry. Chalmers Univ. Technol., Göteborg, Sweden 1994.
- Kneifl MM, Kadavý J, Knott R, Adamec Z, Drápela K An inventory of tree and stand growth empirical modelling approaches with potential application in coppice forestry (A review). Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 2015, 63, 1789-1801.
- Koricheva J, Meurisse N, Brockerhoff EG Tree diversity drives forest stand resistance to natural disturbances. Curr For Rep 2017, 3, 223-243.
- Krajnc L, Farrelly N, Harte AM The effect of thinning on mechanical properties of Douglas fir, Norway Spruce, and Sitka Spruce. Ann. For. Sci. 2019, 76, 3.
- Kramer H, Waldwachstumslehre (Forest growth and yield science) (In German) Paul Parey. Hamburg, Berlin, 1988, 374.
- Kuglin FA Customer-centered supply chain management: a link-by-link guide, 1998. AMACOM, American Management Association, New York. Paletto, 2008
- Lancho JFG, Gonzalez MI Carbon sequestration in a Spanish chestnut coppice. In: Proceedings of the Third International Chestnut (Ed.: Abreu C.G., Rosa, E., Monteiro, A.A.). Acta Horticulturae 2005, 693, 201-207.

- Lanuv (Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen), 2007. Niederwälder in Nordrhein-Westfalen. Galunder-Verlag, Nümbrecht-Elsenroth.
- Larocque GR, Marshall P Wood relative density development in red pine (*Pinus resinosa* Ait.) stands as affected by different initial spacings. For Sci 1995, 41, 709-728.
- Larsen JB (1995) Ecological stability of forest and sustainable silviculture. For Ecol Manag 73, 85-96.
- Lasserre JP, Mason E, Watt M The influence of initial stocking on corewood stiffness in a clonal experiment of 11 year-old *Pinus radiata* D. Don. N. Z. J. Forestry 2004, 49, 18-23.
- Lasserre JP, Mason EG, Watt MS Assessing corewood acoustic velocity and modulus of elasticity with two impact based instruments in 11-year-old trees from a clonal-spacing experiment of *Pinus radiata* D. Don. For. Ecol. Manag. 2007, 239, 217-221.
- Lauteri M, Monteverdi M, Scarascia-Mugnozza G Preservation of chestnut (*Castanea sativa* Mill.) genetic resources and adaptive potential in relation to environmental changes. In: Proceeding of the “1<sup>st</sup> European Congress on Chestnut” (Bounous G, Becarro G eds). ISHS Acta Horticulturae 2009, 866, 677-682.
- Le Master DC, Schmithüsen F The continuing evolution in social, economic, and political values relating to forestry in the United States and in Europe. In: “Working toward Common Goals in Sustainable Forest Management: The Divergence and Re-convergence of European and American Forestry”, Pinchot Institute for Conservation, Washington D.C. 2006.
- Lebourgeois F, Gomez N, Pinto P, Mérian P Mixed stands reduce *Abies alba* tree-ring sensitivity to summer drought in the Vosges mountains, western Europe. For Ecol Manage 2013, 303, 61-71.
- Legg M, Bradley S Measurement of stiffness of standing trees and felled logs using acoustics: A review. J. Acoust. Soc. Am. 2016, 139, 588-604.
- Lei YC, Zhang SY, Jiang Z Models for predicting lumber bending MOR and MOE based on tree and stand characteristics in black spruce. Wood Sci. Technol. 2005, 39, 37-47.

- Leonardi S, Rapp M, Failla M, Guarnaccia D Biomass, productivity and organic matter fluxes in *Castanea sativa* Mill stands of various elevation in the Etna. *Annales Des Sciences Forestieres* 1996, 53, 1031-1048.
- Liang J, Crowther TW, Picard N, Wiser S, Zhou M, Alberti G, Schulze ED, McGuire AD, Bozzato F, Pretzsch H, de-Miguel S, Paquette A, Hérault B, Scherer-Lorenzen M, Barrett CB, Glick HB, Hengeveld GM, Nabuurs GJ, Pfautsch S, Viana H, Vibrans AC, Ammer C, Schall P, Verbyla D, Tchebakova N, Fischer M, Watson JV, Chen HYH, Lei X, Schelhaas MJ, Lu H, Gianelle D, Parfenova EI, Salas C, Lee E, Lee B, Kim HS, Bruelheide H, Coomes DA, Piotta D, Sunderland T, Schmid B, Gourlet-Fleury S, Sonké B, Tavani R, Zhu J, Brandl S, Vayreda J, Kitahara F, Searle EB, Neldner VJ, Ngugi MR, Baraloto C, Frizzera L, Balazy R, Oleksyn J, Zawila-Niedzwiecki T, Bouriaud O, Bussotti F, Finér L, Jaroszewicz B, Jucker T, Valladares F, Jagodzinski AM, Peri PL, Gonmadje C, Marthy W, O'Brien T, Martin EH, Marshall A, Rovero F, Bitariho R, Niklaus PA, Alvarez-Loayza P, Chamuya N, Valencia R, Mortier F, Wortel V, Engone-Obiang NL, Ferreira LV, Odeke DE, Vasquez RM, Reich PB Positive biodiversity–productivity relationship predominant in global forests. *Science* 2016, 354, 196.
- Liu CLC, Kuchma O, Krutovsky KV Mixed species versus monocultures in plantation forestry: development, benefits, ecosystem services and perspectives for the future. *Global Ecol Conserv* 2018, 15, e00419.
- Lombardi F, Lasserre B, Chirici G, Tognetti R, Marchetti M Deadwood occurrence and forest structure as indicators of old-growth forest conditions in Mediterranean mountainous ecosystems, *Écoscience*, 2012, 19:4, 344-355.
- Macdonald H, Hubert J A review of the effect of silviculture on timber quality of Sitka spruce. *Forestry* 2002, 2, 107-138.
- Machado JS, Louzada JL, Santos AJA, Nunes L, Anjos O, Rodrigues J, Simoes RMS, Pereira H Variation of wood density and mechanical properties of blackwood (*Acacia melanoxylon* r. Br.). *Mater Des* 2014, 56, 975-980.

- Magin R Ertragskundliche Untersuchungen in montanen Mischwäldern. Forstwissenschaftliches Centralblatt 1954, 73, 103-113.
- Mahon JM, Jordan L, Schimleck LR, Clark A, Daniels RF A comparison of sampling methods for a standing tree acoustic device", South J Appl For. 2009, 33, 62-68.
- Malcolm DC, Mason WL, Clarke GC The transformation of conifer forests in Britain - regeneration, gap size and silvicultural systems. Forest Ecology and Management 2001, 151, 7- 23.
- Manetti MC, Amorini E, Becagli C New silvicultural models to improve functionality of chestnut stands. Advances in Horticultural Science 2006, 1, 65-69.
- Manetti MC, Amorini E, Becagli C, Pelleri F, Pividori M, Schleppe P, Zingg A, Conedera M Quality wood production from chestnut (*Castanea sativa* Mill.) coppice forests - Comparison between different silvicultural approaches. In: Proceeding of the "1<sup>st</sup> European Congress on Chestnut" (Bounous G, Becarro G eds). ISHSActa Horticulturae 2009, 866, 683-692.
- Manetti MC, Becagli C, Sansone D, Pelleri F Tree-oriented silviculture: a new approach for coppice stands. iForest (early view) 2016, 9, 791-800.
- Marziliano P, Tognetti R, Lombardi F Is tree age or tree size reducing height increment in *Abies alba* Mill. at its southernmost distribution limit?. Annals of Forest Science 2019, 76.
- Marziliano PA, Coletta V, Menguzzato G, Nicolaci A, Pellicone G, Veltri A Effects of planting density on the distribution of biomass in a douglas-fir plantation in southern Italy. iForest 2015, 8, 368-376.
- Marziliano PA, Laforteza R, Colangelo G, Davies C, Sanesi G Structural diversity and height growth models in urban forest plantations: A case-study in northern Italy. Urban Forestry and Urban Greening, 2013, 12, 246-254.
- Marziliano PA, Laforteza R, Medicamento U, Lorusso L, Giannico V, Colangelo C, Sanesi G Estimating belowground biomass and root/shoot ratio of *Phillyrea latifolia* L. in the Mediterranean forest landscapes. Ann. For. Sci. 2015, 72, 585-593.

- Marziliano PA, Menguzzato G, Scuderi A, Corona P Simplified methods to inventory the current annual increment of forest standing volume. *iForest* 2012, 5, 276-282.
- Marziliano PA, Menguzzato G, Scuderi A, Scalise C, Coletta V Biomass conversion and expansion factors in Douglas-fir stands of different planting density: Variation according to individual growth and prediction equations. *For. Syst.* 2017, 26, e003.
- MATT Ministero dell'Ambiente e della Tutela del Territorio (Italy). Manuale per la gestione dei siti Natura 2000. Direzione Protezione della Natura 2004.
- Merlin M, Perot T, Perret S, Korboulewsky N, Vallet P Effects of stand composition and tree size on resistance and resilience to drought in sessile oak and Scots pine. *For Ecol Manage* 2015, 339, 22-33.
- Mettin C Betriebswirtschaftliche und ökologische Zusammenhänge zwischen Standortskraft und Leistung in Fichtenreinbeständen und Fichten Buchen-Mischbeständen. *Allg Forst- u J-Ztg* 1985, 40, 830-810.
- Metz J, Annighöfer P, Schall P, Zimmermann J, Kahl T, Schulze ED, Ammer C Site-adapted admixed tree species reduce drought susceptibility of mature European beech. *Glob Chang Biol* 2016, 22, 903-920.
- Metz JÔ, Seidel D, Schall P, Scheffer D, Schulze ED, Ammer C Crown modeling by terrestrial laser scanning as an approach to assess the effect of aboveground intra- and interspecific competition on tree growth. *For Ecol Manage* 2013, 310, 275-288.
- Mitchell HL A concept of intrinsic wood quality and nondestructive methods for determining quality in standing timber. Report No. 2233, Forest Products Laboratory, Madison, Wisconsin 1961.
- Mitchell SJ Stem growth responses in Douglas-fir and Sitka spruce following thinning, implications for assessing wind-firmness. *For. Ecol. Manag.* 2000, 135, 105-114.
- Mitscherlich G Ertragskundlich-ökologische Untersuchungen im Rein-und Mischbestand. *Mitteilungen der Forstlichen Bundes-Versuchsanstalt* 1967, 77, 9-35.

- Mochan S, Moore J, Conolly T Using Acoustics Tools in Forestry and the Wood Supply Chain; Forestry Commission Technical Note 18; Forestry Commission: Edinburgh, UK 2009.
- Moore JR, Cown DJ, McKinley RB, Sabatia CO Effects of stand density and seedlot on three wood properties of young radiata pine grown at a dry-land site in New Zealand. *NZ J For Sci* 2015, 45, 209.
- Mora CR, Schimleck LR, Isik F, Mahon JM, Clark A, Daniels RF Relationship between acoustic variables and different measures of stiffness in standing *Pinus taeda* trees. *Can. J. For. Res.* 2009, 39, 1421-1429.
- Morin X, Fahse L, Scherer-Lorenzen M, Bugmann H Tree species richness promotes productivity in temperate forests through strong complementarity between species. *Ecol Lett* 2011, 14, 1211-219.
- Moscatelli M, Pettenella D, Spinelli R Produttività e costi della lavorazione meccanizzata dei cedui di Castagno in ambiente appenninico. *Forest@* 2007, 4, 51-62.
- Nakamura N Measurement of the properties of standing trees with ultrasonics and mapping of the properties. *Univ. For. Res.* 1996, 96, 125-135.
- Naso I Una fonte scritta per la storia forestale nel Medioevo: gli statuti delle comunità piemontesi e la salvaguardia dei boschi. In Andreoli B, Montanari M (eds) *Il bosco nel medioevo*. Bologna: Editrice CLUEB, 1988, 149-158.
- Nicolaci A, Travaglini D, Menguzzato G, Nocentini S, Veltri A, Iovino F Ecological and anthropogenic drivers of Calabrian pine (*Pinus nigra* J.F. Arn. ssp. *Laricio* (Poiret) Maire) distribution in the Sila mountain range. *iForest* 2014, 8, 497-508.
- Nocentini S Structure and management of beech (*Fagus sylvatica* L.) forests in Italy. *iForest* 2009, 2, 105-113.
- Ostaff DP, Piene H, Quiring DT, Moreau G, Farrell JCG, Scarr T Influence of pre-commercial thinning on balsam fir defoliation by the balsam fir sawfly. *For. Ecol. Manag.* 2006, 223, 342-348.
- Paquette A, Messier C The effect of biodiversity on tree productivity: from temperate to boreal forests. *Glob Ecol Biogeogr* 2011, 20, 170-180.



- Pastorella F, Giacobelli G, Maesano M, Paletto A, Vivona S, Veltri A, Pellicone G, Mugnozza GS  
Social percep-tion of forest multifunctionality in southern Italy: The case of Calabria Region.  
Journal of Forest Science 2016, 62, 366-79.
- Patricio MS, Monteiro ML, Nunes LF, Mesquita S, Beito S, Casado J, Guerra H Management models  
evaluation of a *Castanea sativa* coppice in the northeast of Portugal. In: Proceedings of the Third  
International Chestnut (Ed.: Abreu C.G., Rosa, E., Monteiro, A.A.). Acta Horticulturae 2005, 693,  
721-725.
- Pavari A. Le classificazioni fitoclimatiche ed i caratteri della stazione [Phytoclimatic classifications  
and station characteristics]. Scritti di Ecologia Selvicoltura e Botanica Forestale 1959, 45-116. (In  
Italian).
- Pawson SM, Brockerhoff EG, Didham RK Native forest generalists dominate carabid assemblages  
along a stand-age chronosequence in an exotic *Pinus radiata* plantation. Forest Ecology and  
Management, 2009, 258S, S108-S116.
- Peltola H, Kilpeläinen A, Sauvala K, Räsänen T, Ikonen VP Effects of early thinning regime and  
tree status on the radial growth and wood density of Scots pine. Silva Fenn. 2007, 41, 489-505.
- Peters R Beech forests. Kluwer, Dordrecht, The Netherlands, Geobotany 1997, 24, 169.
- Petit B, Montagnini F Growth in pure and mixed plantations of tree species used in reforesting rural  
areas of the humid region of Costa Rica, Central America. For Ecol Manage 2006, 233, 338-343.
- Petráš R, Mecko J, Bošelâ M, Šebeň V Wood quality and value production in mixed fir-spruce-beech  
stands: Long-term research in the Western Carpathians. Lesn Cas For J 2016, 62, 98-104.
- Pickett STA Space-for-time substitutions as an alternative to longterm studies. In: Longterm Studies  
in Ecology [Likens GE (ed.)]. Springer, New York, USA 1989.
- Piermattei A, Renzaglia F, Urbinati C Recent expansion of *Pinus nigra* Arn. above the timberline in  
the central Apennines, Italy. Annals of Forest Science 2012, 69, 509-517.
- Piotto D A meta-analysis comparing tree growth in monocultures and mixed plantations. Forest Ecol  
Manage 2008, 255, 781-786.

- Pretzsch H Forest dynamics, growth and yield. From measurement to model. Springer, Berlin, 2010.
- Pretzsch H Species-specific allometric scaling under selfthinning. Evidence from long-term plots in forest stands. *Oecologia* 2006, 146, 572-583.
- Pretzsch H The Effect of Tree Crown Allometry on Community Dynamics in Mixed-Species Stands versus Monocultures. A Review and Perspectives for Modeling and Silvicultural Regulation. *Forests* 2019, 10, 810.
- Pretzsch H, Biber P A re-evaluation of Reineke's rule and stand density index. *For Sci* 2005, 51, 304-320.
- Pretzsch H, Bielak K, Block J, Bruchwald A, Dieler J, Ehrhart HP, Kohnle U, Nagel J, Spellmann H, Zasada M, Zingg A Productivity of mixed versus pure stands of oak (*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L.) and European beech (*Fagus sylvatica* L.) along an ecological gradient. *Eur J For Res* 2013, 132, 263-280.
- Pretzsch H, Bielak K, Bruchwald A, Dieler J, Dudzinska M, Erhart HP, Jensen AM, Johannsen VK, Kohnle U, Nagel J, Spellmann H, Zasada M, Zingg A Mischung und Produktivität von Waldbeständen. Ergebnisse langfristiger ertragskundlicher Versuche. *Allg Forst- u J-Ztg* 2013, 184, 177-196.
- Pretzsch H, Block J, Dieler J, Dong PH, Kohnle U, Nagel J, Comparison between the productivity of pure and mixed stands of Norway spruce and European beech along an ecological gradient. *Ann For Sci* 2010, 67, 712.
- Pretzsch H, Forrester DI Stand dynamics of mixed-species stands compared with monocultures, In: Pretzsch H, Forrester DI, Baushus J (eds) *Mixed-species forests. Ecology and management* 2017, 653.
- Pretzsch H, Rais A Wood quality in complex forests versus even-aged monocultures: review and perspectives. *Wood Sci Technol* 2016, 50, 845-880.
- Pretzsch H, Schütze G Effect of tree species mixing on the size structure, density, and yield of forest stands. *Eur J For Res* 2016, 135, 1-22.

- Pretzsch H, Schütze G Effect of tree species mixing on the size structure, density and yield forest stands. *Eur J For Res* 2015, 135, 1-22.
- Pretzsch H, Schütze G Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: evidence on stand level and explanation on individual tree level. *Eur J Forest Res* 2009, 128, 183-204.
- Pretzsch H, Schütze G Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: evidence on stand level and explanation on individual tree level. *Eur J For Res* 2009, 128, 183-204.
- Pretzsch H, Schütze G, Uhl E Resistance of European tree species to drought stress in mixed versus pure forests: evidence of stress release by inter-specific facilitation. *Plant Biol* 2013, 15, 483-495.
- Proto AR, Macri G, Bernardini V, Russo D, Zimbalatti G Acoustic evaluation of wood quality with a non-destructive method in standing trees: A first survey in Italy. *iForest* 2017, 10, 700-706.
- Puettmann KJ, Messier C, Coates KD Managing forests as complex adaptive systems. Introductory concept and application. In: Messier C, Puettmann KJ, Coates KD (eds) *Managing forests as complex adaptive systems: building resilience to the challenge of global change*. Routledge, New York 2013, 3-16.
- R Core Team R: A Language and Environment for Statistical Computing R Foundation for Statistical Computing. Vienna; 2016.
- Rackham O *Trees and woodland in the British landscape*. Revised edition. London, Dent 1980.
- Richards AE, Forrester DI, Buhus J, Scherer-Lorenzen M The influence of mixed tree plantations on the nutrition of individual species: a review. *Tree Physiol* 2010, 30, 1192-1208.
- Roces-Díaz JV, Díaz-Varela ER, Barrio-Anta M, Álvarez-Álvarez P Sweet chestnut agroforestry systems in North-western Spain: classification, spatial distribution and an ecosystem services assessment. *Forest Systems*, 2018, 27, e03S.
- Romagnoli M, Cavalli D, Spina S Wood Quality of Chestnut: Relationship between Ring Width, Specific Gravity, and Physical and Mechanical Properties. *BioResources* 2014, 9, 1132-1147.

- Ross RJ, McDonald KA, Green DW, Schad KC Relationship between log and lumber modulus of elasticity. *For. Prod. J.* 1997, 47, 89-92.
- Rozenberg P, Franc A, Bastien C, Cahalan C Improving models of wood density by including genetic effects: A case study in Douglas-fir. *Ann. For. Sci.* 2001, 58, 385-394.
- Rubio A, Sánchez O, Gómez V, Graña D, Elena R, Blanco A Autoecología de los castañares de Castilla (España) (Autoecology of chestnut tree forest in Castilla, Spain) *Investigación Agraria: Sistemas de Recursos Forestales* 2002, 11, 373-393.
- Russo D, Marziliano PA, Macri G, Proto AR, Zimbalatti G, Lombardi F Does thinning intensity affect wood quality? An analysis of Calabrian Pine in Southern Italy using a non-destructive acoustic method. *Forests* 2019, 30, 1-16.
- Rydberg D Initial sprouting, growth and mortality of European aspen and birch after selective coppicing in central Sweden. *Forest ecology management* 2000, 130, 27-35.
- Saha S, Kuehne C, Kohnle U, Brang P, Ehring A, Geisel J, Leder B, Muth M, Petersen R, Peter J, Ruhm W, Bauhus J Growth and quality of young oaks (*Quercus robur* and *Quercus petraea*) grown in cluster plantings in central Europe: a weighted meta-analysis. *For Ecol Manage* 2012, 283, 106-118.
- Salisbury EJ, Downs, Dunes: Their Plant Life and Environment. G. Bell and Sons Ltd., London, UK 1952.
- Sandoz JL Non-destructive testing of wood. In Proceedings of the 10th International Symposium on NDT, Presses Polytechniques et Universitaire Romandes, Lausanne, Switzerland, 26-27 August 1996.
- Sanesi G, Laforteza R, Colangelo G, Marziliano PA, Davies C Root system investigation in sclerophyllous vegetation: An overview. *Ital. J. Agron.* 2013, 8, 121-126.
- Saranpää P Wood density and growth. In: Barnett, J.R.; Jeronimidis, G. (eds), *Wood Quality and Its Biological Basis* Blackwell, Published in the USA/Canada by CRC Press, Oxford, Boca Raton, FL, Biological Sciences Series, 2003, 87-113.

- Scarascia-Mugnozza G, Oswald H, Piussi P, Radoglou K Forests of the Mediterranean region: gaps in knowledge and research needs, *Forest Ecology and Management*, 2000, 132, 97-109.
- Scherzinger Naturschutz im Wald Qualitätsziele einer dynamischen Waldentwicklung. Ulmer, Stuttgart W1996.
- Schütt P, et al. Enzyklopädie der Laubbäume: Die große Enzyklopädie. Nikol, Hamburg, 2006.
- Schweingruber HS Tree Rings: Basic and Applications of Dendrochronology; Kluwer: Dordrecht, The Netherland, 1998.
- SFM Madrid ministerial declaration, 25 years together promoting sustainable forest management in Europe, 7th Forest Europe Ministerial conference, Madrid 20–21 October 2015.
- Sharma SK, Rao RV, Shukla SR, Kumar P, Sudheendra R, Sujatha M, Dubey YM Wood quality of coppiced *Eucalyptus tereticornis* for value addition. *IAWA Journal* 2005, 26: 137-147.
- Škorpik P, Konrad H, Geburek T, Schuh M, Vasold D, Eberhardt M, Schuler S Solid wood properties assessed by non-destructive measurements of standing European larch (*Larix decidua* Mill.): Environmental effects on variation within and among trees and forest stands. *Forests* 2018, 9, 276.
- Skov KR, Kolb TE, Wallin KF Tree size and drought affect ponderosa pine physiological response to thinning and burning treatments. *J. Forensic. Sci.* 2004, 50, 81-91.
- Spinelli R, Magagnotti N, Schweier J Trends and Perspectives in Coppice Harvesting. *Croatian journal forestry engineer* 2017, 2, 219-230.
- Štefančík I, Vacek Z, Sharma RP, Vacek S, Rösslová M Effect of thinning regimes on growth and development of crop trees in *Fagus sylvatica* stands of Central Europe over fifty years. *Dendrobiology* 2018, 79, 141-155.
- Swanson FJ, Franklin JF New forestry principles from ecosystem analysis of Pacific Northwest forest. *Ecol Applic* 1992, 2, 262-274.
- Tabacchi G, Di Cosmo L Stima delle grandezze dendrometriche. In: “L’Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio INFC 2005. Secondo inventario forestale nazionale italiano. Metodi e risultati” (Gasparini P, Tabacchi G eds). Ministero delle Politiche Agricole,

- Alimentari e Forestali, Corpo Forestale dello Stato, Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di ricerca per il Monitoraggio e la Pianificazione Forestale. Edagricole-II Sole 24 ore, Bologna, 2011, 81-93.
- Tabacchi G, Di Cosmo L, Gasparini P Aboveground tree volume and phytomass prediction equations for forest species in Italy. *Eur J For Res* 2011, 130, 911-934.
- Teder M, Pilt K, Miljan M, Lainurm M, Kruuda R Overview of some non-destructive methods for in-situ assessment of structural timber. In Proceedings of the 3rd International Conference Civil Engineering, Jelgava, Latvia, 12-13 May 2011.
- Tenorio C, Moya R, Muñoz F Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelina arborea* trees. *J. Wood Sci.* 2011, 57, 134-139.
- Thomas K Man and the natural world. Changing attitudes in England 1500-1800. London: Allen Lane, 1983, 301.
- Tinner W, Conedera M, Gobet E, Hubschmid P, Wehrli M, Ammann BA palaeoecological attempt to classify fire sensitivity of trees in the southern Alps *The Holocene* 2000,10, 565-574.
- Todaro L Influenza delle tecniche colturali sulle qualità del legno di alcune conifere con particolare riferimento alla Douglasia [Influence of silvicultural treatments on wood quality on Douglas-fir trees]. *Monti e Boschi* 2002, 3/4, 3844. (In Italian).
- Todaro L, Macchioni N Wood properties of young Douglas-fir in Southern Italy: Results over a 12-year post-thinning period. *Eur. J. For. Res.* 2011, 130, 251-261.
- Todaro L, Quartulli S, Robusto A, Moretti N Effects of different thinning regimes on stand stability and timber assortments in a Douglas-fir forest. *Ital. For. Mont.* 2002, 5, 451-466.
- Tognetti R, Michelozzi M, Borghetti M The response of European beech (*Fagus sylvatica* L.) seedlings from two Italian populations to drought and recovery. *Trees* 1995, 9, 348-354.

- Torquato LP, Auty D, Herández RE, Duchesne I, Pothier D, Achim A Black spruce trees from fire-origin stands have higher wood mechanical properties than those from older, irregular stands. *Can J For Res* 2014, 44, 118-127.
- Tsehaye A, Buchanan AH, Walker JCF Sorting of logs using acoustics. *Wood Sci. Technol.* 2000, 34, 337-344.
- Tsehaye A, Buchanan AH, Walker JCF Sorting of logs using acoustics. *Wood Sci Technol* 2000, 34, 337-344.
- Turchetti T, Ferretti F, Maresi G, Natural spread of *Cryphonectria parasitica* and persistence of hypovirulence in three Italian coppiced chestnut stands. *Forest Pathology.* 2008, 38, 227-243.
- Urhan OS, Kolpak SE, Jayawickrama KJS, Howe GT Early genetic selection for wood stiffness in juvenile Douglas-fir and western hemlock. *For. Ecol. Manag.* 2014, 320, 104-117.
- Van der Plas F, Manning P, Soliveres S, Allan E, Scherer-Lorenzen M, Verheyen K, Wirth C, Zavala MA, Ampoorter E, Baeten L, Barbaro L, Bauhus J, Benavides R, Benneter A, Bonal D, Bouriaud O, Bruelheide H, Bussotti F, Carnol M, Castagneyroli B, Charbonnier Y, Coomes DA, Coppi A, Bestias CC, Dawud SM, De Wandeler H, Domisch T, Finer L, Gessler A, Granier A, Grossiord C, Guyot V, Hattenschwiler S, Jactel H, Jaroszewicz B, Joly FX, Jucker T, Koricheva J, Milligan H, Mueller S, Muys B, Nguyen D, Pollastrini M, Ratcliffe S, Raulund-Rasmussen K, Selvi F, Stenlid J, Valladares F, Vesterdal L, Zielinski D, Fischer M Biotic homogenization can decrease landscape-scale forest multifunctionality. *Proc Natl Acad Sci USA* 2016, 113, 3557-3562.
- Vanninen P, Ylitalo H, Sievanen R, Makela A Effect of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). *Trees* 1996, 10, 231-238.
- Vargas-Hernandez J, Adams WT Genetic relationships between wood density components and cambial growth rhythm in young coastal Douglas-fir. *Can J For Res* 1994, 24, 1871-1876.
- Vötter D Sustainability Impact Assessment of the Forest-Wood-Supply-Chain based on a Process Modelling Approach - Comparison of Northern and Central Europe as an Example, Albert-Ludwig

- University, Freiburg Davenport TH, Brooks JD (2004) *Journal of Enterprise Information Management* 2009, 17, 8-19.
- Wagner S, Collet C, Madsen P, Nakashizuka T, Nyland R, Sagheb-Talebi K Beech regeneration research: From ecological to silvicultural aspects. *Forest Ecology and Management* 2010, 259, 2171-2182.
- Walker et al. The use of chronosequences in studies of ecological succession and soil development. *Journal of Ecology* 2010, 98, 725-736.
- Wang SY, Lin CJ, Chiu CM, Chen JH, Yang TH Dynamic modulus of elasticity and bending properties of young Taiwania trees grown with different thinning and pruning treatments. *J. Wood Sci.* 2005, 51, 1-6.
- Wang X Acoustic measurements on trees and logs: A review and analysis. *Wood Sci Technol* 2013, 47, 965-975.
- Wang X Advanced sorting technologies for optimal wood products and woody biomass utilization. In *Proceedings of International Conference on Biobase Material Science and Engineering*, Changsha, China, 21-23 October 2012, 175-179.
- Wang X Fundamentals of acoustic measurements on trees and logs and their implication to field application. In *Proceedings of the 17th International Symposium on Non-Destructive Testing and Evaluation of Wood*, University of West-ern Hungary, Sopron, Hungary, 14-16 September, 2011, 25-33.
- Wang X Stress Wave-Based Non-Destructive Evaluation (NDE) Methods for Wood Quality of Standing Trees. Ph.D. Dissertation, Michigan Technological University, Houghton, MI, USA 1999, 187.
- Wang X, Ross RJ Nondestructive Evaluation for Sorting red maple logs. In *Proceedings of the 28th Annual Hardwood Symposium, West Virginia Now—The Future for the Hardwood Industry?;* Edited by Meyer, D.A., Davis, West Virginia 11-13 May, 2000 95-101.



- Wang X, Ross RJ, Carter P Acoustic evaluation of wood quality in standing trees-Part I. Acoustic wave behavior. *Wood Fiber Sci.* 2007, 39, 28-38.
- Wang X, Ross RJ, Green DW, Brashaw B, Englund K, Wolcott M Stress wave sorting of red maple logs for structural quality. *Wood Sci. Technol.* 2004, 37, 531-537.
- Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD Non-destructive evaluation of standing trees with stress wave method. *Wood Fiber Sci.* 2001, 33, 522-533.
- Wang X, Ross RJ, Panches J, Barbour RJ, Forsman JW, Erickson JR Evaluation of small-diameter timber for valued-added manufacturing - A stress wave approach. In *Proceedings of the II International Precision Forestry Symposium; Institute of Forest Resources, University of Washington: Seattle, WA, USA 2003*, 91-96.
- WCED Official record of the General Assembly Forty-second Session, supplements 1987, 25 (A/42/25).
- Wessels CB, Malan FS, Rypstra T A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. *Eur J For Res* 2011, 130, 881-893.
- Wolynski A Evoluzione storica della selvicoltura naturalistica. *Sherwood* 1994, 40, 5-11. Grumbine RE What is ecosystem management? *Conservation Biology.* 1998, 8, 27-39.
- Yachi S, Loreau M Does complementary resource use enhance ecosystem functioning? A model of light competition in plant communities. *Ecol Lett* 2007, 10, 54-62.
- Yanai, Ruth; Currie, William; Goodale, Christine 2003 Soil Carbon Dynamics after Forest Harvest: An Ecosystem Paradigm Reconsidered. *Ecosystems*, 6, 197-212.
- Yang H, Yu L, Wang L Effect of moisture content on the ultrasonic acoustic properties of wood. *J. For. Res.* 2015, 26, 753-757.
- Zaghi D Management of Natura 2000 habitats. 9530 \*Sub-Mediterranean pine forests with endemic black pines. Technical Report 24/24, European Commission 2008.
- Zar JH *Biostatistical Analysis*, fourth ed. Prentice Hall, Upper Saddle River, New Jersey 1999.

- Zeide B Optimal stand density: A solution. *Can. J. For. Res.* 2004, 34, 846-854.
- Zeller L, Ammer Ch, Annighöfer P, Biber P, Marshall J, Schütze G, del Río Gaztelurrutia M, Pretzsch H Tree ring wood density of Scots pine and European beech lower in mixed-species stands compared with monocultures. *Forest Ecol Manage* 2017, 400, 363-374.
- Zhang SY Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. *Wood Sci. Technol.* 1995, 29, 451-465.
- Zhang SY, Chauret G, Ren HQ, Desjardins R Impact of plantation black spruce initial spacing on lumber grade yield, bending properties and MSR yield. *Wood Fiber Sci.* 2002, 34, 460-475.
- Zhang SY, Chauret G, Swift DE, Duchesne I Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. *Can J For* 2006, 36, 945-952.
- Zhang SY, Owoundi RE, Nepveu G, Mothe F, Dhôte JF “Modelling density in European oak (*Quercus petraea* and *Quercus robur*) and simulating silvicultural influence,” *Can. J. For. Res.* 1993, 23, 2587-2593.
- Zhang Y, Chen HYH, Reich PB Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. *J Ecol* 2012, 100, 742-749.
- Zhembo L, Yixing L, Haipeng Y, Junqi Y Measurement of the dynamic modulus of elasticity of wood panels. *Frontiers of Forestry in China* 2006, 1, 425-430.
- Zingg A and Ramp B “Thinning and Stem Quality in Pure and Mixed Beech (*Fagus sylvatica* L.) Stands” Proceedings from the 7th International Beech Symposium IUFRO Research Group 1.10.00 10-20, Tehran, Iran, May 2004, 169 Surmiński J., 1990 “Właściwości techniczne i możliwości zastosowania drewna” Buk zwyczajny *Fagus sylvatica* L. Nasze Drzewa Leśne, PWN Warszawa-Poznań 1990. In Polish.
- Zobel BJ and van Buijten JP *Wood Variation: Its Causes and Control*, Springer Verlag, New York 1989.
- Zobel BJ, van Buijtenen JP *Wood Variation: Its Causes and Control*; Springer: Berlin, Germany, 1989.

- Adamopoulos S, Chavenetidou M, Passialis C, Voulgaridis E “Effect of cambium age and ring width on density and fiber length of black locust and chestnut wood,” Wood Research 2010, 55, 25-36.
- Agnoletti M Bosco ceduo e paesaggio: processi generali e fattori locali. In: Ciancio O, Nocentini S (Eds) Il bosco ceduo in Italia, Firenze: Accademia Italiana di Scienze Forestali 2002, 21-62.
- Agnoletti M Man, forestry, and forest landscapes. Trends and perspectives in the evolution of forestry and woodland history research. Schweizerische Zeitschrift für Forstwesen 2006, 9, 384-392.
- Vos W (1996) Changing forest functions in new Europe: from alienation to involvement. In: Glück P, Weiss G (Eds) Forestry in the context of rural development: future research needs, EFI Proceedings 15, 127-139.
- Aide TM, Zimmerman JK, Pascarella JB, Rivera L, Marcano-Vega H Forest regeneration in a chronosequence of tropical abandoned pastures: Implications for restoration ecology. Restoration Ecology, 2000, 8, 328-338.
- Altieri V, De Franco S, Lombardi F, Marziliano PA, Menguzzato G, Porto P The role of silvicultural systems and forest types in preventing soil erosion processes in mountain forests: a methodological approach using cesium-137 measurements. J of Soils Sedimen 2018, 1-10.
- Amorini E, Manetti MC Le ‘fustaie da legno’ di castagno del Monte Amiata. Ann. Ist. Sper. Selv., Arezzo 1997, 28, 53-61.
- Andrews M Where are we with sonics, in Proceedings of the Wood Technology Research Centre Workshop 2000: Capturing the Benefits of Forestry Research, University of Canterbury, Christchurch, New Zealand, 2000, pp. 57-61.
- Ansen JK, Jorgensen BB, Stoltze P, “Variation of Quality and Predicted Economic Returns between European beech (*Fagus sylvatica* L.) Provenances”, Silvae Genetica 2003, 52, 185-197.
- Aratake S, Arima T Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs. II. Possibility of application for sugi square lumber with pith. Mokuzai Gakkaishi 1994, 40, 1003-1007.

- Augusto L, Ranger J, Binkley D, Rothe A Impact of several tree species of European temperate forests on soil fertility. *Ann For Sci* 2002, 59, 233-253.
- Avanzato D, Following Chestnut Footprints (*Castanea* spp.) – Cultivation and Culture, Folklore and History, Tradition and Uses, 2009, 9 of *Scripta Horticulturae* (International Society for Horticultural Science).
- Aviolo S Il castagno in Italia meridionale (1. parte). *Cellulosa e Carta*, 1987, 3, 12-23.
- Bacher M, Krosek S Bending and tension strength classes in European standards. *Annals of Warsaw University of Life Sciences - SGGW. For Wood Tech* 2014, 88.
- Bagnaresi U, Giannini R La selvicoltura delle faggete: sintesi dello stato dell'arte. In: "Ecologia strutturale e funzionale di faggete italiane" (Scarascia Mugnozza G ed). Edagricole, Bologna, Italy, 1999, 187-199.
- Bailleres H, Hopewell G, Boughton G MOE and MOR assessment technologies for improving graded recovery of exotic pines in Australia. Technical Report PNB0400708, Forest and Wood Products Australia Limited, Melbourne, VIC, Australia, 2009, 85 pp.
- Balvanera P, Pfister AB, Buchmann N, He JS, Nakashizuka T, Raffaelli D, Schmid B Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecol Lett* 2006, 9:1146-1156.
- Barbour RJ, Foyle DC, Chauret G, Cook JA, Karsh MB, Ran S Breast height relative density and radial growth in mature Jack pine (*Pinus banksiana*) for 38 years after thinning. *Can. J. For. Res.* 1994, 24, 2439-2447.
- Battipaglia G, Pelleri F, Lombardi F, Altieri S, Vitone A, Conte E, Tognetti R Effects of associating *Quercus robur* L. and *Alnus cordata* Loisel. on plantation productivity and water use efficiency. *Forest Ecol Manage* 2017, 391, 106-114.
- Bauhus J, Puettmann KJ, Kühne C Close-to-nature forest management in Europe: does it support complexity and adaptability of forest ecosystems. In: Messier C, Puettmann KJ, Coates KD (eds)

- Managing forests as complex adaptive systems: building resilience to the challenge of global change. Routledge, New York 2013, 187-213.
- Bengtsson J, Nilsson SG, Franc A, Menozzi P Biodiversity, disturbances, ecosystem function and management of European forests. For Ecol Manag 2000, 132, 39-50.
- Bielak K, Dudzinska M, Pretzsch H Mixed stands of Scots pine (*Pinus sylvestris* L.) and Norway spruce [*Picea abies* (L.) Karst] can be more productive than monocultures. Evidence from over 100 years of observation of long-term experiments. Forest Syst 2014, 23, 573.
- Binkley D, Dunkin KA, DeBell D, Ryan MG Production and nutrient cycling in mixed plantations of eucalyptus and albizia in Hawaii. For Sci 1992, 38, 393-408.
- Binkley D, Stape JL, Ryan MG Thinking about efficiency of resource use in forests. For Ecol Manage 2004, 193, 5-16.
- Bolte A, Ammer C, Löf M, Madsen P, Nabuurs GJ, Schall P, Spathelf P, Rock J Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. Scand J For Res 2009, 24, 473-482.
- Bolte A, Czajkowski T, Coccozza C, Tognetti R, de Miguel M, Pšidová E, Ditmarová Ľ, Dinca L, Delzon S, Cochard H, Ræbild A, de Luis M, Cvjetkovic B, Heiri C, Müller J Desiccation and mortality dynamics in seedlings of different European beech (*Fagus sylvatica* L.) populations under extreme drought conditions. Front Plant Sci 2016, 7, 751.
- Bonavita S, Vendramin GG, Bernardini V, Avolio S, Regina TMR The first SSR-based assessment of genetic variation and structure among *Pinus laricio* Poiret populations within their native area. Plant Biosyst. 2015, 150, 1-20.
- Bourgoise C Améliorer les taillis de châtaignier [Improve chestnut coppice]. Forêt Entreprise 1987, 44, 8-15. [in French]
- Brang P, Spathelf P, Larsen JB, Bauhus J, Bončina A, Chauvin C, Drössler L, Carlos GarcíaGüemes C, Caroline Heiri C, Kerr G, Lexer MJ, Mason B, Mohren F, Mühlethaler U, Nocentini S, Svoboda

- M Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry* 2014, 87, 492-503.
- Brashaw BK, Bucur V, Divos F, Goncalves R, Lu JX, Meder R, Pellerin RF, Potter S, Ross RJ, Wang XP Non-destructive testing and evaluation of wood: A worldwide research update. *For. Prod. J.* 2009, 59, 7-14.
- Brazier JD, Mobbs ID The influence of planting distance on structural wood yields of unthinned Sitka spruce. *Forestry* 1993, 66, 333-352.
- Briggs DG, Smith WR Effects of Silvicultural Practices on Wood Properties of Conifers: A review. In *Douglas-fir Stand Management for the Future*; Oliver, C., Hanley, D., Johnson, J., Eds.; University of Washington Press: Seattle, WA, USA, 1986; 108-116.
- Briggs DG, Thienel G, Turnblom EC, Lowell E, Dykstra D, Ross R, Wang X, Carter P Influence of thinning on acoustic velocity of douglas-fir trees in western Washington and western Oregon. In *Proceedings of the 15th International Symposium on Non-destructive Testing of Wood*, Duluth, MN, USA, 10-12 September 2007; Forest Products Society: Madison, WI, USA, 2008; 113-123.
- Brissette JC, Frank RM, Stone TL, Skratt TA Precommercial thinning in a northern conifer stand: 18-year results. *For. Chron.* 1999, 75, 967-972.
- Brüchert F, Gardiner B The effect of wind exposure on the tree aerial architecture and biomechanics of Sitka spruce (*Picea sitchensis*, Pinaceae). *American Journal of Botany* 2006, 93, 1512-1521.
- Buckley GP *Ecology and management of coppice woodlands*. Chapman & Hall, London 1992.
- Burkhart HE Development of empirical growth and yield models. In *Proceedings of the Empirical and Process-Based Models for Forest Tree and Stand Growth Simulation, A Workshop/Ph.D. Course Jointly Organized by Technical University of Lisbon and IUFRO 4.01*, Oeiras, Portugal, 21-27 September 1997, 10.
- Bussotti F *Pinus nigra* Arnold. In *Pines of silvicultural importance*. Wallingford: CABI Publishing 2002, 266-286.

- Cameron AD Importance of early selective thinning in the development of long-term stand stability and improved log quality: a review. *Forestry* 2002, 75, 25-35.
- Candel-Pérez D, Lo YH, Blanco J, Chiu CM, Camarero J, González de Andrés E, Imbert J, Castillo F Drought-induced changes in wood density are not prevented by thinning in *Scots pine* stands. *Forests* 2018, 9, 4.
- Cantiani MG, Cantiani P Conversione ad alto fusto di un ceduo “composto” di faggio nell’Appennino toscano. *Cellulosa e Carta* 1994, 45, 36-46.
- Cantiani P, Plutino M, Amorini E Effects of silvicultural treatment on the stability of black pine plantations. *Ann. Silv. Res.* 2010, 36, 49-58.
- Cantiani P, Plutino M, Amorini E Effects of silvicultural treatment on the stability of black pine plantations. *Annals of Silvicultural Research* 2010, 36, 49-58.
- Carter P, Briggs D, Ross RJ, Wang X Acoustic Testing to Enhance Western Forest Values and Meet Customer Wood Quality Needs; Department of Agriculture Forest Service, US Department of Agriculture (USDA): Madison, WI, USA, 2005; 121-129.
- Castera P, Faye C, Ouadrani AEI Prediction of the bending strength of timber with a multivariate statistical approach. *Ann. For. Sci.* 1996, 53, 885-898.
- Chauhan SS, Walker JCF Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. *For. Ecol. Manag.* 2006, 229, 388-394.
- Chiu CM, Lin CH, Yang TH Application of nondestructive methods to evaluate mechanical properties of 32-year-old Taiwan incense cedar (*Calocedrus formosana*) wood. *BioResources* 2012, 8, 688-700.
- Chomel M, DesRochers A, Baldy V, Larchevêque M, Gauquelin T Non-additive effects of mixing hybrid poplar and white spruce on aboveground and soil carbon storage in boreal plantations. *For. Ecol. Manage* 2014, 328, 292-299.
- Ciancio O, Eccher A La gestione dei cedui. *Italia Agricola* (eds) 1983, 120, 64-102.

- Ciancio O, Garfì V, Iovino F, Menguzzato G, Nicolaci A I cedui di castagno in Calabria: caratteristiche culturali, produttività e assortimenti ritraibili. *L'Italia forestale e montana rivista di politica economia e tecnica* 2004, FDC 222: 176.1 *Castanea sativa*: (450.78).
- Ciancio O, Iovino F, Mendicino V, Menguzzato G, Nicolaci A, Nocentini S Structure and management of Aleppo pine forests. *Options Méditerranéennes, series A*, 2008, 75, 61-72.
- Ciancio O, Iovino F, Menguzzato G, Nicolaci A Interventi selvicolturali in cedui di faggio che hanno superato il turno consuetudinario valutazione della biomassa legnosa ritraibile. *L'Italia Forestale e Montana* 2007, 62 (5/6), 339-353.
- Ciancio O, Iovino F, Menguzzato G, Nicolaci A, Nocentini S Structure and growth of a small group selection forest of Calabrian pine in Southern Italy: A hypothesis for continuous cover forestry based on traditional silviculture. *For. Ecol. Manag.* 2006, 224, 229-234.
- Ciancio O, Iovino F, Menguzzato G, Nicolaci A, Nocentini S Structure and growth of a small group selection forest of Calabrian pine in Southern Italy: a hypothesis for continuous cover forestry based on traditional silviculture. *For Ecol Manag* 2006, 224, 229-234.
- Ciancio O, Nocentini S The coppice forest. Silviculture, regulation, management. In: "Il bosco ceduo. Selvicoltura, assestamento, gestione". Accademia Italiana di Scienze Forestali, Firenze, 2004, 679-701.
- Clark A, Daniels RF Modelling the effect of physiographic region on wood properties of planted loblolly pine in southeast United States. In *Proceedings of the Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software, Fourth Workshop IUFRO Working Party S5.01-04*, Harrison Hot Springs, BC, Canada, 8-15 September, 2002, 663.
- Clutter JL, Fortson JC, Pienaar LV, Brister GH, Bailey RL Timber management: a quantitative approach. New York: John Wiley and Sons, Inc.; 1983, 333.
- Cocozza C, de Miguel M, Pšidová E, Ditmarová L, Marino S, Maiuro L, Alvino A, Czajkowski T, Bolte A, Tognetti R Variation in ecophysiological traits and drought tolerance of beech (*Fagus sylvatica* L.) seedlings from different populations. *Front Plant Sci* 2016, 7, 886.



- Coletta V, Menguzzato G, Pellicone G, Veltri A, Marziliano P Effect of thinning on above-ground biomass accumulation in a Douglas-fir plantation in southern Italy. *J. For. Res.* 2016, 27, 1313-1320.
- Condés S, del Río M, Sterba H Mixing effect on volume growth of *Fagus sylvatica* and *Pinus sylvestris* is modulated by stand density. *For Ecol Manage* 2013, 292, 86-95.
- Conedera M, Krebs P, Tinner W, Pradella M, Torriani D The cultivation of *Castanea sativa* (Mill.) in Europe, from its origin to its diffusion on a continental scale. *Veget Hist Archaeobot* 2004, 13,161-179.
- Conedera M, Manetti MC, Giudici F, Amorini E Distribution and economic potential of the Sweet chestnut (*Castanea sativa* Mill.) in Europe. *Ecologia Mediterranea* 2004, 30, 179-193.
- Conedera M, Stanga P, Oester B, Bachmann P Different post-culture dynamics in abandoned chestnut orchards. *For. Snow Landsc. Res.*, 2001, 76, 487-492.
- Conedera M, Tinner W, Krebs P, de Rigo D, Caudullo *Castanea sativa* in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G. (Eds.), *European Atlas of Forest Tree Species* 2016. Publ. Off. EU, Luxembourg (pp. e0125e0+). G. Bounous, ed., *Il castagno* (Edagricole, Bologna, 2014). Edagricole-New Business Media. ISBN: 8850654154. Pagine: XII-420
- Conte E, Lombardi F, Battipaglia G, Palombo C, Altieri S, La Porta N, Marchetti M, Tognetti R Growth dynamics, climate sensitivity and water use efficiency in pure vs. mixed pine and beech stands in Trentino (Italy) *For Ecol Manage* 2018, 409, 707-718.
- Coppini M, Hermanin L Restoration of selective beech coppices: A case study in the Apennines (Italy). *Forest Ecology and Management* 2007, 249: 18-27.
- Coppini M, Hermanin L Restoration of se-lective beech coppices: a case study in the Apen-nines (Italy). *Forest Ecology and Management* 2007, 249, 18-27.
- Cown DJ Comparison of the effects of two thinning regimes on some wood properties of radiata pine. *NZ J. Forest Sci.* 1974, 4, 540-551.

- Cown DJ, McConchie DL Wood property variations in an old-crop stand of radiata pine, N. Z. J. For. Sci. 1980, 10, 508-520.
- Cucchi CC Premesse alla selvicoltura di un acrocoro Appenninico. Italia Forestale e Montana 1990, 45, 29-54.
- Cudlín P, Klopčič M, Tognetti R, Máliš F, Alados CL, Bebi P, Grunewald K, Zhiyanski M, Andonowski V, La Porta N, Bratanova-Doncheva S, Kachaunova E, Edwards-Jonášová M, Ninot J M, Rigling A, Hofgaard A, Hlásny T, Skalák P Frans Emil Wielgolaski Drivers of treeline shift in different European mountains. Clim Res 2017, 73, 135-150.
- De Dios J Gestión para la diversidad forestal: una oportunidad. Jornadas Red Natura en la Comarca del Noroeste. Situación actual y perspectivas de futuro. Caravaca de la Cruz. Murcia, January 2006, 24-26.
- Del Río M, Pretzsch H, Ruíz-Peinado R, Ampoorter E, Annighöfer P, Barbeito I, Bielak K, Brazaitis G, Coll L, Drössler L Species interactions increase the temporal stability of community productivity in *Pinus sylvestris*-*Fagus sylvatica* mixtures across Europe. J Ecol 2017, 105, 1032-1043.
- Del Río MD, Schütze G, Pretzsch H Temporal variation of competition and facilitation in mixed species forests in Central Europe. Plant Biol 2014, 16, 166-176.
- Demers C, Andreu M, McGowan B Thinning Southern Pines-A Key to Greater Returns; Series of the School of Forest Resources and Conservation, SS FOR 24; Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida: Tallahassee, FL, USA 2013, 6.
- Detter A, Cowell C, McKeown L, Howard P Evaluation of current rigging and dismantling practices used in arboriculture. Research Report RR668): Health and Safety Executive (HSE) and Forestry Commission (FC), UK, 2008, 370.
- Dickson RL, Joe B, Harris P, Holtorf S, Wilkinson C Acoustic segregation of Australian-grown *Pinus radiata* logs for structural board production. Aust. For. 2004, 47, 261-266.

- Divos F Acoustic tools for seedling, tree and log selection, in *The Future of Quality Control for Wood and Wood Products*. 2010, Edinburgh, UK, pp. 5-9.
- Divos F Acoustic Tools for Seedling, Tree and Log Selection. In *Proceedings of the Final Conference of COST Action E53 The Future of Quality Control for Wood and Wood Products*, Napier University, Edinburgh, UK, 4-7 May 2010, 5.
- Dobšínská Z, Rathke J, Weber N Synthesis report COST ACTION FP 1207, WG1 Forestrelated policy targets and measures. IUFRO occasional paper 2015, 29.
- Duncker PS, Barreiro SM, Hengeveld GM, Lind T, Mason WL, Ambrozy S, Spiecker H Classification of forest management approaches: A new conceptual framework and its applicability to European forestry. *Ecol. Soc.* 2012, 17, 51.
- Duncker PS, Raulund-Rasmussen K, Gundersen P, Katzensteiner K, De Jong J, Ravn HP, Smith M, Eckmüllner O, Spiecker H How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. *Ecology and Society* 2012, 17, 50.
- Eckard JT, Isik F, Bullock B, Li B, Gumpertz M Selection efficiency for solid wood traits in *Pinus taeda* using time-of-flight acoustic and micro-drill resistance methods. *For. Sci.* 2010, 56, 233-241.
- Ekö PM, Petterson N, Bjerregaard J “Pre-commercial Thinning in European Beech (*Fagus sylvatica* L.). Results from field trial.” *For. & Landsc. Res.* 1995, 1, 207-226.
- Ellenberg H *The vegetation ecology of Europe*. 4<sup>th</sup> Edition, Cambridge University Press, Cambridge, UK 1988, 731.
- Ellenberg H, Leuschner C *Vegetation Mitteleuropas mit den Alpen in ökologischer, dynamischer und historischer Sicht*. Eugen Ulmer, Stuttgart 2010.
- Enescu CM, de Rigo D, Caudullo G, Mauri A, Houston Durrant T *Pinus nigra* in Europe: distribution, habitat, usage and threats. In San-Miguel-Ayanz J, de Rigo D, Caudullo G, Houston Durrant T, Mauri A (Eds) *European atlas of forest tree species*. Publ. Off. EU, Luxembourg, 2016, 126-127.

- Esaro G, Colpi C Conversione a fustaia e “invecchiamento naturale”: il caso di un ceduo di faggio sulle Prealpi venete. In: “Il bosco ceduo in Italia” (Ciancio O, Nocentini S eds). Accademia Italiana di Scienze Forestali, Firenze, 2002, 305-324
- Esteban E, Spinelli R, Aminti G, Laina RL; Vicens I Productivity, Efficiency and Environmental Effects of Whole-Tree Harvesting in Spanish Coppice stands Using a Drive-to-Tree Disc Saw Feller-Buncher. *Croatian Journal of Forest Engineering* 2018, 39, 163-172.
- Everard J, Christie JM Sweet chestnut: Silviculture, timber quality and yield in the Forest of Dean. *Forestry* 1995, 68, 133-144.
- Fabbio G Coppice forests, or the changeable aspect of things, a review. *Annals of Silvicultural Research* 2016, 40, 108-132.
- FAO World Reference Base for Soil Resources; International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106; FAO: Roma, Italy 2014.
- Fioravanti M “Valutazione tecnologica dell’influenza delle pratiche selvicolturali sulla qualità del legno,” in: *Il Legno di Castagno e di Douglasia della Toscana. Qualità del Legno e Selvicoltura, Classificazione e Valori Caratteristici del Legname Strutturale*, Quaderno Arsia 1999, 9/99, 23-37.
- Fioravanti M The influence of juvenile wood and growthrate on the quality of Chestnut (*Castanea sativa* Mill.) wood. International Wood Quality Workshop in Québec City/Canada, August 18-22, 1997. Proceedings-Chapter VIII: Timber Management Toward Wood Quality and End-Product Value, p. VIII/31-VIII/3.
- Ford ED and Newbould PJ Stand structure and dry weight production through the sweet chestnut (*Castanea sativa*) coppice cycle. *Journal ecology* 1970, 58, 275-296.
- Forest Europe Resolution H1, general guidelines for the sustainable forest management of forests in Europe, 16-17 June 1993, Helsinki, Finland. Second Ministerial Conference on the Protection of Forests in Europe, Madrid, Spain.

- Forrester DI The spatial and temporal dynamics of species interactions in mixed-species forests: from pattern to process. *For Ecol Manage* 2014, 312, 282-292.
- Forrester DI, Ammer C, Annighöfer PJ Effects of crown architecture and stand structure on light absorption in mixed and monospecific *Fagus sylvatica* and *Pinus sylvestris* forests along a productivity and climate gradient through Europe. *J Ecol* 2018, 106, 746-760.
- Forrester DI, Lancaster K, Collopy JJ, Warren CR, Tausz M Photosynthetic capacity of *Eucalyptus globulus* is higher when grown in mixture with *Acacia mearnsii*. *Trees* 2012, 26, 1203-1213.
- Gamfeldt L, Snäll T, Bagchi R, Jonsson M, Gustafsson L, Kjellander P, Ruiz-Jaen MC, Fröberg M, Stendahl J, Philipson CD, Mikusiński G, Andersson E, Westerlund B, Andrén H, Moberg F, Moen J, Bengtsson J Higher levels of multiple ecosystem services are found in forests with more tree species. *Nat Commun* 2013, 4,1340.
- Gasparini P, Tabacchi G L'Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio INFC 2005. Secondo inventario forestale nazionale italiano. Metodi e risultati [National Forest and Carbon sink Inventory INFC 2005. Second Italian national forest inventory. Methods and results]. Ministero delle Politiche Agricole, Alimentari e Forestali, Corpo Forestale dello Stato, Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di ricerca per il Monitoraggio e la Pianificazione Forestale, Edagricole- Il Sole 24 ore, Bologna, Italy, 2011, 653. [in Italian].
- Genet A, Auty D, Achim A, Bernier M, Pothier D, Cogliastro A Consequences of faster growth for wood density in northern red oak (*Quercus rubra* Liebl.). *Forestry* 2012, 86, 99-110.
- Gerhards C Effect of knots on stress waves in lumber. Technical Report FPL-384, Forest Service, Forest Products Laboratory, US Department of Agriculture, Madison, WI, 1982, 28 pp.
- Giannini R, Maltoni A, Mariotti B, Paffetti D, Tani A, Travaglini D Valorizzazione della produzione legnosa dei boschi di castagno. *L'Italia Forestale e Montana*, 2014, 69, 307-317.
- Giannini R, Piussi P La conversion destailis en futaie: l'expérience italienne. *Proceed-ings of XVI IUFRO World Congress, Norway*, 1976, 388-396

- Gonçalves R, Pedroso CB, Massak MV, Batista F, Secco CB Technical note: Velocity of ultrasonic waves in live trees and in freshly-felled logs. *Wood Fiber Sci.* 2011, 43, 232-235.
- Gorman TM, Wagner FG, Wu SY Assessment of intensive stress-wave scanning of Douglas-fir trees for predicting lumber modulus of elasticity. In Proceedings of the 13th International Symposium on Nondestructive Testing of Wood, University of California: Richmond, BC, Canada, 19-21 August 2002, 143-148.
- Grabianowski M, Manley B, Walker J Acoustic measurements on standing trees, logs and green lumber. *Wood Sci. Technol.* 2006, 40, 205-216.
- Grabianowski M, Manley B, Walker J Impact of stocking and exposure on outerwood acoustic properties of *Pinus radiata* in Eyrewell Forest. *N. Z. J. For.* 2004, 49, 13-17.
- Grammel R Zusammenhänge zwischen Wachstumsbedingungen und holztechnologischen Eigenschaften der Fichte. *Forst Central* 1990, 109, 119-129.
- Grant CD, Norman MA, Smith MA Fire and silvicultural management of restored bauxite mines in Western Australia. *Restor. Ecol.* 2007, 15, 127-136.
- Griess VC, Acevedo R, Härtl F, Staupendahl K, Knoke T Does mixing tree species enhance stand resistance against natural hazards? A case study for spruce. *For Ecol Manag* 2012, 267, 284-296.
- Griess VC, Knoke T Bioeconomic modelling of mixed Norway spruce – European beech stands. Economic consequences of considering ecological effects. *Eur J For Res* 2013, 132, 511-522.
- Grossiord C, Granier A, Gessler A, Jucker T, Bonal D Does drought influence the relationship between biodiversity and ecosystem functioning in boreal forests? *Ecosystems* 2014, 17, 394-404.
- Guilley É, Hervé JC, Huber F, Nepveu G “Modelling variability of within- ring density components in *Quercus petraea* Liebl. with mixed-effect models and simulating the influence of contrasting silvicultures on wood density,” *Annals of Forest Science* 1999, 56, 449-458.
- Guntekin G, Emiroglu ZG, Yolmaz T Prediction of bending properties for Turkish red pine (*Pinus brutia* Ten.) Lumber using stress wave method. *Bioresources* 2013, 8, 231-237.

- Gunter H, Grote G, Thees O Information technology in supply networks Does it lead to better collaborative planning? *Journal of Enterprise Information Management* 2006, 19, 540-550.
- Haartveit EY, Flate PO Mechanical properties of Norway spruce lumber from monocultures and mixed stand-modelling bending stiffness and strength using stand and tree characteristics. In *Proceedings of the Connection between Silviculture and Wood Quality: Modelling Approach and Simulation Software*, IUFRO WP S5.01-04 Workshop, BC, Canada, 8-15 September 2002, 2002.
- Hanewinkel M, Cullmann D, Schelhaas MJ, Nabuurs GJ, Zimmermann NE Climate change may cause severe loss in economic value of European forestland. *Nat Clim Chang* 2013, 3, 204-207.
- Hausser K, Troeger R Beitrag zur Frage der Massen und Wertleistung gepflanzter Weisstannen und Fichtenbestände auf gleichen Standorten. *Allg Forst- u J-Ztg* 1967, 138, 150-157.
- He Y, Qin L, Li Z, Liang X, Shao M, Tan L Carbon storage capacity of monoculture and mixed-species plantations in subtropical China. *For Ecol Manag* 2013, 295, 193-198.
- Hedde M, Aubert M, Decaëns T, Bureau F, Dynamics of soil carbon in a beechwood chronosequence forest, *Forest Ecology and Management*, 255, 193-202.
- Hédli R, Kopecký M, Komárek J Half a century of succession in a temperate oakwood: from species-rich community to mesic forest. *Diversity and Distributions* 2010, 16, 267-276.
- Heinimann HR “Business process re-engineering – a framework for designing logistics systems for wood procurement”, *Proceedings of the 1st World Symposium on Logistics in the Forest Sector, Supply Chain Management for the Paper and Timber Industries* 2000.
- Heinimann HR “Logistics in timber production – state-of-the-art and perspectives”. *Forstwissenschaftliches Centralblatt* 1999, 118, 24-38.
- Heitz R, Hasenauer H Reconversion of Norway spruce (*Picea abies* (L.) Karst.) stands into mixed forests: effects on soil properties and nutrient fluxes. In: *Proceedings of the International Conference “Forest ecosystem restoration: ecological and economical impacts of restoration processes in secondary coniferous forests”*. Vienna (Austria) 10-12 Apr 2000. Institute of Forest Growth Research, Vienna, Austria 2000, 119-125.

- Hink V Das Wachstum von Fichte und Tanne auf den wichtigsten Standortseinheiten des Einzelwuchsbezirks "Flächenschwarzwald" (Südwestfalen-Lippe). Allgemeine Forst und Jagdzeitung 1972, 143, 80-85.
- Hofmann A Il faggio e le faggete in Italia. MAF CFS, Collana Verde 1991, 81, 140.
- Holmes RL Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull 1983, 43, 69-78.
- Ikeda K, Kino N Quality evaluation of standing trees by a stress-wave propagation method and its application I. Seasonal changes of moisture contents of sugi standing trees and evaluation with stress-wave propagation velocity. Mokuzai Gakkaishi 2000, 46, 181-188.
- Iovino F, Menguzzato G Gestione sostenibile dei boschi in ambiente mediterraneo, 2004. In: Atti del Convegno "Selvicoltura: a che punto siamo?", Vallombrosa (Firenze) 23-24 ottobre 2003. Ed. Fondazione San Giovanni Gualberto-Osservatorio Foreste e Ambiente, pp. 143-151.
- IPCC. Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change (Core Writing Team, Pachauri RK, Meyer LA (eds)), IPCC, Geneva 2014, 151.
- IPCC. Meeting report of the intergovernmental panel on climate change expert meeting on mitigation, sustainability and climate stabilization scenarios. In: IPCC Working Group III Technical Support Unit, eds PRJ Shukla, R Skea, K van Diemen, Ø Calvin, F Christophersen, J Creutzig, et al. London: Imperial College London, 2017.
- IUSS Working Group WRB. World Reference Base for Soil Resources; International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106; FAO: Roma, Italy, 2014.
- Jactel H, Bauhus J, Boberg J, Bonal D, Castagneyrol B, Gardiner B, Gonzalez-Olabarria JR, Koricheva J, Meurisse N, Brockerhoff EG Tree Diversity Drives Forest Stand Resistance to Natural Disturbances. Curr Forestry Rep 2017, 3, 223.



- Jactel H, Nicoll BC, Branco M, Gonzalez-Olabarria JR, Grodzki W, Långström B, Moreira F, Netherer S, Orazio C, Piou D, Santos H, Schelhaas MJ, Tojic K, Vodde F The influences of forest stand management on biotic and abiotic risks of damage. *Ann For Sci* 2009, 66, 701.
- Johansson K “Effect of early competition on wood properties of Norway spruce”, *Acta Universitatis Agriculturae Sueciae, Silvestria* 1997, 19.
- Johnson EA and Miyanishi K Testing the assumptions of chronosequences in succession. *Ecology Letters* 2008, 11, 419-431.
- Jones TG, Emms GW Influence of acoustic velocity, density, and knots on the stiffness grade outturn of radiata pine logs. *Wood Fiber Sci.* 2010, 42, 1-9.
- Jozsa L, Middleton G A Discussion of Wood Quality Attributes and Their Practical Implications; Special Publication No. SP-34; Forintek Canada Corp: Vancouver, BC, Canada, 1994.
- Jucker T, Bouriaud O, Avacaritei D, Coomes DA Stabilizing effects of diversity on aboveground wood production in forest ecosystems: linking patterns and processes. *Ecol Lett* 2014, 17, 1560-1569.
- Kanowski J, Catterall CP, Wardell-Johnson GW Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. *For Ecol Manage* 2005, 208, 359-372.
- Keith CT Defining wood quality: what's important? *Wood Quality Considerations in Tree Improvement Programs*. Workshop Forintek Canada Corp Quebec, Canada 1985, 21-25.
- Kelty MJ Comparative productivity of monocultures and mixed-species stands. In: *The Ecology and Silviculture of Mixed-Species Forests*. Springer, Netherlands, 1992, 125-141.
- Kelty MJ The role of species mixtures in plantation forestry. *For Ecol Manage* 2006, 233, 195-204.
- Kennel R Soziale Stellung, Nachbarschaft und Zuwachs. *Forstwissenschaftliches Centralblatt* 1966, 85, 193-204.
- Kennel R Untersuchungen über die Leistung von Fichte und Buche im Reinund Mischbestand. *Allg Forst u Jagdztg* 1965, 136, 149-161.

- Kint V, Geudens G, Mohren GMJ, Lust N Silvicultural interpretation of natural vegetation dynamics in ageing Scots pine stands for their conversion into mixed broadleaved stands. *Forest Ecology and Management* 2006, 223, 363-370.
- Klang F, "The influence of Silvicultural Practices on Tree Properties in Norway spruce". Doctoral thesis Swedish University of Agricultural Sciences, Alnarp 2000.
- Kliger IR, Johansson G, Perstorper M, Engström D Formulation of requirements for the quality of wood properties used by the construction industry. Chalmers Univ. Technol., Göteborg, Sweden 1994.
- Kneifl MM, Kadavý J, Knott R, Adamec Z, Drápela K An inventory of tree and stand growth empirical modelling approaches with potential application in coppice forestry (A review). *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 2015, 63, 1789-1801.
- Koricheva J, Meurisse N, Brockerhoff EG Tree diversity drives forest stand resistance to natural disturbances. *Curr For Rep* 2017, 3, 223-243.
- Krajnc L, Farrelly N, Harte AM The effect of thinning on mechanical properties of Douglas fir, Norway Spruce, and Sitka Spruce. *Ann. For. Sci.* 2019, 76, 3.
- Kramer H, *Waldwachstumslehre (Forest growth and yield science) (In German)* Paul Parey. Hamburg, Berlin, 1988, 374.
- Krauss A Kúdela J Ultrasonic wave propagation and Young's modulus of elasticity along the grain of Scots pine wood (*Pinus Sylvestris* L.) varying with distance from the pith. *Wood Res.* 2001, 56, 479-488.
- Kuglin FA *Customer-centered supply chain management: a link-by-link guide*, 1998. AMACOM, American Management Association, New York. Paletto, 2008
- Lancho JFG, Gonzalez MI Carbon sequestration in a Spanish chestnut coppice. In: *Proceedings of the Third International Chestnut* (Ed.: Abreu C.G., Rosa, E., Monteiro, A.A.). *Acta Horticulturae* 2005, 693, 201-207.

- Lanuv (Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen), 2007. Niederwälder in Nordrhein-Westfalen. Galunder-Verlag, Nümbrecht-Elsenroth.
- Larocque GR, Marshall P Wood relative density development in red pine (*Pinus resinosa* Ait.) stands as affected by different initial spacings. For Sci 1995, 41, 709-728.
- Larsen JB (1995) Ecological stability of forest and sustainable silviculture. For Ecol Manag 73, 85-96.
- Lasserre JP, Mason E, Watt M The influence of initial stocking on corewood stiffness in a clonal experiment of 11 year-old *Pinus radiata* D. Don. N. Z. J. For. 2004, 18-23.
- Lasserre JP, Mason EG, Watt MS Assessing corewood acoustic velocity and modulus of elasticity with two impact based instruments in 11-year-old trees from a clonal-spacing experiment of *Pinus radiata* D. Don. For. Ecol. Manag. 2007, 239, 217-221.
- Lauteri M, Monteverdi M, Scarascia-Mugnozza G Preservation of chestnut (*Castanea sativa* Mill.) genetic resources and adaptive potential in relation to environmental changes. In: Proceeding of the “1<sup>st</sup> European Congress on Chestnut” (Bounous G, Becarro G eds). ISHS Acta Horticulturae 2009, 866, 677-682.
- Le Master DC, Schmithüsen F The continuing evolution in social, economic, and political values relating to forestry in the United States and in Europe. In: “Working toward Common Goals in Sustainable Forest Management: The Divergence and Re-convergence of European and American Forestry”, Pinchot Institute for Conservation, Washington D.C. 2006.
- Lebourgeois F, Gomez N, Pinto P, Mérian P Mixed stands reduce *Abies alba* tree-ring sensitivity to summer drought in the Vosges mountains, western Europe. For Ecol Manage 2013, 303, 61-71.
- Legg M, Bradley S Measurement of stiffness of standing trees and felled logs using acoustics: A review. J. Acoust. Soc. Am. 2016, 139, 588-604.
- Lei YC, Zhang SY, Jiang Z Models for predicting lumber bending MOR and MOE based on tree and stand characteristics in black spruce. Wood Sci. Technol. 2005, 39, 37-47.

- Leonardi S, Rapp M, Failla M, Guarnaccia D Biomass, productivity and organic matter fluxes in *Castanea sativa* Mill stands of various elevation in the Etna. *Annales Des Sciences Forestieres* 1996, 53, 1031-1048.
- Liang J, Crowther TW, Picard N, Wiser S, Zhou M, Alberti G, Schulze ED, McGuire AD, Bozzato F, Pretzsch H, de-Miguel S, Paquette A, Hérault B, Scherer-Lorenzen M, Barrett CB, Glick HB, Hengeveld GM, Nabuurs GJ, Pfautsch S, Viana H, Vibrans AC, Ammer C, Schall P, Verbyla D, Tchebakova N, Fischer M, Watson JV, Chen HYH, Lei X, Schelhaas MJ, Lu H, Gianelle D, Parfenova EI, Salas C, Lee E, Lee B, Kim HS, Bruelheide H, Coomes DA, Piotta D, Sunderland T, Schmid B, Gourlet-Fleury S, Sonké B, Tavani R, Zhu J, Brandl S, Vayreda J, Kitahara F, Searle EB, Neldner VJ, Ngugi MR, Baraloto C, Frizzera L, Balazy R, Oleksyn J, Zawila-Niedzwiecki T, Bouriaud O, Bussotti F, Finér L, Jaroszewicz B, Jucker T, Valladares F, Jagodzinski AM, Peri PL, Gonmadje C, Marthy W, O'Brien T, Martin EH, Marshall A, Rovero F, Bitariho R, Niklaus PA, Alvarez-Loayza P, Chamuya N, Valencia R, Mortier F, Wortel V, Engone-Obiang NL, Ferreira LV, Odeke DE, Vasquez RM, Reich PB Positive biodiversity–productivity relationship predominant in global forests. *Science* 2016, 354, 196.
- Liu CLC, Kuchma O, Krutovsky KV Mixed species versus monocultures in plantation forestry: development, benefits, ecosystem services and perspectives for the future. *Global Ecol Conserv* 2018, 15, e00419.
- Lombardi F, Lasserre B, Chirici G, Tognetti R, Marchetti M Deadwood occurrence and forest structure as indicators of old-growth forest conditions in Mediterranean mountainous ecosystems, *Écoscience*, 2012, 19:4, 344-355.
- Macdonald H, Hubert J A review of the effect of silviculture on timber quality of Sitka spruce. *Forestry* 2002, 2, 107-138.
- Machado JS, Louzada JL, Santos AJA, Nunes L, Anjos O, Rodrigues J, Simoes RMS, Pereira H Variation of wood density and mechanical properties of blackwood (*Acacia melanoxylon* r. Br.). *Mater Des* 2014, 56, 975-980.

- Magin R Ertragskundliche Untersuchungen in montanen Mischwäldern. Forstwissenschaftliches Centralblatt 1954, 73, 103-113.
- Malcolm DC, Mason WL, Clarke GC The transformation of conifer forests in Britain - regeneration, gap size and silvicultural systems. Forest Ecology and Management 2001, 151, 7- 23.
- Manetti MC, Amorini E, Becagli C New silvicultural models to improve functionality of chestnut stands. Advances in Horticultural Science 2006, 1, 65-69.
- Manetti MC, Amorini E, Becagli C, Pelleri F, Pividori M, Schleppe P, Zingg A, Conedera M Quality wood production from chestnut (*Castanea sativa* Mill.) coppice forests - Comparison between different silvicultural approaches. In: Proceeding of the "1<sup>st</sup> European Congress on Chestnut" (Bounous G, Becarro G eds). ISHSActa Horticulturae 2009, 866, 683-692.
- Manetti MC, Becagli C, Sansone D, Pelleri F Tree-oriented silviculture: a new approach for coppice stands. iForest (early view) 2016, 9, 791-800.
- Marziliano PA, Tognetti R, Lombardi F Is tree age or tree size reducing height increment in *Abies alba* Mill. at its southernmost distribution limit?. Ann. For. Sci. 2019, 76.
- Marziliano PA, Coletta V, Menguzzato G, Nicolaci A, Pellicone G, Veltri A Effects of planting density on the distribution of biomass in a douglas-fir plantation in southern Italy. iForest 2015, 8, 368-376.
- Marziliano PA, Laforteza R, Colangelo G, Davies C, Sanesi G Structural diversity and height growth models in urban forest plantations: A case-study in northern Italy. Urban Forestry and Urban Greening, 2013, 12, 246-254.
- Marziliano PA, Laforteza R, Medicamento U, Lorusso L, Giannico V, Colangelo C, Sanesi G Estimating belowground biomass and root/shoot ratio of *Phillyrea latifolia* L. in the Mediterranean forest landscapes. Ann. For. Sci. 2015, 72, 585-593.
- Marziliano PA, Menguzzato G, Scuderi A, Corona P Simplified methods to inventory the current annual increment of forest standing volume. iForest 2012, 5, 276-282.

- Marziliano PA, Menguzzato G, Scuderi A, Scalise C, Coletta V Biomass conversion and expansion factors in Douglas-fir stands of different planting density: Variation according to individual growth and prediction equations. *For. Syst.* 2017, 26, e003.
- Matheson A, Gapare W, Ilic J, Wu H Inheritance and genetic gain in wood stiffness in radiata pine assessed acoustically in young standing trees. *Silvae Genet.* 2008, 57, 56-64
- MATT Ministero dell’Ambiente e della Tutela del Territorio (Italy). Manuale per la gestione dei siti Natura 2000. Direzione Protezione della Natura 2004.
- Merlin M, Perot T, Perret S, Korboulewsky N, Vallet P Effects of stand composition and tree size on resistance and resilience to drought in sessile oak and Scots pine. *For Ecol Manage* 2015, 339, 22-33.
- Mettin C Betriebswirtschaftliche und ökologische Zusammenhänge zwischen Standortskraft und Leistung in Fichtenreinbeständen und Fichten Buchen-Mischbeständen. *Allg Forst- u J-Ztg* 1985, 40, 830-810.
- Metz J, Annighöfer P, Schall P, Zimmermann J, Kahl T, Schulze ED, Ammer C Site-adapted admixed tree species reduce drought susceptibility of mature European beech. *Glob Chang Biol* 2016, 22, 903-920.
- Metz JÔ, Seidel D, Schall P, Scheffer D, Schulze ED, Ammer C Crown modeling by terrestrial laser scanning as an approach to assess the effect of aboveground intra- and interspecific competition on tree growth. *For Ecol Manage* 2013, 310, 275-288.
- Mitchell HL A concept of intrinsic wood quality and nondestructive methods for determining quality in standing timber. Report No. 2233, For. Prod. Lab., Madison, Wisconsin 1961.
- Mitchell SJ Stem growth responses in Douglas-fir and Sitka spruce following thinning, implications for assessing wind-firmness. *For. Ecol. Manag.* 2000, 135, 105-114.
- Mitscherlich G Ertragskundlich-ökologische Untersuchungen im Rein-und Mischbestand. *Mitteilungen der Forstlichen Bundes-Versuchsanstalt* 1967, 77, 9-35.

- Mochan S, Moore J, Conolly T Using Acoustics Tools in Forestry and the Wood Supply Chain; Forestry Commission Technical Note 18; Forestry Commission: Edinburgh, UK 2009.
- Moore JR, Cown DJ, McKinley RB, Sabatia CO Effects of stand density and seedlot on three wood properties of young radiata pine grown at a dry-land site in New Zealand. NZ J For Sci 2015, 45, 209.
- Mora CR, Schimleck LR, Isik F, Mahon JM, Clark A, Daniels RF Relationship between acoustic variables and different measures of stiffness in standing *Pinus taeda* trees. Can. J. For. Res. 2009, 39, 1421-1429.
- Morin X, Fahse L, Scherer-Lorenzen M, Bugmann H Tree species richness promotes productivity in temperate forests through strong complementarity between species. Ecol Lett 2011, 14, 1211-219.
- Moscatelli M, Pettenella D, Spinelli R Produttività e costi della lavorazione meccanizzata dei cedui di Castagno in ambiente appenninico. Forest@ 2007, 4, 51-62.
- Nakamura N Measurement of the properties of standing trees with ultrasonics and mapping of the properties. Univ. For. Res. 1996, 96, 125-135.
- Naso I Una fonte scritta per la storia forestale nel Medioevo: gli statuti delle comunità piemontesi e la salvaguardia dei boschi. In Andreoli B, Montanari M (eds) Il bosco nel medioevo. Bologna: Editrice CLUEB, 1988, 149-158.
- Nicolaci A, Travaglini D, Menguzzato G, Nocentini S, Veltri A, Iovino F Ecological and anthropogenic drivers of Calabrian pine (*Pinus nigra* J.F. Arn. ssp. *Laricio* (Poiret) Maire) distribution in the Sila mountain range. iForest 2014, 8, 497-508.
- Nocentini S Structure and management of beech (*Fagus sylvatica* L.) forests in Italy. iForest 2009, 2, 105-113.
- Ostaff DP, Piene H, Quiring DT, Moreau G, Farrell JCG, Scarr T Influence of pre-commercial thinning on balsam fir defoliation by the balsam fir sawfly. For. Ecol. Manag. 2006, 223, 342-348.

- Palmer DJ, Kimberley MO, Cown DJ, McKinley RB Assessing prediction accuracy in a regression kriging surface of *Pinus radiata* outerwood density across New Zealand. *For. Ecol. Manage.* 2013, 308, 9-16.
- Paquette A, Messier C The effect of biodiversity on tree productivity: from temperate to boreal forests. *Glob Ecol Biogeogr* 2011, 20, 170-180.
- Pastorella F, Giacobelli G, Maesano M, Paletto A, Vivona S, Veltri A, Pellicone G, Mugnozza GS Social perception of forest multifunctionality in southern Italy: The case of Calabria Region. *Journal of Forest Science* 2016, 62, 366-79.
- Patricio MS, Monteiro ML, Nunes LF, Mesquita S, Beito S, Casado J, Guerra H Management models evaluation of a *Castanea sativa* coppice in the northeast of Portugal. In: *Proceedings of the Third International Chestnut* (Ed.: Abreu C.G., Rosa, E., Monteiro, A.A.). *Acta Horticulturae* 2005, 693, 721-725.
- Pavari A. Le classificazioni fitoclimatiche ed i caratteri della stazione [Phytoclimatic classifications and station characteristics]. *Scritti di Ecologia Selvicoltura e Botanica Forestale* 1959, 45-116. (In Italian).
- Pawson SM, Brockerhoff EG, Didham RK Native forest generalists dominate carabid assemblages along a stand-age chronosequence in an exotic *Pinus radiata* plantation. *Forest Ecology and Management*, 2009, 258S, S108-S116.
- Peltola H, Kilpeläinen A, Sauvala K, Räsänen T, Ikonen VP Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. *Silva Fenn.* 2007, 41, 489-505.
- Peters R *Beech forests*. Kluwer, Dordrecht, The Netherlands, *Geobotany* 1997, 24, 169.
- Petit B, Montagnini F Growth in pure and mixed plantations of tree species used in reforesting rural areas of the humid region of Costa Rica, Central America. *For Ecol Manage* 2006, 233, 338-343.
- Petráš R, Mecko J, Bošelâ M, Šebeň V Wood quality and value production in mixed fir-spruce-beech stands: Long-term research in the Western Carpathians. *Lesn Cas For J* 2016, 62, 98-104.



- Pickett STA Space-for-time substitutions as an alternative to longterm studies. In: Longterm Studies in Ecology [Likens GE (ed.)]. Springer, New York, USA 1989.
- Piermattei A, Renzaglia F, Urbinati C Recent expansion of *Pinus nigra* Arn. above the timberline in the central Apennines, Italy. *Annals of Forest Science* 2012, 69, 509-517.
- Piotto D A meta-analysis comparing tree growth in monocultures and mixed plantations. *Forest Ecol Manage* 2008, 255, 781-786.
- Pretzsch H Forest dynamics, growth and yield. From measurement to model. Springer, Berlin, 2010.
- Pretzsch H Species-specific allometric scaling under selfthinning. Evidence from long-term plots in forest stands. *Oecologia* 2006, 146, 572-583.
- Pretzsch H The Effect of Tree Crown Allometry on Community Dynamics in Mixed-Species Stands versus Monocultures. A Review and Perspectives for Modeling and Silvicultural Regulation. *Forests* 2019, 10, 810.
- Pretzsch H, Biber P A re-evaluation of Reineke's rule and stand density index. *For Sci* 2005, 51, 304-320.
- Pretzsch H, Bielak K, Block J, Bruchwald A, Dieler J, Ehrhart HP, Kohnle U, Nagel J, Spellmann H, Zasada M, Zingg A Productivity of mixed versus pure stands of oak (*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L.) and European beech (*Fagus sylvatica* L.) along an ecological gradient. *Eur J For Res* 2013, 132, 263-280.
- Pretzsch H, Bielak K, Bruchwald A, Dieler J, Dudzinska M, Erhart HP, Jensen AM, Johannsen VK, Kohnle U, Nagel J, Spellmann H, Zasada M, Zingg A Mischung und Produktivität von Waldbeständen. Ergebnisse langfristiger ertragskundlicher Versuche. *Allg Forst- u J-Ztg* 2013, 184, 177-196.
- Pretzsch H, Block J, Dieler J, Dong PH, Kohnle U, Nagel J, Comparison between the productivity of pure and mixed stands of Norway spruce and European beech along an ecological gradient. *Ann For Sci* 2010, 67, 712.

- Pretzsch H, Forrester DI Stand dynamics of mixed-species stands compared with monocultures, In: Pretzsch H, Forrester DI, Baushus J (eds) Mixed-species forests. Ecology and management 2017, 653.
- Pretzsch H, Rais A Wood quality in complex forests versus even-aged monocultures: review and perspectives. Wood Sci Technol 2016, 50, 845-880.
- Pretzsch H, Schütze G Effect of tree species mixing on the size structure, density, and yield of forest stands. Eur J For Res 2016, 135, 1-22.
- Pretzsch H, Schütze G Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: evidence on stand level and explanation on individual tree level. Eur J Forest Res 2009, 128, 183-204.
- Pretzsch H, Schütze G, Uhl E Resistance of European tree species to drought stress in mixed versus pure forests: evidence of stress release by inter-specific facilitation. Plant Biol 2013, 15, 483-495.
- Proto AR, Macri G, Bernardini V, Russo D, Zimbalatti G Acoustic evaluation of wood quality with a non-destructive method in standing trees: A first survey in Italy. iForest 2017, 10, 700-706.
- Puettmann KJ, Messier C, Coates KD Managing forests as complex adaptive systems. Introductory concept and application. In: Messier C, Puettmann KJ, Coates KD (eds) Managing forests as complex adaptive systems: building resilience to the challenge of global change. Routledge, New York 2013, 3-16.
- R Core Team R: A Language and Environment for Statistical Computing R Foundation for Statistical Computing. Vienna; 2016.
- Rackham O Trees and woodland in the British landscape. Revised edition. London, Dent 1980.
- Richards AE, Forrester DI, Bauhus J, Scherer-Lorenzen M The influence of mixed tree plantations on the nutrition of individual species: a review. Tree Physiol 2010, 30, 1192-1208.
- Roces-Díaz JV, Díaz-Varela ER, Barrio-Anta M, Álvarez-Álvarez P Sweet chestnut agroforestry systems in North-western Spain: classification, spatial distribution and an ecosystem services assessment. Forest Systems, 2018, 27, e03S.

- Romagnoli M, Cavalli D, Spina S Wood Quality of Chestnut: Relationship between Ring Width, Specific Gravity, and Physical and Mechanical Properties. *BioResources* 2014, 9, 1132-1147.
- Ross RJ, McDonald KA, Green DW, Schad KC Relationship between log and lumber modulus of elasticity. *For. Prod. J.* 1997, 47, 89-92.
- Rozenberg P, Franc A, Bastien C, Cahalan C Improving models of wood density by including genetic effects: A case study in Douglas-fir. *Ann. For. Sci.* 2001, 58, 385-394.
- Rubio A, Sánchez O, Gómez V, Graña D, Elena R, Blanco A Autoecología de los castañares de Castilla (España) (Autoecology of chestnut tree forest in Castilla, Spain) *Investigación Agraria: Sistemas de Recursos Forestales* 2002, 11, 373-393.
- Russo D, Marziliano PA, Macri G, Proto AR, Zimbalatti G, Lombardi F Does thinning intensity affect wood quality? An analysis of Calabrian Pine in Southern Italy using a non-destructive acoustic method. *Forests* 2019, 30, 1-16.
- Rydberg D Initial sprouting, growth and mortality of European aspen and birch after selective coppicing in central Sweden. *Forest ecology management* 2000, 130, 27-35.
- Saha S, Kuehne C, Kohnle U, Brang P, Ehring A, Geisel J, Leder B, Muth M, Petersen R, Peter J, Ruhm W, Bauhus J Growth and quality of young oaks (*Quercus robur* and *Quercus petraea*) grown in cluster plantings in central Europe: a weighted meta-analysis. *For Ecol Manage* 2012, 283, 106-118.
- Salisbury EJ, Downs, Dunes: Their Plant Life and Environment. G. Bell and Sons Ltd., London, UK 1952.
- Sandoz JL Non-destructive testing of wood. In *Proceedings of the 10th International Symposium on NDT*, Presses Polytechniques et Universitaire Romandes, Lausanne, Switzerland, 26-27 August 1996.
- Sanesi G, Laforteza R, Colangelo G, Marziliano PA, Davies C Root system investigation in sclerophyllous vegetation: An overview. *Ital. J. Agron.* 2013, 8, 121-126.

- Saranpää P Wood density and growth. In: Barnett, J.R.; Jeronimidis, G. (eds), Wood Quality and Its Biological Basis Blackwell, Published in the USA/Canada by CRC Press, Oxford, Boca Raton, FL, Biological Sciences Series, 2003, 87-113.
- Scarascia-Mugnozza G, Oswald H, Piussi P, Radoglou K Forests of the Mediterranean region: gaps in knowledge and research needs, Forest Ecology and Management, 2000, 132, 97-109.
- Scherzinger Naturschutz im Wald Qualitätsziele einer dynamischen Waldentwicklung. Ulmer, Stuttgart W1996.
- Schütt P, et al. Enzyklopädie der Laubbäume: Die große Enzyklopädie. Nikol, Hamburg, 2006.
- Schweingruber HS Tree Rings: Basic and Applications of Dendrochronology; Kluwer: Dordrecht, The Netherland, 1998.
- Searles G Acoustic segregation and structural timber production. Ph.D. thesis, Edinburgh Napier University, Edinburgh, UK, 2012, 218 pp.
- SFM Madrid ministerial declaration, 25 years together promoting sustainable forest management in Europe, 7th Forest Europe Ministerial conference, Madrid 20–21 October 2015.
- Sharma SK, Rao RV, Shukla SR, Kumar P, Sudheendra R, Sujatha M, Dubey YM Wood quality of coppiced *Eucalyptus tereticornis* for value addition. IAWA Journal 2005, 26: 137-147.
- Škorpič P, Konrad H, Geburek T, Schuh M, Vasold D, Eberhardt M, Schuler S Solid wood properties assessed by non-destructive measurements of standing European larch (*Larix decidua* Mill.): Environmental effects on variation within and among trees and forest stands. Forests 2018, 9, 276.
- Skov KR, Kolb TE, Wallin KF Tree size and drought affect ponderosa pine physiological response to thinning and burning treatments. J. Forensic. Sci. 2004, 50, 81-91.
- Spinelli R, Magagnotti N, Schweier J Trends and Perspectives in Coppice Harvesting. Croatian journal forestry engineer 2017, 2, 219-230.
- Štefančík I, Vacek Z, Sharma RP, Vacek S, Rösslová M Effect of thinning regimes on growth and development of crop trees in *Fagus sylvatica* stands of Central Europe over fifty years. Dendrobiology 2018, 79, 141-155.

- Swanson FJ, Franklin JF New forestry principles from ecosystem analysis of Pacific Northwest forest. *Ecol Applic* 1992, 2, 262-274.
- Tabacchi G, Di Cosmo L Stima delle grandezze dendrometriche. In: “L’Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio INFC 2005. Secondo inventario forestale nazionale italiano. Metodi e risultati” (Gasparini P, Tabacchi G eds). Ministero delle Politiche Agricole, Alimentari e Forestali, Corpo Forestale dello Stato, Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Unità di ricerca per il Monitoraggio e la Pianificazione Forestale. Edagricole-II Sole 24 ore, Bologna, 2011, 81-93.
- Tabacchi G, Di Cosmo L, Gasparini P Aboveground tree volume and phytomass prediction equations for forest species in Italy. *Eur J For Res* 2011, 130, 911-934.
- Teder M, Pilt K, Miljan M, Lainurm M, Kruuda R Overview of some non-destructive methods for in-situ assessment of structural timber. In Proceedings of the 3rd International Conference Civil Engineering, Jelgava, Latvia, 12-13 May 2011.
- Tenorio C, Moya R, Muñoz F Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelina arborea* trees. *J. Wood Sci.* 2011, 57, 134-139.
- Thomas K Man and the natural world. Changing attitudes in England 1500-1800. London: Allen Lane, 1983, 301.
- Tinner W, Conedera M, Gobet E, Hubschmid P, Wehrli M, Ammann BA palaeoecological attempt to classify fire sensitivity of trees in the southern Alps *The Holocene* 2000,10, 565-574.
- Todaro L Influenza delle tecniche colturali sulle qualità del legno di alcune conifere con particolare riferimento alla Douglasia [Influence of silvicultural treatments on wood quality on Douglas-fir trees]. *Monti e Boschi* 2002, 3/4, 3844. (In Italian).
- Todaro L, Macchioni N Wood properties of young Douglas-fir in Southern Italy: Results over a 12-year post-thinning period. *Eur. J. For. Res.* 2011, 130, 251-261.

- Todaro L, Quartulli S, Robusto A, Moretti N Effects of different thinning regimes on stand stability and timber assortments in a Douglas-fir forest. *Ital. For. Mont.* 2002, 5, 451-466.
- Tognetti R, Michelozzi M, Borghetti M The response of European beech (*Fagus sylvatica* L.) seedlings from two Italian populations to drought and recovery. *Trees* 1995, 9, 348-354.
- Torquato LP, Auty D, Herández RE, Duchesne I, Pothier D, Achim A Black spruce trees from fire-origin stands have higher wood mechanical properties than those from older, irregular stands. *Can J For Res* 2014, 44, 118-127.
- Tsehaye A, Buchanan AH, Walker JCF Sorting of logs using acoustics. *Wood Sci. Technol.* 2000, 34, 337-344.
- Turchetti T, Ferretti F, Maresi G, Natural spread of *Cryphonectria parasitica* and persistence of hypovirulence in three Italian coppiced chestnut stands. *Forest Pathology.* 2008, 38, 227-243.
- Urhan OS, Kolpak SE, Jayawickrama KJS, Howe GT Early genetic selection for wood stiffness in juvenile Douglas-fir and western hemlock. *For. Ecol. Manag.* 2014, 320, 104-117.
- Van der Plas F, Manning P, Soliveres S, Allan E, Scherer-Lorenzen M, Verheyen K, Wirth C, Zavala MA, Ampoorter E, Baeten L, Barbaro L, Bauhus J, Benavides R, Benneter A, Bonal D, Bouriaud O, Bruelheide H, Bussotti F, Carnol M, Castagneyroli B, Charbonnier Y, Coomes DA, Coppi A, Bestias CC, Dawud SM, De Wandeler H, Domisch T, Finer L, Gessler A, Granier A, Grossiord C, Guyot V, Hattenschwiler S, Jactel H, Jaroszewicz B, Joly FX, Jucker T, Koricheva J, Milligan H, Mueller S, Muys B, Nguyen D, Pollastrini M, Ratcliffe S, Raulund-Rasmussen K, Selvi F, Stenlid J, Valladares F, Vesterdal L, Zielinski D, Fischer M Biotic homogenization can decrease landscape-scale forest multifunctionality. *Proc Natl Acad Sci USA* 2016, 113, 3557-3562.
- Vanninen P, Ylitalo H, Sievanen R, Makela A Effect of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). *Trees* 1996, 10, 231-238.
- Vargas-Hernandez J, Adams WT Genetic relationships between wood density components and cambial growth rhythm in young coastal Douglas-fir. *Can J For Res* 1994, 24, 1871-1876.

- Vötter D Sustainability Impact Assessment of the Forest-Wood-Supply-Chain based on a Process Modelling Approach - Comparison of Northern and Central Europe as an Example, Albert-Ludwig University, Freiburg Davenport TH, Brooks JD (2004) Journal of Enterprise Information Management 2009, 17, 8-19.
- Waghorn MJ, Mason EG, Watt MS Influence of initial stand density and genotype on longitudinal variation in modulus of elasticity for 17-year-old *Pinus radiata*. For. Ecol. Manage. 2007, 252, 67-72.
- Wagner S, Collet C, Madsen P, Nakashizuka T, Nyland R, Sagheb-Talebi K Beech regeneration research: From ecological to silvicultural aspects. Forest Ecology and Management 2010, 259, 2171-2182.
- Walker et al. The use of chronosequences in studies of ecological succession and soil development. Journal of Ecology 2010, 98, 725-736.
- Wang SY, Lin CJ, Chiu CM, Chen JH, Yang TH Dynamic modulus of elasticity and bending properties of young Taiwania trees grown with different thinning and pruning treatments. J. Wood Sci. 2005, 51, 1-6.
- Wang X Acoustic measurements on trees and logs: A review and analysis. Wood Sci Technol 2013, 47, 965-975.
- Wang X Advanced sorting technologies for optimal wood products and woody biomass utilization. In Proceedings of International Conference on Biobase Material Science and Engineering, Changsha, China, 21-23 October 2012, 175-179.
- Wang X Fundamentals of acoustic measurements on trees and logs and their implication to field application. In Proceedings of the 17th International Symposium on Non-Destructive Testing and Evaluation of Wood, University of West-ern Hungary, Sopron, Hungary, 14-16 September, 2011, 25-33.

- Wang X Stress Wave-Based Non-Destructive Evaluation (NDE) Methods for Wood Quality of Standing Trees. Ph.D. Dissertation, Michigan Technological University, Houghton, MI, USA 1999, 187.
- Wang X, Ross RJ Nondestructive Evaluation for Sorting red maple logs. In Proceedings of the 28th Annual Hardwood Symposium, West Virginia Now—The Future for the Hardwood Industry?; Edited by Meyer, D.A., Davis, West Virginia 11-13 May, 2000 95-101.
- Wang X, Ross RJ, Carter P Acoustic evaluation of wood quality in standing trees-Part I. Acoustic wave behavior. *Wood Fiber Sci.* 2007, 39, 28-38.
- Wang X, Ross RJ, Green DW, Brashaw B, Englund K, Wolcott M Stress wave sorting of red maple logs for structural quality. *Wood Sci. Technol.* 2004, 37, 531-537.
- Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD Non-destructive evaluation of standing trees with stress wave method. *Wood Fiber Sci.* 2001, 33, 522-533.
- Wang X, Ross RJ, Panches J, Barbour RJ, Forsman JW, Erickson JR Evaluation of small-diameter timber for valued-added manu-facturing - A stress wave approach. In Proceedings of the II International Precision Forestry Symposium; Institute of Forest Resources, University of Washington: Seattle, WA, USA 2003, 91-96.
- Watson L Evaluating the effects of initial stocking, physiological age and species on wood stiffness. Bachelor thesis, School of Forestry, University of Canterbury, Christchurch, New Zealand, 2013, 42 pp.
- Watt MS, Clinton PW, Coker G, Davis MR, Simcock R, Parfitt RL, Dando J Modelling the influence of environment and stand characteristics on basic density and modulus of elasticity for young *Pinus radiata* and *Cupressus lusitanica*. *For. Ecol. Manage.* 2008, 255, 1023-1033.
- WCED Official record of the General Asssembly Forty-second Sessio, supplements 1987, 25 (A/42/25).



- Wessels CB, Malan FS, Rypstra T A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. *Eur J For Res* 2011, 130, 881-893.
- Wolynski A Evoluzione storica della selvicoltura naturalistica. *Sherwood* 1994, 40, 5-11. Grumbine RE What is ecosystem management? *Conservation Biology*. 1998, 8, 27-39.
- Yachi S, Loreau M Does complementary resource use enhance ecosystem functioning? A model of light competition in plant communities. *Ecol Lett* 2007, 10, 54-62.
- Yanai, Ruth; Currie, William; Goodale, Christine 2003 Soil Carbon Dynamics after Forest Harvest: An Ecosystem Paradigm Reconsidered. *Ecosystems*, 6, 197-212.
- Yang H, Yu L, Wang L Effect of moisture content on the ultrasonic acoustic properties of wood. *J. For. Res.* 2015, 26, 753-757.
- Yin Y, Nagao H, Liu X, Nakai T Mechanical properties assessment of *Cunninghamia lanceolata* plantation wood with three acoustic-based nondestructive methods *J. Wood Sci.* 2010, 56, 33-40.
- Zaghi D Management of Natura 2000 habitats. 9530 \*Sub-Mediterranean pine forests with endemic black pines. Technical Report 24/24, European Commission 2008.
- Zar JH *Biostatistical Analysis*, fourth ed. Prentice Hall, Upper Saddle River, New Jersey 1999.
- Zeide B Optimal stand density: A solution. *Can. J. For. Res.* 2004, 34, 846-854.
- Zeller L, Ammer Ch, Annighöfer P, Biber P, Marshall J, Schütze G, del Río Gaztelurrutia M, Pretzsch H Tree ring wood density of Scots pine and European beech lower in mixed-species stands compared with monocultures. *Forest Ecol Manage* 2017, 400, 363-374.
- Zhang SY Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. *Wood Sci. Technol.* 1995, 29, 451-465.
- Zhang SY, Chauret G, Ren HQ, Desjardins R Impact of plantation black spruce initial spacing on lumber grade yield, bending properties and MSR yield. *Wood Fiber Sci.* 2002, 34, 460-475.
- Zhang SY, Chauret G, Swift DE, Duchesne I Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. *Can J For* 2006, 36, 945-952.

- Zhang SY, Owoundi RE, Nepveu G, Mothe F, Dhôte JF “Modelling density in European oak (*Quercus petraea* and *Quercus robur*) and simulating silvicultural influence,” *Can. J. For. Res.* 1993, 23, 2587-2593.
- Zhang Y, Chen HYH, Reich PB Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. *J Ecol* 2012, 100, 742-749.
- Zhembo L, Yixing L, Haipeng Y, Junqi Y Measurement of the dynamic modulus of elasticity of wood panels. *Frontiers of Forestry in China* 2006, 1, 425-430.
- Zingg A and Ramp B “Thinning and Stem Quality in Pure and Mixed Beech (*Fagus sylvatica* L.) Stands” Proceedings from the 7th International Beech Symposium IUFRO Research Group 1.10.00 10-20, Tehran, Iran, May 2004, 169 Surmiński J., 1990 “Właściwości techniczne i możliwości zastosowania drewna” Buk zwyczajny *Fagus sylvatica* L. Nasze Drzewa Leśne, PWN Warszawa-Poznań 1990. In Polish.
- Zobel BJ and van Bujten JP *Wood Variation: Its Causes and Control*, Springer Verlag, New York 1989.

**Appendix 1**

Article

# Does Thinning Intensity Affect Wood Quality? An Analysis of Calabrian Pine in Southern Italy Using a Non-Destructive Acoustic Method

Diego Russo, Pasquale A. Marziliano \* , Giorgio Macri, Andrea R. Proto , Giuseppe Zimbalatti and Fabio Lombardi

Department of AGRARIA, Mediterranean University of Reggio Calabria, 89122 Reggio Calabria, Italy; diego.russo@unirc.it (D.R.); giorgio.macri@unirc.it (G.M.); andrea.proto@unirc.it (A.R.P.); gzimbalatti@unirc.it (G.Z.); fabio.lombardi@unirc.it (F.L.)

\* Correspondence: pasquale.marziliano@unirc.it; Tel.: +39-0965-1694256

Received: 15 February 2019; Accepted: 29 March 2019; Published: 2 April 2019



**Abstract:** In the middle of XIX century, Calabrian pine was planted in southern Italy to increase the forest cover in mountainous areas. Many of these forest stands were never managed, since they were considered non-profitable for wood production. Therefore, in order to promote timber value, it is fundamental to study, more deeply, the characteristics and management options for this species. The acoustic technologies applied to predict the mechanical and physical properties of timber are well-established practices in forest research. In this study, we hypothesized that the tree stand density could influence the dynamic modulus of elasticity (MOEd) and, therefore, the future wood quality. We specifically aimed to verify if different management options, when applied, could influence the timber quality of Calabrian pine growing in similar environmental conditions. The study was conducted in the Aspromonte National Park (Calabria, Southern Italy). We derived the MOEd values from data obtained by the acoustic velocity measured through the TreeSonic™ timer. Calabrian pine trees were selected in stands where different intensities of thinning were applied eleven years before this study began (no thinning, thinning 25%, thinning 50%, and thinning 75%). The percentage refers to the number of trees cut with respect to the total number of occurring trees. The analyses were conducted on a total of 804 trees (201 trees for each intensity of thinning). A strong positive correlation was observed between the acoustic velocity, the thinning treatments and diameter at breast height (DBH). The thinning realized at 25% induced better tree wood quality. We also analyzed the best predictors for MOEd estimation, using variables easily measurable in the field, such as tree diameter, tree height, or their transformations (number of trees per hectare, basal area per hectare). We provide, here, a useful tool for predicting the wood stiffness in relation to stand parameters easily measurable in forest inventories.

**Keywords:** *Pinus nigra* Arnold subsp. *calabrica*; thinning intensity; Mediterranean mountain forests; acoustic velocity; modulus of elasticity; predictors for wood quality

## 1. Introduction

In Southern Europe, the Calabrian pine (*Pinus nigra* Arnold subsp. *calabrica*) occurs mainly in Italy (Calabria and Sicilia) and in France (Corsica). In Southern Italy, Calabrian pine forests are strongly related to the complex geological history, lithological and climatic characteristics, and also to the long history of human exploitation of the related forest stands [1]. In the past, Calabrian pine has provided valuable timber useful for building houses and vessels, as well as offering resinous substances (pitch) employed for a variety of purposes [2].

This species is particularly common in Sicily and on the Etna Volcano, but is mainly found in the Sila and Aspromonte National Parks in Calabria Region. Calabrian pine covers an area of approximately 114,000 ha, mostly characterized by pure stands of natural origin and plantations. The latter originated from extensive reforestation projects carried out between 1950 and 1970 on the basis of a specific Italian state law [3]. These plantations were realized with the aim of reducing the hydrological risk in mountainous areas, but also for facilitating the natural succession toward mixed forests with a significant component of deciduous species [4]. Together with soil and watershed protection, Calabrian pine has an important role in the local forest economy. In order to increase the economic value of these forests, the best silvicultural options should be selected and adopted at stand level, to achieve specific objectives. Therefore, different management practices and related intensities can change the tree species composition and richness and, also, the stand density and tree age distribution [5]. Moreover, management practices can increase the quality and quantity of merchantable timber, reducing also the risks derived from diseases and forest fires [6,7]. Forest management is aimed to create a vigorous stand, increasing tree growth and developing structural characteristics useful for timber production. Furthermore, thinning activities can also favor the creation of new habitats for wildlife, favoring the occurrence of healthy and vigorous forests [8].

Thinning activities control the forest stand density, improving the growth of the remaining trees [9] based on sustainable approaches [10], and decreasing, also, the tree mortality rates from a long-term perspective [11]. Thus, selective thinning should be encouraged for proper and sustainable forest management, supporting the forest stability, productivity, and quality.

Furthermore, forest management can determine variation in the physical and mechanical properties of harvested wood, both at stand and tree level [12]. For this reason, the identification of certain wood properties that can increase timber quality is essential, as it is important to select the best forest management options to improve wood quality.

Wood quality can be described as a set of characteristics that make woody materials economically valuable for their end uses [13]. Briggs and Smith [14] defined wood quality as “a measure of the aptness of wood for a given use”. These properties can include, for example, the wood density, the uniformity in tree ring size, the percent of knot-free wood, and the proportion between early wood and late wood.

The objective evaluation of the wood quality and quantity is then critical for quantifying the productive value of a forest [15,16]. For this purpose, several non-destructive technologies (NDTs) have been developed in the past years to evaluate the quality of woody materials. For example, at belowground level, (mini) rhizotrons and ground-penetrating radar allows for evaluating tree rooting distribution and growth [17,18]. Moreover, at aboveground level, NDT measures allow for evaluation of the mechanical and technological properties of standing trees [19–22]. More specifically, stress wave-based non-destructive acoustic techniques have been extensively investigated during the past few decades [23], resulting in very useful methods for predicting the mechanical properties of woody materials.

The use of stress wave-based non-destructive tests is relatively common in the forest-to-mill woody supply chain in Australia [24] and in North America [25,26], while it is less common in Europe. Specifically, research developments [27] in acoustic sensing technology can, nowadays, permit the estimation of wood quality and intrinsic woody properties for standing trees, stems, and logs. The information derived from NDT measures could be used to sort and grade trees and logs according to their suitability for different end uses, such as structural products, advanced composites, pulp, and paper, and also for bioenergetics purposes.

Among the parameters measurable by acoustic methods, one of the most important is the modulus of elasticity of wood (MOE). The MOE, also known as wood stiffness, is essentially one of the fundamental wood quality parameters and measures the resistance to deflection [28]. For example, it is important since some woody products, such as laminated veneer and dimension lumber, require stiff and strong woody properties [29].

The recent literature has focused on determining whether stress wave techniques could be used to determine wood quality [30]. Several studies shown a good relationship between the stress wave-based modulus of elasticity (MOE) and the static MOE of lumber cut from logs [31,32]. This methodological approach is also applied to determine the relationships between the environmental conditions, silvicultural practices, and wood fiber properties [33]. The modulus of elasticity and the density of the woody materials strongly affect the acoustic properties of wood [34]. One of the most important mechanical properties, measurable by NDT methods, is Young's modulus, i.e., the modulus of elasticity (MOEd), which describes the material's stiffness.

Many portable instruments have been developed to measure the wood stiffness of standing trees, logs, and sawn timber using acoustic technology [35]. These instruments are able to measure the speed at which an induced sound (stress) wave propagates through a woody sample, which is proportional to its stiffness [36]. When the stress is applied to the wood surface, the generated disturbance propagates through the wood as stress wave. Several studies have hypothesized that the characteristics of the resulting wave are related to the mechanical properties of the wood [37,38].

Stress wave propagation in wood is a dynamic process correlated to several factors, such as the stand developmental stage [39], genetic characteristics [40,41], and also the silvicultural activities and their intensities [42]. More specifically, the quality and properties of wood are generally affected by silvicultural practices, especially the anthropic control of stand density. Silvicultural practices might not only increase the biomass production of trees, but also improve the quality and the related physical and mechanical characteristics of the wood in trees [43,44].

Furthermore, some authors have reported how high thinning intensities adversely influence the patterns of tree ring width and the tree competitive position within a forest stand [45–47].

Wang [48], examining the effect of thinning treatments on the wood quality of radiata pine, found that trees were characterized by higher acoustic velocity and stiffness mostly occurred in uncut stands and in forests characterized by light and medium intensities of thinning, whereas the lowest values occurred in stands that received the most intensive thinning approaches.

In Southern Italy, Todaro and Macchioni [43] and Proto et al. [16] showed a significant improvement of wood properties induced by a medium thinning operation for Douglas fir and Calabrian pine trees, respectively. Moreover, Cown et al. [49] and Barbour et al. [50] reported that heavy thinning approaches caused a slight decrease in wood density for radiata pine and Douglas fir. Finally, Wang et al. [51] indicated that heavy thinning induced the creation of more woody knots and larger-diameter knots than the medium thinning, or where no thinning had been applied.

The general objective of this study was the evaluation of the wood mechanical properties for Calabrian pine trees occurring in a forest stand located in the "Aspromonte" National Park (Calabria, Southern Italy) using innovative non-destructive methods (stress wave techniques). In detail, the evaluation of wood quality was carried out through acoustic measurements useful for assessing the MOE. Specifically, we hypothesized that different intensities of thinning can influence the wood quality of Calabrian pine trees. Three areas characterized by different management options as well as a no-thinning area, as control, were assessed. They were characterized by similar environmental conditions, such that the only discriminating parameter was the applied silviculture.

Furthermore, we also verified if the MOEd values may be predicted by easily recordable variables such as tree diameter (D), height (H), H/D ratio, or their transformations (number of trees per hectare, basal area per hectare).

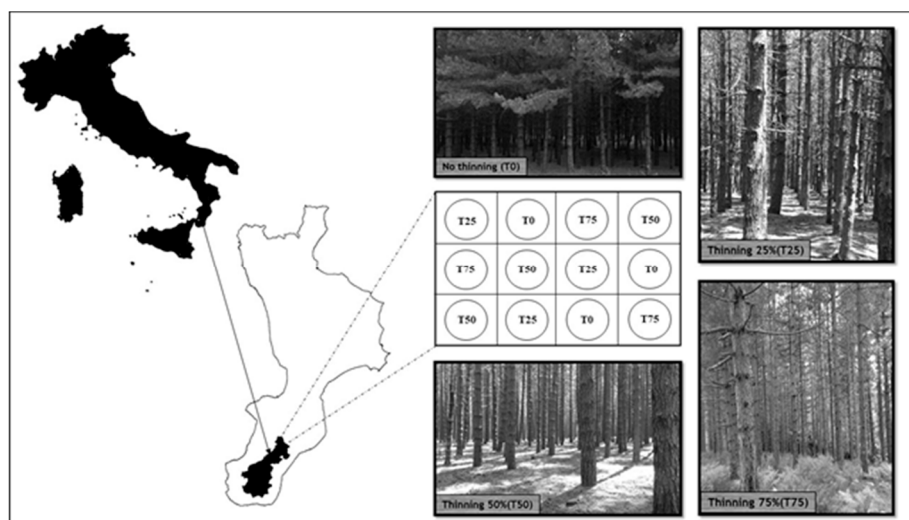
## 2. Materials and Methods

### 2.1. Study Area and Experimental Design

The study area was located in Zervò (Municipality of Santa Cristina d'Aspromonte), in the context of the Aspromonte National Park (Calabria Region—38°14'30" N; 16°01'09" E), at an elevation of 1100 m a.s.l. The climate is temperate, with an annual mean temperature of around 10 °C and minimum

monthly means of 3 °C (coldest month) and 17 °C (warmest month), respectively. The annual rainfall is 1508 mm, with minimum precipitation occurring in summer, but is, however, unevenly distributed over the year (Meteorological station of Santa Cristina d'Aspromonte—980 m a.s.l.). According to Pavari's phytoclimatic classification [52] the study area belongs to the *Castanetum/Fagetum* zone. The whole area is characterized by gently undulating slopes with northeast exposure and soils developed from high-rank metamorphic rocks, such as schist and biotitic gneisses, and classified according to the IUSS WRB [53].

The investigated forest stands are plantations of Calabrian pine which were established in 1968, with a planting density of 2000 trees per hectare (2.0 m × 2.5 m). In 2007, at the age of 39 years, the whole plantation has been subject to different intensities of thinning, following a randomized block experimental design with three intensities of thinning repeated three times. Moreover, a portion of the stand was not characterized by cutting and considered as control. Then, twelve plots in total were considered in the field measurements. Each block had an extension of 5 hectares (Figure 1).



**Figure 1.** Location of the study area in Southern Italy (Calabrian Region) and the applied experimental design.

The treatments (intensity of thinning) can be described as follows: (1) No thinning (T0—Control); (2) Thinning where the 25% of the occurring trees were cut (T25); (3) Thinning where the 50% of the occurring trees were cut (T50); (4) Thinning where the 75% of the occurring trees were cut (T75).

## 2.2. Field and Laboratory Activity

In 2018, eleven years after the thinning operation (age of the plantation: 50 years), 804 trees were selected in total. Particular care was taken to select trees in good vegetative conditions, with canopies well separated from each other and referring to the dominant tree layer. The 804 trees were distributed between three blocks containing the four treatments, containing 201 trees for each treatment (67 trees for each replicate).

The diameter at breast height (DBH) and height of trees were measured. Moreover, for each tree, the acoustic wave tests were conducted at breast height. The measurements were conducted from June to July 2018, in order to reduce the effect of air humidity which could affect the obtained results [54]. More specifically, the relative air humidity was measured in the study area during the sampling period 1 m above the ground, using a HOB01 Pro RH/Temp Data Logger (Onset Computer Corporation, Pocasset, MA, USA).

The system used for measuring acoustic velocity was the TreeSonic™ (Fakopp Enterprise, Agfalva, Hungary), a tool which has already applied in other studies [55]. This tool is characterized by an handheld hammer and two probes, a transmitting accelerometer, and a receiving accelerometer.



The operation consists in the insertion of two sensor probes (a transmit probe and a receiver probe) into the sapwood, introducing, then, the acoustic energy into the tree through a hammer impact. The probes were aligned within a vertical plane on the same face. In our study, a 1.00 m testing span was roughly centered at breast height. The lower probes were placed about 60–70 cm above the forest floor. Three measurements were realized for each selected tree and the average of the three recordings was used as the final transit time. In order to measure the acoustic velocity wave, the start and stop sensors were driven at a 45° angle through the bark and into the wood of the standing tree [56]. Indeed, the TreeSonic™ was developed to operate in the longitudinal direction of the tree. The acoustic velocity was then calculated from the span between the two sensor probes and the time-of-flight (TOF) data using the following formula (Equation (1)):

$$CT = S/TOF, \quad (1)$$

where CT = tree acoustic velocity (m/s), S = distance between the two probes (sensors) (m), TOF = time of flight (s).

For determination of the MOEd, it was necessary to determine the wood density. A subsample of trees was selected, considering trees where the TOF was also measured. In detail, woody cores were extracted, bark to bark, at breast height (1.30 m) with a Pressler borer from trees, referring to each of the diameter classes occurring in the different treatments (three cores for each treatment and diameter class). The fresh weight and volume of the tree cores were measured in the laboratory. Samples were then weighed to the nearest 0.01 gram with an electronic scale. Oven drying of all samples was done at 105 °C to constant weight. Density ( $\text{kg m}^{-3}$ ) was calculated by dividing the dry weight with the fresh sample volume.

Afterwards, it was possible to calculate the modulus of elasticity (MOE), according to the following equation (Equation (2)):

$$MOEd = WD_{ij} \cdot CT^2, \quad (2)$$

where  $WD_{ij}$  = tree wood density ( $\text{kg m}^{-3}$ ), shared by diameter class (i) and treatment (j); and CT = velocity ( $\text{m s}^{-1}$ ).

The MOE estimated using the above cited formula [57] is called the dynamic modulus of elasticity (MOEd) [58], since the stress wave propagation in wood is a dynamic process and internally related to the physical and mechanical properties of the wood [51].

### 2.3. Statistical Analysis

The preliminary shape indexes (skewness and kurtosis) were calculated, and the Shapiro–Wilk test was performed to evaluate the distribution of the acquired data. Afterwards, the analysis of variance (ANOVA), based on a scheme of randomized blocks (four treatments repeated three times), was carried out to test the differences in MOEd values obtained among the four treatments and in relation to the occurring diameter classes. The significance level of the differences was tested using Tukey’s method. When the significance level (*p*-value) was  $\leq 0.05$ , the null hypothesis was rejected and significant differences in the means were accepted.

For the estimation of the MOEd, the following parameters (easily measurable in the field) were considered as predictors: diameter at breast height (DBH), height (H), height/diameter ratio (H/DBH), basal area (BA), stand density (number of trees per hectare) and their mutual interactions.

As a preliminary analysis, the correlations between these variables and the MOEd were analyzed using the Spearman correlation coefficient (*r*). Subsequently, the analysis was carried out by comparing different transformations and combinations of the variables correlated with the MOEd, suitable for expressing the relationship between MOEd and the above cited variables. The process involved regression analysis with a stepwise procedure (in each step, a variable was considered for addition to or subtraction from the set of explanatory variables based on F-tests). We then evaluated the fit of the final model using and analyzing the value of root mean square error (RMSE) and the coefficient



of determination ( $R^2$ ) value. Finally, the Shapiro–Wilk test was used to verify the normality of the error distribution.

Data analysis were carried out using the statistical software R version 3.2.5 [59].

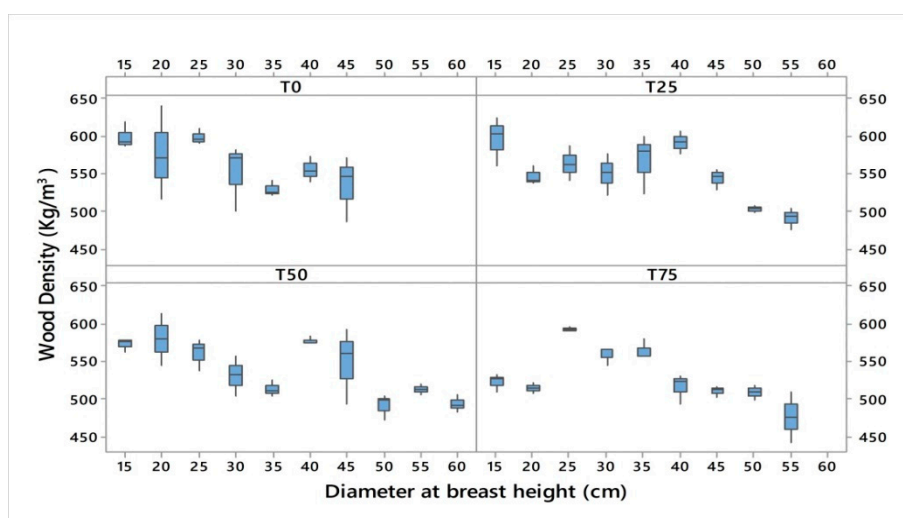
### 3. Results

The relative air humidity measured in the study area during the sampling period ranged from 39% to 56%. For each treatment, the main measured structural parameters and the derived values of stand density and basal area are reported in Table 1. The skewness and kurtosis values, as well as the Shapiro–Wilk test (SWT), revealed that all the attributes were characterized by normal distribution. Tree diameters varied from about 25 to 32 cm, while tree heights showed similar values (19–20 m).

**Table 1.** The main parameters measured and the related structural characteristics for the four treatments analyzed (DBH: diameter at breast height; H; total tree height; N ha<sup>-1</sup>: number of trees per hectare; SD: standard deviation; SWTsig: *p*-values of the Shapiro–Wilk Test).

Treatments	Parameters	Mean	SD	Skewness	Kurtosis	SWTsig
T0	DBH (cm)	24.9	6.07	0.228	−0.408	0.106
	H (m)	18.84	2.83	0.447	0.483	0.112
	Stand density (N ha <sup>-1</sup> )	1977	134	0.468	−0.62	0.125
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	95.9	7.16	−0.873	0.024	0.095
T25	DBH (cm)	26.7	8.19	0.352	0.242	0.053
	H (m)	20.03	2.76	0.298	0.237	0.131
	Stand density (N ha <sup>-1</sup> )	1548	77	0.045	−0.938	0.096
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	86.88	11	0.049	−0.965	0.364
T50	DBH (cm)	26.4	8.73	0.646	1.001	0.064
	H (m)	20.05	3.65	−0.326	0.042	0.055
	Stand density (N ha <sup>-1</sup> )	939	49	0.676	1.055	0.118
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	51.45	4.28	−0.451	−0.579	0.247
T75	DBH (cm)	32.5	9.96	0.444	−0.46	0.217
	H (m)	21.1	3.68	−0.503	0.399	0.146
	Stand density (N ha <sup>-1</sup> )	514	29	−0.281	−0.684	0.214
	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	42.67	3.05	0.194	−0.544	0.079

Figure 2 reports the variability and the distribution of the wood density in relation to the type of treatment and the different diameter classes.



**Figure 2.** Variability of the tree wood density for each treatment as shared by diameter classes.

Table 2 shows the stress wave times and the related mechanical properties (wave velocity and MOEd) for the sampled trees in relation to the different silvicultural treatments. Moreover, the tree wood density (on average) is also shown.

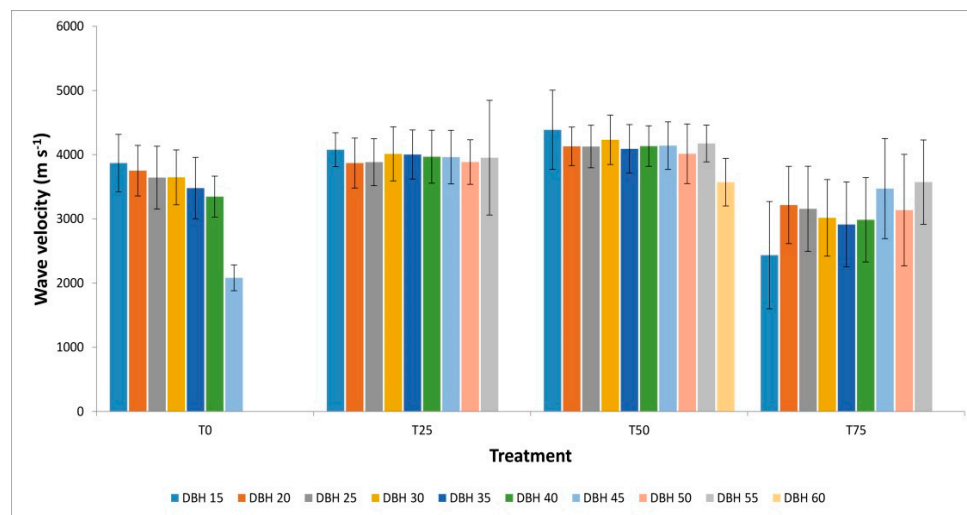
**Table 2.** Tree wood density, stress wave time, and mechanical properties for the sampled trees among the different treatments considered (SD: standard deviation; MOEd: dynamic modulus of elasticity). Means in the same column followed by the same letter are not statistically different at  $p \leq 0.05$  (Tukey test).

Treatments	Tree Wood Density (kg/m <sup>3</sup> )		Stress Wave Time (μs)		Wave Velocity (m s <sup>-1</sup> )		MOEd (MPa)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T0	563	30.2	282.5 <sup>b</sup>	48.0	3637.9 <sup>d</sup>	465	7206.2 <sup>c</sup>	1699.9
T25	550	35.5	257.0 <sup>c</sup>	27.0	3959.7 <sup>ab</sup>	397	8487.5 <sup>b</sup>	1695.4
T50	538	28.2	245.2 <sup>cd</sup>	22.0	4141.6 <sup>a</sup>	371	9275.8 <sup>a</sup>	1717.5
T75	529	27.4	344.5 <sup>a</sup>	90.8	3090.1 <sup>c</sup>	681	5371.9 <sup>d</sup>	2242.2

With reference to the stress wave time, significant differences were recorded among the different intensities of thinning ( $F_{3;794} = 134.24$ ;  $p \leq 0.001$ ), while no difference between blocks ( $F_{2;794} = 2.012$ ;  $p = 0.134$ ) were observed. The treatment characterized by the higher thinning intensity (T75) revealed a longer stress wave time (344.5 μs), also differing significantly with respect to all other conditions: T75 was about 22% and 40% higher than T0 and T50, respectively. Moreover, each treatment differs significantly in stress wave time from all the others, except T25 and T50, which had similar values.

The wave velocity is positively correlated to the thinning intensities, up to the T50 treatment (Table 2); afterwards, it significantly decreased for the higher thinning intensity (T75) ( $F_{3;794} = 174.55$ ;  $p \leq 0.001$ ). No differences between blocks ( $F_{2;794} = 1.579$ ;  $p = 0.207$ ) were observed.

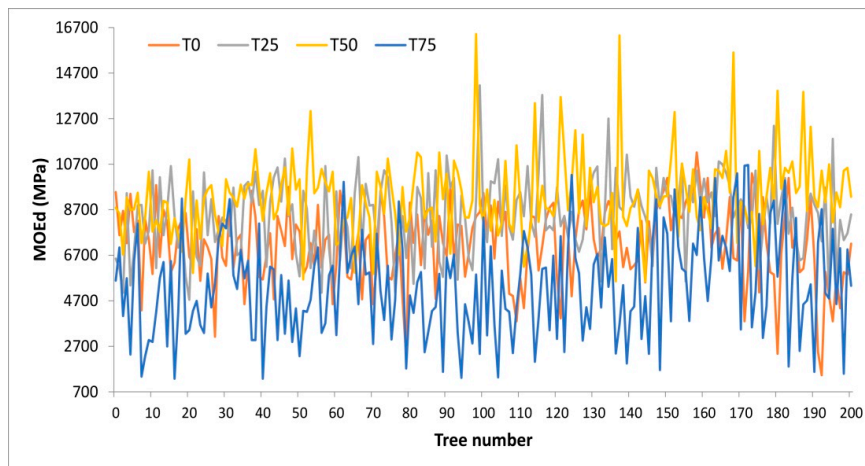
In Figure 3, the variation of the wave velocity in relation to the tree diameter classes is reported for each treatment.



**Figure 3.** Wave velocity in relation to the diameter classes for each intensity of thinning. DBH: diameter at breast height. For Control,  $F_{6;191} = 3.371$ ;  $p = 0.006$ ; for T25,  $F_{8;189} = 0.658$ ;  $p = 0.728$ ; for T50,  $F_{9;188} = 1.600$ ;  $p = 0.118$ ; for T75,  $F_{8;189} = 2.330$ ;  $p = 0.021$ .

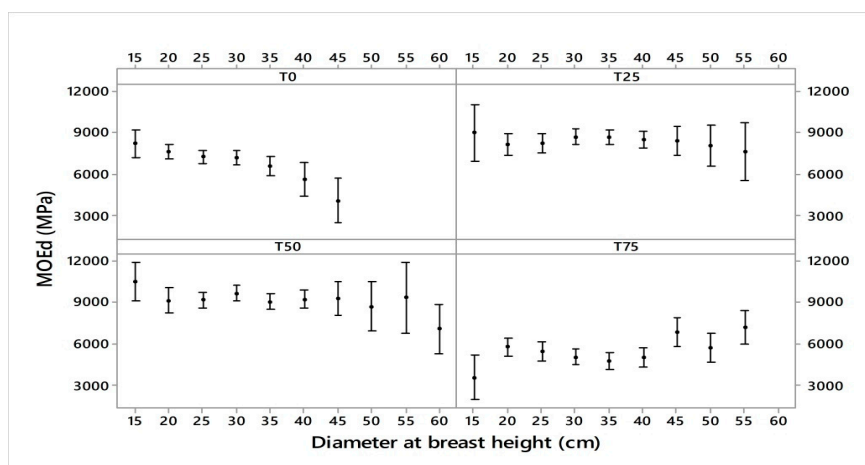
In the control plots, the wave velocity tends to decrease as the tree diameters increase; more specifically, the 45 cm diameter class had significant lower values when compared to all other diameter classes. No significant differences were observed between diameter classes for T25 and T50. On the contrary, the wave velocity values were the lowest for the T75 treatment, revealing significant differences also between diameter classes.

Furthermore, Figure 4 shows the MOEd values obtained for all the sampled trees in each intensity of thinning.



**Figure 4.** MOEd values obtained for all the sampled trees. Different colors refer to the four intensities of thinning.

Generally, for each tree, lower values always occurred in T75, while higher values occurred in T25 and T50. The analysis of variance (ANOVA) showed a significant effect of the thinning intensity on MOEd values ( $F_{3,794} = 170.82$ ;  $p \leq 0.001$ ). Table 2 shows that the MOEd was significantly higher in T25 (on average, equal to 8487 MPa) and T50 (on average, 9275 MPa) than in T0 (on average, 7206 MPa) and T75 (on average 5371 MPa). Furthermore, the MOEd values for treatment T75 were always lower than in the T0 (Table 2). No difference between blocks was observed ( $F_{2,794} = 1.574$ ;  $p = 0.208$ ). Furthermore, the analysis of variance showed a significant effect of the diameter classes on MOEd values for the thinning intensities T0 and T75, while no significant effects were observed in treatments T25 and T50 (Figure 5).



**Figure 5.** Dynamic modulus of elasticity (MOEd) in relation to the diameter classes for each intensity of thinning. For Control,  $F_{6,191} = 3.371$ ;  $p = 0.006$ ; for T25,  $F_{8,189} = 0.658$ ;  $p = 0.728$ ; for T50,  $F_{9,188} = 1.600$ ;  $p = 0.118$ ; for T75,  $F_{8,189} = 2.330$ ;  $p = 0.021$ .

The MOEd values decrease as the diameters for T0 increase, with significant differences observed between the smallest and largest diameter classes. On the contrary, for the T25 and T50 treatments, the MOEd values were not significantly different when the diameter increased (Figure 5). The thinning, especially in the T25 treatment and, to a lesser extent, in the T50 treatment, had the effect of aligning

the MOEd values, making the wood quality uniform in each diameter class. On the contrary, for the T75 treatment, the MOEd values not only were significantly lower than the T0, T25, and T50 treatments, but they also varied significantly with the increase of diameters.

In analyzing the best predictors for the estimation of MOEd, the applied analysis showed correlations between MOEd and DBH ( $r = 0.011$ ), between MOEd and H ( $r = 0.040$ ) and between MOEd and H/D ( $r = 0.033$ ) that were not considered significant. On the contrary, significant correlations emerged between the MOEd and the stand density ( $r = 0.474$ ) and basal area ( $r = 0.217$ ).

Therefore, a model that allows for computing the MOEd as a function of the stand density (number of trees per hectare) and basal area ( $\text{m}^2$  per hectare) was applied. According to the stepwise regression procedure, the variables were combined in the following model (Equation (3)):

$$MOEd = \beta_0 + \beta_1 \cdot \frac{1}{BA} + \beta_2 \cdot SD + \beta_3 \cdot SD^2 + \beta_4 \cdot SD^3, \quad (3)$$

where  $BA$  = basal area per hectare;  $SD$  = number of trees per hectare.

Figure 6 shows the variation of the MOEd in relation to the number of trees per hectare for different basal areas. The analysis covered a basal area lapse ranging from 40 to 70  $\text{m}^2 \text{ha}^{-1}$ . The MOEd curve is lower for high values of basal area (70  $\text{m}^2 \text{ha}^{-1}$ ) and higher when basal area values decrease (40  $\text{m}^2 \text{ha}^{-1}$ ). The root mean square error (RMSE) was 1850.69 MPa and  $R^2$  was 0.368. Moreover, the Shapiro–Wilk normality test ( $W = 0.9614$ ;  $p = 0.096$ ) confirmed the absence of deviation from normality. Furthermore, Table 3 reports the statistical values obtained by the application of the Equation (3).

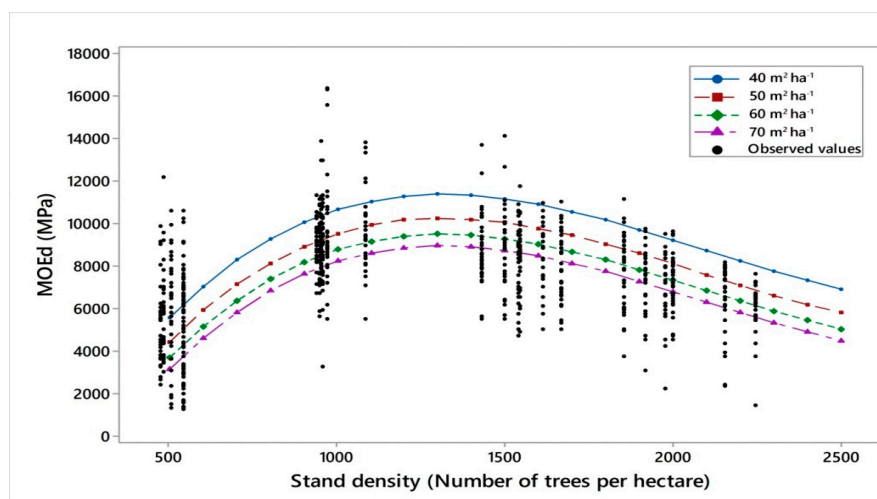


Figure 6. MOEd values in relation to the stand density and to the basal area.

Table 3. Statistical parameters obtained in the model and their significance (BA: basal area; SD: number of trees per hectare; T: results of the Student  $t$ -test).

Model	Coefficients	Standard Error of Coefficients	T	Significance
(Constant)	−11895.537	1349.925	−8.782	$p < 0.0001$
1/BA	227408.509	44672.651	5.068	$p < 0.0001$
SD	31.669	2.538	12.458	$p < 0.0001$
SD <sup>2</sup>	−0.018	0.002	−7.941	$p < 0.0001$
SD <sup>3</sup>	0.00000281	0.000	5.371	$p < 0.0001$

#### 4. Discussion

The obtained results demonstrate how the effect of silvicultural practices on wood quality can be successfully identified by measurement of MOEd.

The MOEd values recorded in standing trees were significantly influenced by thinning intensities, since they determined significant variations in MOEd values with respect to the control. Specifically, the T25 and T50 treatments produced significant benefits in terms of wood quality, while a higher thinning intensity (T75) induced a significant decrease of the MOEd, even lower than the control. The strong diametric increment induced by the intensive thinning probably resulted in a less-stiff mature wood, resulting in a significant loss of wood quality.

On other hand, many authors confirmed that wood quality and intrinsic wood properties are generally affected by thinning [16,60,61], especially by stand density [62,63]. In this study, density values were measured on a subsample, rather than all, of the trees. This could lead to slight variations in MOEd values, but should not compromise the obtained results. In Southern Italy, Todaro and Macchioni [43] also found a significant variation of wood properties caused by thinning operations in a Douglas fir forest.

Generally, in the management of forest stands, it is common to apply a strong intensity of thinning in order to obtain a high assortment of diameters [64]. However, our results show that these assortments are of a lower quality compared to those derived from moderate intensities of thinning.

It is also interesting that the increase in the MOEd values from T0 to T25 is more sustained than the increase in MOEd from T25 to T50. This indicates that light thinning has a significant and positive effect on the wood quality, while increasing thinning intensities are always less significant. On the other hand, the T25 treatment had a positive effect on MOEd, both at the stand level and at the diametric class level, making the MOEd values almost equal for each diameter class. On the contrary, in the T0 and T75 treatments, we observed a decrease in wood quality when diameters increased. Other studies conducted on trees of the same age for different conifers (Sitka spruce (*Picea sitchensis* Bongard, Carrière, 1855), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), jack pine (*Pinus banksiana* Lamb.), ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), and radiata pine (*Pinus radiata* D. Don) [65,66]) reported that the stress wave velocity was higher for trees with a slower growth rate or narrower rings.

The results obtained here are interesting on the basis of their practical and scientific applications, since they can provide useful silvicultural indications: the application of moderate thinning can favor, at least for the Calabrian pine, the formation of woody materials of good quality, regardless of the tree size from which the assortments are obtained.

More specifically, the MOEd values increase as the number of trees rise, up to 1200–1500 trees per hectare: this tree density seems to be the optimal value for obtaining the best woody materials for Calabrian pine. Briggs [67] showed that the tree acoustic velocity measured in Douglas fir increases as tree age rises, and decreases with increasing DBH; moreover, it is affected by the initial stand density.

Furthermore, higher values of basal area, when the number of trees and tree age are similar, determine lower values of the MOEd. We can then observe that a rapid diameter increment can negatively affect the wood quality.

In Douglas fir forests, Zhang [68] and Todaro and Macchioni [43] also reported that large trees deriving from higher growth rates would generally produce wood of lower stiffness. Furthermore, Chauhan and Walker [69] showed how, in fast-growing trees of radiata pine, the increased diameter with its larger second moment of inertia induced a lower tendency for high material stiffness; moreover, for trees of the same age, slow-growing trees tend to have a high stiffness, helping to sustain the trees under various environmental disturbances. Furthermore, Lasserre et al. [70] have observed that outerwood stiffness increases dramatically with stocking (and so with smaller tree DBH).

The low values of MOEd therefore appeared to be associated to a higher growth rate in trees, which adversely affects the specific gravity as well as the wood's strength and stiffness. Younger wood is lower in specific gravity and stiffness, while fast-growing wood has a larger diameter core of juvenile wood [71].

The moderate thinnings not only increase the biomass production of trees [72–74], but also improve the wood quality in trees, as highlighted in this study. However, Nakamura [75], using

ultrasonically induced waves to assess the wood quality in larch trees, had already observed significant differences in the wave velocity and in MOEd values for forest stands characterized by different density some decades ago. In addition, Wang [48], assessing the effect of thinning treatments on the technological properties of Sitka spruce trees in southeast Alaska, showed that trees with higher acoustic velocity and stiffness were mostly found in forest stands that were uncut and/or slightly thinned, while the lowest values were found in stands subjected to high intensity thinning.

These results are encouraging, and indicate that the time of flight in the acoustic technologies may be applied, in the future, to monitor the wood property changes in forest stands. The technology can also be used to determine how silvicultural treatments affect the wood and fiber properties; consequently, the most effective treatment can be selected for maximizing the wood value, improving the timber quality of future plantations [22]. Finally, the precision of the acoustic technology has been strongly improved: nowadays, the tree quality, but also the intrinsic wood properties, can be predicted and correlated with the economic value of the final products [33].

In this study, the model developed can be used as a decision support system useful for the woody supply chain: the determination of the MOEd is fundamental for the final end uses of the woody products.

However, even if many studies have been carried out for estimating the MOEd through various non-destructive tests [76,77], few of them have, in any case, examined the relationships between MOEd and the stand structural features (e.g., stand density, DBH, total tree height, tree taper).

Gorman et al. [78] confirmed that the stress wave velocity is not affected by knots and other defects; nevertheless, it is important to underline that this method only measures the sound velocity within the outermost growth tree rings.

Furthermore, we identified, here, the most useful variables for predicting the MOEd, based on stand and tree characteristics in Calabrian pine.

In accordance with other studies [16,79–81], significant relationships between the dendrometric parameters and MOEd values were found. However, the relationships between MOEd and stand density, which showed a decrease in MOEd at high stand density, have not been previously described. While the MOEd always decreased with higher basal area, MOEd only decreased from a certain number of trees per hectare. However, in addition to the stand density (number of trees per hectare and basal area), the tree diameter classes could be considered for explaining the MOEd values in trees, as also already highlighted by Lei et al. [81]. Finally, as some of these stand structural features are commonly measured in forest inventories we provide, here, a useful tool for predicting the wood stiffness in relation to the tree and stand characteristics measured in the field. This approach allows for determination of the wood quality directly from inventory data.

However, the model used is site- and species-specific since, in other silvicultural systems, the implemented equation can differ. In any case, a pioneer of forest modeling [82] confirmed that no single model can be expected to be the “best” for all the conditions which are common in forest prediction.

## 5. Conclusions

This study showed that silvicultural practices might not only increase biomass production, but also improve the wood quality in trees. We verified here, through innovative and non-destructive methods, that different intensities of thinning can influence the wood quality of Calabrian pine trees in Southern Italy. Our results demonstrated that the effect of silvicultural practices on the properties of wood can be successfully identified by stress wave MOEd. Furthermore, we proved that MOEd values may be predicted by easily recordable variables in the field.

More specifically, for Calabrian pine, different intensities of thinning can affect the wood quality and, therefore, the final obtainable woody products. We also demonstrated that using a low intensity of thinning could be the best option for obtaining woody materials of good quality, regardless of the tree size from which the assortments derive. The results obtained are encouraging, since they demonstrate the potential of the non-destructive acoustic technique to determine the influence of



thinning treatments performed on Calabrian pine. However, it could be interesting to also test the same methodological approach on other tree species and in different ecological contexts.

Finally, we tested a useful tool for predicting the wood stiffness in relation to tree and stand characteristics commonly measured in the field. This approach allows for determination of the wood quality directly from inventory data, even if the model used is site- and species-specific and the implemented equation can differ in other silvicultural systems.

**Author Contributions:** Conceptualization, D.R., P.A.M., G.M. and F.L.; Data curation, D.R. and G.M.; Formal analysis, D.R., P.A.M., G.M., A.R.P., G.Z. and F.L.; Investigation, D.R. and G.M.; Methodology, D.R., P.A.M. and F.L.; Resources, A.R.P. and G.Z.; Writing—original draft, D.R., P.A.M., G.M. and F.L.; Writing—review & editing, P.A.M. and F.L.

**Acknowledgments:** We are grateful to the Aspromonte National Park for the economic support given to realize this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Ciancio, O.; Iovino, F.; Menguzzato, G.; Nicolaci, A.; Nocentini, S. Structure and growth of a small group selection forest of Calabrian pine in Southern Italy: A hypothesis for continuous cover forestry based on traditional silviculture. *For. Ecol. Manag.* **2006**, *224*, 229–234. [[CrossRef](#)]
2. Bonavita, S.; Vendramin, G.G.; Bernardini, V.; Avolio, S.; Regina, T.M.R. The first SSR-based assessment of genetic variation and structure among *Pinus laricio* Poiret populations within their native area. *Plant Biosyst.* **2015**, *150*, 1–20. [[CrossRef](#)]
3. Nicolaci, A.; Travaglini, D.; Menguzzato, G.; Nocentini, S.; Veltri, A.; Iovino, F. Ecological and anthropogenic drivers of Calabrian pine (*Pinus nigra* J.F. Arn. ssp. *Laricio* (Poiret) Maire) distribution in the Sila mountain range. *iForest* **2014**, *8*, 497–508. [[CrossRef](#)]
4. Cantiani, P.; Plutino, M.; Amorini, E. Effects of silvicultural treatment on the stability of black pine plantations. *Ann. Silvicult. Res.* **2010**, *36*, 49–58.
5. Duncker, P.S.; Barreiro, S.M.; Hengeveld, G.M.; Lind, T.; Mason, W.L.; Ambrozy, S.; Spiecker, H. Classification of forest management approaches: A new conceptual framework and its applicability to European forestry. *Ecol. Soc.* **2012**, *17*, 51. [[CrossRef](#)]
6. Skov, K.R.; Kolb, T.E.; Wallin, K.F. Tree size and drought affect ponderosa pine physiological response to thinning and burning treatments. *J. Forensic. Sci.* **2004**, *50*, 81–91.
7. Ostaff, D.P.; Piene, H.; Quiring, D.T.; Moreau, G.; Farrell, J.C.G.; Scarr, T. Influence of pre-commercial thinning on balsam fir defoliation by the balsam fir sawfly. *For. Ecol. Manag.* **2006**, *223*, 342–348. [[CrossRef](#)]
8. Demers, C.; Andreu, M.; McGowan, B. *Thinning Southern Pines—A Key to Greater Returns*; Series of the School of Forest Resources and Conservation, SS FOR 24; Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida: Tallahassee, FL, USA, 2013; 6p.
9. Grant, C.D.; Norman, M.A.; Smith, M.A. Fire and silvicultural management of restored bauxite mines in Western Australia. *Restor. Ecol.* **2007**, *15*, 127–136. [[CrossRef](#)]
10. Zeide, B. Optimal stand density: A solution. *Can. J. For. Res.* **2004**, *34*, 846–854. [[CrossRef](#)]
11. Brissette, J.C.; Frank, R.M.; Stone, T.L.; Skratt, T.A. Precommercial thinning in a northern conifer stand: 18-year results. *For. Chron.* **1999**, *75*, 967–972. [[CrossRef](#)]
12. Machado, J.S.; Louzada, J.L.; Santos, A.J.A.; Nunes, L.; Anjos, O.; Rodrigues, J.; Simoes, R.M.S.; Pereira, H. Variation of wood density and mechanical properties of blackwood (*Acacia melanoxylon* r. Br.). *Mater. Des.* **2014**, *56*, 975–980. [[CrossRef](#)]
13. Jozsa, L.; Middleton, G. *A Discussion of Wood Quality Attributes and Their Practical Implications*; Special Publication No. SP-34; Forintek Canada Corp: Vancouver, BC, Canada, 1994.
14. Briggs, D.G.; Smith, W.R. Effects of Silvicultural Practices on Wood Properties of Conifers: A review. In *Douglas-fir Stand Management for the Future*; Oliver, C., Hanley, D., Johnson, J., Eds.; University of Washington Press: Seattle, WA, USA, 1986; pp. 108–116.
15. Marziliano, P.A.; Menguzzato, G.; Scuderi, A.; Corona, P. Simplified methods to inventory the current annual increment of forest standing volume. *iForest* **2012**, *5*, 276–282. [[CrossRef](#)]

16. Proto, A.R.; Macri, G.; Bernardini, V.; Russo, D.; Zimbalatti, G. Acoustic evaluation of wood quality with a non-destructive method in standing trees: A first survey in Italy. *iForest* **2017**, *10*, 700–706. [[CrossRef](#)]
17. Sanesi, G.; Laforteza, R.; Colangelo, G.; Marziliano, P.A.; Davies, C. Root system investigation in sclerophyllous vegetation: An overview. *Ital. J. Agron.* **2013**, *8*, 121–126. [[CrossRef](#)]
18. Marziliano, P.A.; Laforteza, R.; Medicamento, U.; Lorusso, L.; Giannico, V.; Colangelo, C.; Sanesi, G. Estimating belowground biomass and root/shoot ratio of *Phillyrea latifolia* L. in the Mediterranean forest landscapes. *Ann. For. Sci.* **2015**, *72*, 585–593. [[CrossRef](#)]
19. Škorpik, P.; Konrad, H.; Geburek, T.; Schuh, M.; Vasold, D.; Eberhardt, M.; Schuler, S. Solid wood properties assessed by non-destructive measurements of standing European larch (*Larix decidua* Mill.): Environmental effects on variation within and among trees and forest stands. *Forests* **2018**, *9*, 276. [[CrossRef](#)]
20. Carter, P.; Briggs, D.; Ross, R.J.; Wang, X. *Acoustic Testing to Enhance Western Forest Values and Meet Customer Wood Quality Needs*; Department of Agriculture Forest Service, US Department of Agriculture (USDA): Madison, WI, USA, 2005; pp. 121–129.
21. Wang, X.; Ross, R.J.; Carter, P. Acoustic evaluation of wood quality in standing trees-Part I. Acoustic wave behavior. *Wood Fiber Sci.* **2007**, *39*, 28–38.
22. Krajnc, L.; Farrelly, N.; Harte, A.M. The effect of thinning on mechanical properties of Douglas fir, Norway Spruce, and Sitka Spruce. *Ann. For. Sci.* **2019**, *76*, 3. [[CrossRef](#)]
23. Guntekin, G.; Emiroglu, Z.G.; Yolmaz, T. Prediction of bending properties for Turkish red pine (*Pinus brutia* Ten.) Lumber using stress wave method. *BioResources* **2013**, *8*, 231–237. [[CrossRef](#)]
24. Tsehaye, A.; Buchanan, A.H.; Walker, J.C.F. Sorting of logs using acoustics. *Wood Sci. Technol.* **2000**, *34*, 337–344. [[CrossRef](#)]
25. Wang, X.; Ross, R.J. Nondestructive Evaluation for Sorting red maple logs. In Proceedings of the 28th Annual Hardwood Symposium, West Virginia Now—The Future for the Hardwood Industry? Davis, WV, USA, 11–13 May 2000; pp. 95–101.
26. Wang, X.; Ross, R.J.; Green, D.W.; Brashaw, B.; Englund, K.; Wolcott, M. Stress wave sorting of red maple logs for structural quality. *Wood Sci. Technol.* **2004**, *37*, 531–537. [[CrossRef](#)]
27. Mora, C.R.; Schimleck, L.R.; Isik, F.; Mahon, J.M.; Clark, A.; Daniels, R.F. Relationship between acoustic variables and different measures of stiffness in standing *Pinus taeda* trees. *Can. J. For. Res.* **2009**, *39*, 1421–1429. [[CrossRef](#)]
28. Wessels, C.B.; Malan, F.S.; Rypstra, T. A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. *Eur. J. For. Res.* **2011**, *130*, 881–893.
29. Tenorio, C.; Moya, R.; Muñoz, F. Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelina arborea* trees. *J. Wood Sci.* **2011**, *57*, 134–139. [[CrossRef](#)]
30. Brashaw, B.K.; Bucur, V.; Divos, F.; Goncalves, R.; Lu, J.X.; Meder, R.; Pellerin, R.F.; Potter, S.; Ross, R.J.; Wang, X.P.; et al. Non-destructive testing and evaluation of wood: A worldwide research update. *For. Prod. J.* **2009**, *59*, 7–14.
31. Aratake, S.; Arima, T. Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs. II. Possibility of application for sugi square lumber with pith. *Mokuzai Gakkaishi* **1994**, *40*, 1003–1007.
32. Ross, R.J.; McDonald, K.A.; Green, D.W.; Schad, K.C. Relationship between log and lumber modulus of elasticity. *For. Prod. J.* **1997**, *47*, 89–92.
33. Wang, X. Advanced sorting technologies for optimal wood products and woody biomass utilization. In Proceedings of the International Conference on Biobase Material Science and Engineering, Changsha, China, 21–23 October 2012; pp. 175–179.
34. Teder, M.; Pilt, K.; Miljan, M.; Lainurm, M.; Kruuda, R. Overview of some non-destructive methods for in-situ assessment of structural timber. In Proceedings of the 3rd International Conference Civil Engineering, Jelgava, Latvia, 12–13 May 2011.
35. Legg, M.; Bradley, S. Measurement of stiffness of standing trees and felled logs using acoustics: A review. *J. Acoust. Soc. Am.* **2016**, *139*, 588–604. [[CrossRef](#)] [[PubMed](#)]
36. Mochan, S.; Moore, J.; Conolly, T. *Using Acoustics Tools in Forestry and the Wood Supply Chain*; Forestry Commission Technical Note 18; Forestry Commission: Edinburgh, UK, 2009.



37. Wang, X. Fundamentals of acoustic measurements on trees and logs and their implication to field application. In Proceedings of the 17th International Symposium on Non-Destructive Testing and Evaluation of Wood, Sopron, Hungary, 14–16 September 2011; pp. 25–33.
38. Wang, X. Acoustic measurements on trees and logs: A review and analysis. *Wood Sci. Technol.* **2013**, *47*, 965–975. [[CrossRef](#)]
39. Vanninen, P.; Ylitalo, H.; Sievanen, R.; Makela, A. Effect of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). *Trees* **1996**, *10*, 231–238. [[CrossRef](#)]
40. Vargashernandez, J.; Adams, W.T. Genetic relationships between wood density components and cambial growth rhythm in young coastal Douglas-fir. *Can. J. For. Res.* **1994**, *24*, 1871–1876. [[CrossRef](#)]
41. Rozenberg, P.; Franc, A.; Bastien, C.; Cahalan, C. Improving models of wood density by including genetic effects: A case study in Douglas-fir. *Ann. For. Sci.* **2001**, *58*, 385–394. [[CrossRef](#)]
42. Zobel, B.J.; van Buijtenen, J.P. *Wood Variation: Its Causes and Control*; Springer: Berlin, Germany, 1989.
43. Todaro, L.; Macchioni, N. Wood properties of young Douglas-fir in Southern Italy: Results over a 12-year post-thinning period. *Eur. J. For. Res.* **2011**, *130*, 251–261. [[CrossRef](#)]
44. Todaro, L.; Quartulli, S.; Robusto, A.; Moretti, N. Effects of different thinning regimes on stand stability and timber assortments in a Douglas-fir forest. *Ital. For. Mont.* **2002**, *5*, 451–466, (In Italian with English Summary).
45. Schweingruber, H.S. *Tree Rings: Basic and Applications of Dendrochronology*; Kluwer: Dordrecht, The Netherlands, 1998.
46. Wang, S.Y.; Lin, C.J.; Chiu, C.M.; Chen, J.H.; Yang, T.H. Dynamic modulus of elasticity and bending properties of young Taiwania trees grown with different thinning and pruning treatments. *J. Wood Sci.* **2005**, *51*, 1–6. [[CrossRef](#)]
47. Peltola, H.; Kilpeläinen, A.; Sauvala, K.; Räisänen, T.; Ikonen, V.P. Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. *Silva Fenn.* **2007**, *41*, 489–505. [[CrossRef](#)]
48. Wang, X. Stress Wave-Based Non-Destructive Evaluation (NDE) Methods for Wood Quality of Standing Trees. Ph.D. Dissertation, Michigan Technological University, Houghton, MI, USA, 1999; p. 187.
49. Cown, D.J. Comparison of the effects of two thinning regimes on some wood properties of radiata pine. *NZ J. Forest Sci.* **1974**, *4*, 540–551.
50. Barbour, R.J.; Foyle, D.C.; Chauret, G.; Cook, J.A.; Karsh, M.B.; Ran, S. Breast height relative density and radial growth in mature Jack pine (*Pinus banksiana*) for 38 years after thinning. *Can. J. For. Res.* **1994**, *24*, 2439–2447. [[CrossRef](#)]
51. Wang, X.; Ross, R.J.; McClellan, M.; Barbour, R.J.; Erickson, J.R.; Forsman, J.W.; McGinnis, G.D. Non-destructive evaluation of standing trees with stress wave method. *Wood Fiber Sci.* **2001**, *33*, 522–533.
52. Pavari, A. Le classificazioni fitoclimatiche ed i caratteri della stazione [Phytoclimatic classifications and station characteristics]. *Scritti di Ecologia Selvicoltura e Botanica Forestale* **1959**, 45–116. (In Italian)
53. IUSS Working Group WRB. *World Reference Base for Soil Resources*; International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106; FAO: Roma, Italy, 2014.
54. Yang, H.; Yu, L.; Wang, L. Effect of moisture content on the ultrasonic acoustic properties of wood. *J. For. Res.* **2015**, *26*, 753–757. [[CrossRef](#)]
55. Divos, F. Acoustic Tools for Seedling, Tree and Log Selection. In Proceedings of the Final Conference of COST Action E53 The Future of Quality Control for Wood and Wood Products, Edinburgh, UK, 4–7 May 2010; p. 5.
56. Eckard, J.T.; Isik, F.; Bullock, B.; Li, B.; Gumpertz, M. Selection efficiency for solid wood traits in *Pinus taeda* using time-of-flight acoustic and micro-drill resistance methods. *For. Sci.* **2010**, *56*, 233–241.
57. Lasserre, J.P.; Mason, E.G.; Watt, M.S. Assessing corewood acoustic velocity and modulus of elasticity with two impact based instruments in 11-year-old trees from a clonal-spacing experiment of *Pinus radiata* D. Don. *For. Ecol. Manag.* **2007**, *239*, 217–221. [[CrossRef](#)]
58. Urhan, O.S.; Kolpak, S.E.; Jayawickrama, K.J.S.; Howe, G.T. Early genetic selection for wood stiffness in juvenile Douglas-fir and western hemlock. *For. Ecol. Manag.* **2014**, *320*, 104–117. [[CrossRef](#)]
59. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2016.

60. Candel-Pérez, D.; Lo, Y.H.; Blanco, J.; Chiu, C.M.; Camarero, J.; González de Andrés, E.; Imbert, J.; Castillo, F. Drought-induced changes in wood density are not prevented by thinning in Scots pine stands. *Forests* **2018**, *9*, 4. [[CrossRef](#)]
61. Mitchell, S.J. Stem growth responses in Douglas-fir and Sitka spruce following thinning, implications for assessing wind-firmness. *For. Ecol. Manag.* **2000**, *135*, 105–114. [[CrossRef](#)]
62. Todaro, L. Influenza delle tecniche colturali sulle qualità del legno di alcune conifere con particolare riferimento alla Douglasia [Influence of silvicultural treatments on wood quality on Douglas-fir trees]. *Monti e Boschi* **2002**, *3/4*, 3844. (In Italian)
63. Macdonald, H.; Hubert, J. A review of the effect of silviculture on timber quality of Sitka spruce. *Forestry* **2002**, *2*, 107–138. [[CrossRef](#)]
64. Štefančík, I.; Vacek, Z.; Sharma, R.P.; Vacek, S.; Rösslová, M. Effect of thinning regimes on growth and development of crop trees in *Fagus sylvatica* stands of Central Europe over fifty years. *Dendrobiology* **2018**, *79*, 141–155.
65. Ikeda, K.; Kino, N. Quality evaluation of standing trees by a stress-wave propagation method and its application I. Seasonal changes of moisture contents of sugi standing trees and evaluation with stress-wave propagation velocity. *Mokuzai Gakkaishi* **2000**, *46*, 181–188.
66. Wang, X.; Ross, R.J.; Punches, J.; Barbour, R.J.; Forsman, J.W.; Erickson, J.R. Evaluation of small-diameter timber for valued-added manu-facturing—A stress wave approach. In *Proceedings of the II International Precision Forestry Symposium*; Institute of Forest Resources, University of Washington: Seattle, WA, USA, 2003; pp. 91–96.
67. Briggs, D.G.; Thienel, G.; Turnblom, E.C.; Lowell, E.; Dykstra, D.; Ross, R.; Wang, X.; Carter, P. Influence of thinning on acoustic velocity of douglas-fir trees in western Washington and western Oregon. In *Proceedings of the 15th International Symposium on Non-destructive Testing of Wood*, Duluth, MN, USA, 10–12 September 2007; Forest Products Society: Madison, WI, USA, 2008; pp. 113–123.
68. Zhang, S.Y. Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. *Wood Sci. Technol.* **1995**, *29*, 451–465. [[CrossRef](#)]
69. Chauhan, S.S.; Walker, J.C.F. Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. *For. Ecol. Manag.* **2006**, *229*, 388–394. [[CrossRef](#)]
70. Lasserre, J.P.; Mason, E.; Watt, M. The influence of initial stocking on corewood stiffness in a clonal experiment of 11 year-old *Pinus radiata* D. Don. *N. Z. J. Forestry* **2004**, *49*, 18–23.
71. Clark, A.; Daniels, R.F. Modelling the effect of physiographic region on wood properties of planted loblolly pine in southeast United States. In *Proceedings of the Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software*, Fourth Workshop IUFRO Working Party S5.01-04, Harrison Hot Springs, BC, Canada, 8–15 September 2002; p. 663.
72. Marziliano, P.A.; Coletta, V.; Menguzzato, G.; Nicolaci, A.; Pellicone, G.; Veltri, A. Effects of planting density on the distribution of biomass in a douglas-fir plantation in southern Italy. *iForest* **2015**, *8*, 368–376. [[CrossRef](#)]
73. Coletta, V.; Menguzzato, G.; Pellicone, G.; Veltri, A.; Marziliano, P. Effect of thinning on above-ground biomass accumulation in a Douglas-fir plantation in southern Italy. *J. For. Res.* **2016**, *27*, 1313–1320. [[CrossRef](#)]
74. Marziliano, P.A.; Menguzzato, G.; Scuderi, A.; Scalise, C.; Coletta, V. Biomass conversion and expansion factors in Douglas-fir stands of different planting density: Variation according to individual growth and prediction equations. *For. Syst.* **2017**, *26*, e003. [[CrossRef](#)]
75. Nakamura, N. Measurement of the properties of standing trees with ultrasonics and mapping of the properties. *Univ. For. Res.* **1996**, *96*, 125–135.
76. Sandoz, J.L. Non-destructive testing of wood. In *Proceedings of the 10th International Symposium on NDT*, Lausanne, Switzerland, 26–27 August 1996.
77. Zhang, S.Y.; Chauret, G.; Ren, H.Q.; Desjardins, R. Impact of plantation black spruce initial spacing on lumber grade yield, bending properties and MSR yield. *Wood Fiber Sci.* **2002**, *34*, 460–475.
78. Gorman, T.M.; Wagner, F.G.; Wu, S.Y. Assessment of intensive stress-wave scanning of Douglas-fir trees for predicting lumber modulus of elasticity. In *Proceedings of the 13th International Symposium on Nondestructive Testing of Wood*, Richmond, BC, Canada, 19–21 August 2002; pp. 143–148.
79. Castera, P.; Faye, C.; El Ouadrani, A. Prevision of the bending strength of timber with a multivariate statistical approach. *Ann. For. Sci.* **1996**, *53*, 885–898. [[CrossRef](#)]

80. Haartveit, E.Y.; Flate, P.O. Mechanical properties of Norway spruce lumber from monocultures and mixed stand-modelling bending stiffness and strength using stand and tree characteristics. In Proceedings of the Connection between Silviculture and Wood Quality: Modelling Approach and Simulation Software, IUFRO WP S5.01-04 Workshop, Harrison Hot Springs, BC, Canada, 8–15 September 2002; p. 2002.
81. Lei, Y.C.; Zhang, S.Y.; Jiang, Z. Models for predicting lumber bending MOR and MOE based on tree and stand characteristics in black spruce. *Wood Sci. Technol.* **2005**, *39*, 37–47. [[CrossRef](#)]
82. Burkhart, H.E. Development of empirical growth and yield models. In Proceedings of the Empirical and Process-Based Models for Forest Tree and Stand Growth Simulation, A Workshop/Ph.D. Course Jointly Organized by Technical University of Lisbon and IUFRO 4.01, Oeiras, Portugal, 21–27 September 1997; p. 10.






© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

**Appendix 2**

Article

# Tree Growth and Wood Quality in Pure Vs. Mixed-Species Stands of European Beech and Calabrian Pine in Mediterranean Mountain Forests

Diego Russo <sup>1</sup>, Pasquale A. Marziliano <sup>1,\*</sup> , Giorgio Macrì <sup>1</sup>, Giuseppe Zimbalatti <sup>1</sup>, Roberto Tognetti <sup>2,3</sup>  and Fabio Lombardi <sup>1</sup> 

<sup>1</sup> Department of AGRARIA, Mediterranean University of Reggio Calabria, 89122 Reggio Calabria, Italy; diego.russo@unirc.it (D.R.); giorgio.macri@unirc.it (G.M.); gzimbalatti@unirc.it (G.Z.); fabio.lombardi@unirc.it (F.L.)

<sup>2</sup> Department of Agricultural, Environmental and Food Sciences, University of Molise, 86100 Campobasso, Italy; tognetti@unimol.it

<sup>3</sup> The EFI Project Centre on Mountain Forests (MOUNTFOR), Edmund Mach Foundation, Via Edmund Mach, 38010 San Michele all'Adige, Italy

\* Correspondence: pasquale.marziliano@unirc.it; Tel.: +3909651694256

Received: 2 October 2019; Accepted: 16 December 2019; Published: 18 December 2019



**Abstract:** Mixed-species forests may deliver more forest functions and services than monocultures, as being considered more resistant to disturbances than pure stands. However, information on wood quality in mixed-species vs. corresponding pure forests is poor. In this study, nine plots grouped into three triplets of pure and mixed-species stands of European beech and Calabrian pine (three dominated by European beech, three dominated by Calabrian pine, and three mixed-species plots) were analysed. We evaluated tree growth and wood quality through dendrochronological approaches and non-destructive technologies (acoustic detection), respectively, hypothesizing that the mixture might improve the fitness of each species and its wood quality. A linear mixed model was applied to test the effects of exogenous influences on the basal area index (BAI) and the dynamic modulus of elasticity (MOEd). The recruitment period (Rp) was studied to verify whether wood quality was independent from stem radial growth patterns. Results showed that the mixture effect influenced both wood quality and BAI. In the mixed-species plots, for each species, MOEd values were significantly higher than in the corresponding pure stands. The mixture effect aligned MOEd values, making wood quality uniform across the different diameter classes. In the mixed-species plots, a significant positive relationship between MOEd and Rp, but also significantly higher BAI values than in the pure plots, were found for European beech, but not for Calabrian pine. The results suggest the promotion of mixing of European beech and Calabrian pine in this harsh environment to potentially improve both tree growth and wood quality.

**Keywords:** TreeSonic; MOEd; forest productivity; dendrochronology; recruitment period; Aspromonte National Park

## 1. Introduction

Mixed-species forests may deliver forest functions and services more effectively than monocultures [1,2], particularly in threatened mountain environments [3] and in man-made mixed-species forests. Therefore, their spread is an important option to adapt European mountain forests and forestry to future disturbances and extreme events [4]. Mixed-species forests may show less temporal variation in growth and more stable productivity in comparison with pure stands, due to reduced tree species competition for resources [5–13]. Nevertheless, contradictory mixed-species effects

on tree growth have been found under conditions favouring drought stress or in dry years [14–16]. Gebauer et al. [17] observed that stand-level canopy transpiration was not higher in mixed broad-leaved forests than in pure European beech stands and that the spatial complementarity in root water uptake of mixed-species stands could be masked by edaphic conditions preventing the vertical stratification of species-specific root systems. An increase in the frequency and severity of drought events, as predicted for the coming decades [18,19], will have dramatic implications for the resilience of Mediterranean mountain ecosystems, particularly in the case of forest stands with a simplified vertical structure [20]. Indeed, species-specific functional traits and allometric relations can be more important for stand water use than tree species diversity *per se*. Therefore, more insight into species mixing, structural diversity and forest dynamics is essential for modeling risk assessment and forest functions aimed at fostering alternative silvicultural practices in harsh environments.

Although mixed-species stands can be more productive in comparison with monocultures [21–24] up to 30% [25], site conditions, stand age, and tree species interactions affect these responses [26,27]. Focusing on the causes of differences in tree growth and stand productivity between mixed-species and pure forests, most research addressed environmental settings and relationships with climatic conditions, species composition, mixture type, and stand age [28–36]. Indeed, few studies exist on the quality and value of wood produced in mixed-species vs. corresponding pure stands [37]. Information on how wood quality can be affected in relation to tree species composition is essential for decision making in adaptive forestry, especially where forest planning and thinning activities favour the occurrence of mixed-species stands [27].

Liu et al. [38] showed that spacing and thinning experiments in pure stands highlighted the strong effect of the surrounding spatial stand structure on tree growth and morphology and, ultimately, wood structure and timber quality. Chomel et al. [39] demonstrated that, in mixed-species plantations, mixing hybrid poplar and white spruce might increase the wood production of poplar in comparison with monocultures of either poplar or white spruce. Battipaglia et al. [40] showed a considerable increase in cumulative basal area and in intrinsic water use efficiency in mixed-species stands of pedunculate oak and Italian alder, largely resulting from an increase in N fixation, which levelled off, when natural mortality or management practices decreased the competitive ability of Italian alder. In addition to stand productivity and water use efficiency, species mixtures with structural stratification may also enhance individual-tree growth rates and stem quality of species in the upper canopies, minimizing the proportion of taller species that reach the highest production [6,41].

Forest management practices oriented to obtain mixed-species stands potentially determine variation in the physical and mechanical properties of the harvested wood, both at stand and tree level [42]. Nevertheless, although mixed-species forestry is gaining popularity in Europe [10,43], a greater understanding of the differences in wood quality between mixed-species vs. corresponding pure stands is needed. In the last decades, the evaluation of wood quality has been preferentially based on non-destructive technologies (NDTs) [44]. More specifically, stress wave-based non-destructive acoustic techniques resulted in very useful methods for predicting the mechanical properties of woody materials [45]. Nowadays, acoustic sensing technology allows for the estimation of wood quality and intrinsic woody properties for standing trees, stems and logs. Among the parameters measurable by acoustic methods, the most important is the dynamic modulus of elasticity (MOEd), being related to wood anatomy and tree physiology. This parameter can be used for the evaluation of wood quality, providing information on the stiffness of material [46,47].

In this study, the wood quality term refers to the use of wood in the field of construction. The wood properties that determine the structural requirements are defined by indicators, such as strength grades, that depend on knottiness, stiffness and density of the wood [48]. These parameters are commonly used worldwide to define strength grades [49]. With reference to stiffness, the dynamic modulus of elasticity (MOEd) is considered a good predictor, so as to be used as a proxy variable for assessing the wood quality and, in particular, its stiffness [50]. As a matter of fact, profound implications for



wood properties and utilization derive from the growth and ecophysiological responses of trees to environmental conditions.

We focused on two important tree species, European beech (*Fagus sylvatica* L.) and Calabrian pine (*Pinus nigra* Arnold subsp. *calabrica*), widespread in mountainous forest ecosystems of Southern Italy; European beech is a late-successional broadleaved tree species, here occurring in its southernmost ecological limit, whereas Calabrian pine is an early-successional conifer, providing timber of high quality. In the Calabrian Apennines, these species occur in both pure and corresponding mixed-species stands, which may help test the effects of mixture on tree growth and wood quality in a drought-prone environment. Our study comprises nine plots grouped into three triplets of pure and mixed-species stands of European beech and Calabrian pine (three dominated by European beech, BP, three dominated by Calabrian pine, PP, and three mixed-species plots, MBP), in the Aspromonte National Park. The three stands grow in the same environmental conditions and show similar structural traits. We hypothesized that the mixture effect may improve the physiological fitness of each species and, thus, the wood quality. The specific objectives of the study were to: (Q1) evaluate the wood quality (MOEd), (Q2) analyse tree growth patterns through the basal area index (BAI), and (Q3) highlight potential relationships between wood quality and tree growth, in mixture vs. monocultures. In particular, we tested whether (i) the mean wood quality in mixed-species and corresponding pure stands are equal, (ii) the mean BAI in pure and mixed-species stands are equal, and if (iii) the wood quality and tree growth patterns are independent.

## 2. Materials and Methods

### 2.1. Study Area

The study area is located in the Aspromonte National Park, Calabria (Southern Italy), near the village of Bagaladi (RC). The climate is temperate, with an annual mean temperature of around 8 °C and minimum and maximum monthly means of 0.5 °C (coldest month) and 16 °C (warmest month), respectively. Annual precipitation is 1611 mm unevenly distributed over the year (Meteorological station of Gambarie d'Aspromonte—1187 m above sea level (a.s.l.)).

The study is based on nine plots (each with an extension of 5000 m<sup>2</sup> and square shape), grouped into three triplets of pure and mixed-species stands of European beech and Calabrian pine, using a randomized block design. Plots within each block were randomly assigned to the units. Each triplet, extended over 1.5 ha, contains two monospecific plots, dominated by European beech (BP) or Calabrian pine (PP), and one mixed-species European beech—Calabrian pine stand (MBP). The pure stands were selected if the target species represented ~90% of the stand basal area. The mixed-species stand was defined as the stand in which the two species together represented at least ~80% of the total stand basal area and the sum of the basal area of other species was lower than that of each of the two studied species. In order to quantify the mixing effects, the pure stands were used as reference for the mixed-species stand.

Plots are located in similar environmental conditions in terms of environmental settings (topography, slope, substrate) and climatic conditions. Soils developed from igneous and metamorphic rocks and are classified as Umbrisols, Cambisols and Leptosols [51], with an udic soil regime moisture. Further details on the main environmental conditions characterizing the study site are reported in Table 1.

These forest stands are of natural origin, with a dominant age ranging from 70 to 120 years old. They evolved naturally in the last 70 years. However, these forests (approximately until the Second World War) were cut following a management approach based on the “selection cutting” criteria, in which few trees were cut approximately every 20 years in the same forest section [52]. This type of management has preserved the typical forest landscape by maintaining a continuous forest cover, determining a stand structure consisting of clusters of trees in different age classes. These clusters are

the result of the natural regeneration occurring in the gaps opened by the selection cutting previously applied [52].

**Table 1.** The main geographical features of the investigated triplets located nearby the village of Bagaladi, RC (Aspromonte National Park).

	Triplet 1	Triplet 2	Triplet 3
Latitude (N)	38°06′50.53″	38°05′54.59″	38°06′15.69″
Longitude (E)	15°51′53.25″	15°50′37.72″	15°51′23.37″
Exposure (°)	59	59	59
Altitude (m a.s.l.)	1521	1511	1497
Slope (°)	28	30	34

## 2.2. Tree Sampling and BAI Analyses

In 2017, in order to derive the dendrometric variables at the stand level, the nine plots were fully inventoried. The diameters at breast height (DBH) and the total heights (Ht) of all trees were measured. Tree volume was calculated using the equations derived for the prediction of the aboveground tree volume [53]. Canopy dominant/co-dominant trees were targeted for sampling (coring and measuring MOEd) and were selected through a stratified random sampling, in relation to the frequency of the diameter classes at the plot level. In detail, in each monospecific stand (BP and PP), 30 dominant trees per species were cored, while 60 dominant trees were cored (30 for European beech and 30 for Calabrian pine) in MBP. For each selected tree, two increment cores were collected at breast height and at an angle of 120° to each other. Particular care was taken to select trees with canopies well separated from each other. Moreover, to avoid the effect of wood alteration and exogenous disturbances on tree ring growth, only trees without abrasion scars or other visible evidence of injury were selected. Cores were then mounted on channeled wood, seasoned in a fresh-air dry store and sanded a few weeks later. Ring widths were measured with a resolution of 0.01 mm using the LINTAB measurement equipment (Frank Rinn, Heidelberg, Germany) fitted with a Leica MS5 stereoscope (Leica Microsystems, Wetzlar, Germany). Tree ring widths were then statistically cross-dated and verified with the software TSAP software package (version 4.81c) and COFECHA (version 6.06) [54]. Once all measurement series were validated, tree-ring chronologies were developed for each species. Subsequently, tree ring widths were converted into tree basal area increment (BAI), according to the following standard formula:

$$BAI = \pi(r_n^2 - r_{(n-1)}^2)$$

where  $r$  is the radius of the stem at breast height and  $n$  is the year of tree-ring formation. In order to examine the mean growth trend for the sampled trees, BAI for each year was averaged over all the individuals for removing the variation in radial growth attributable to the increasing tree circumference.

The latest fully built tree ring valid for our analysis was related to 2016. We considered only the tree-ring chronologies starting from 1900, because few trees had rings formed before the year 1900.

## 2.3. Wood Quality

In order to evaluate the wood quality, acoustic wave tests were conducted at breast height on the same 120 trees from which the woody cores were collected. In order to reduce the effect of air humidity [55], the tests were carried out in the summer of 2017, from June to July.

TreeSonic (FAKOPP TreeSonic™ Fakopp Enterprise, Agfalva, Hungary) [44,56] was used for measuring the acoustic velocity. It is characterized by a hand-held hammer and two probes, a transmitting accelerometer and a receiving accelerometer. The system consists in the insertion of two sensor probes (a transmitting probe and a receiving one) into the sapwood, applying acoustic energy into the tree stem through hammer impact. The probes were aligned within a vertical plane on the same face. In our study, a 1.00-m testing span was roughly centered at breast height. The lowest probe



was placed about 60–70 cm above the forest floor. Three measurements were realized for each selected tree and the average of the three recordings was used as final transit time. In order to measure the acoustic velocity wave, the start and stop sensors were driven at a 45° angle through the bark into the wood of the standing tree [57]. Acoustic velocity was determined on the upstream side of the tree (according to standard procedure), the same side where the stem diameter was measured. The acoustic velocity (CT) was then calculated from the span between the two sensor probes and the time-of-flight (TOF) data, using the following formula:

$$CT = S/TOF \quad (1)$$

where CT = tree acoustic velocity (m/s), S = distance between the two probes (sensors) (m), TOF = time-of-flight (s).

The wood density of each measured tree was also determined on the woody cores. The fresh weight and volume of the tree cores were measured in the laboratory. Woody samples were weighed to the nearest 0.01 g with an electronic scale. After ring width measurements, the woody cores were dried in oven at 105 °C, to constant weight. Density ( $\text{kg m}^{-3}$ ) was calculated by dividing the dry weight by the fresh volume.

Afterwards, it was possible to calculate the modulus of elasticity (MOE), according to the following equation:

$$MOEd = WD_i \times CT^2; \quad (2)$$

where  $WD_i$  = tree wood density  $i$  ( $\text{kg m}^{-3}$ ) and  $CT$  = velocity ( $\text{km s}^{-1}$ ).

When MOE is estimated using the above formula, it is termed dynamic modulus of elasticity (MOEd) [58], as the stress wave propagation in wood is a dynamic process, internally related to the physical and mechanical properties of wood [59].

#### 2.4. Relationship between Wood Quality and Tree Growth

In standing trees, the stress wave propagation is affected by tree stem diameter, wood travel distance and internal wood conditions [60]. Furthermore, the mean tree values of timber grade-determining properties (elastic modulus, bending strength, and wood density) are related to the acoustic velocity and tree slenderness. Signals are transferred through the whole stem, depending on stem diameter: when smaller is the diameter, then the signal is more transferred inside the stem [61]. In this study, we used the tree final growth time to evaluate the relationship between wood quality and tree growth, in order to verify if the wood quality was independent from tree growth. In detail, the final growth time is given by the number of radial rings included in the outermost 2.5 cm of the sampled trees. This parameter is called “recruitment period” (RP), which indicates the number of years needed to pass from a diameter class  $x_i$  to the largest class  $x_i + 5$ , assuming classes of 5 cm [62]. Therefore, for each sampled tree, we counted the number of rings contained in the last 2.5 cm.

#### 2.5. Statistical Analysis

The data collected were characterized by a nested structure and they were not independent from each other: in detail, an inter-correlation among samples occurred, since they were referred to the same triplets, and the single tree ring chronologies belonged to one single tree. Therefore, an analysis based on a linear mixed model was used, including both fixed and random effects. We then set up the model functions to test the effect of mixing on tree ring width (expressed as BAI) and on the MOEd. The linear mixed models incorporated the triplet identifier as a random effect, thus considering both the mixing effect (expressed as percentage of basal area of the examined species of beech or pine, compared to the total area) and the nested structure of the data. The initial model included the following independent variables: basal area, stem DBH, tree height, tree age. A stepwise procedure (in each step, a variable was considered for addition to or subtraction from the set of explanatory variables based on  $F$ -tests) eliminated all variables, except for the basal area, the only variable that had a significant effect on

the dependent variable. Therefore, the below model, based only on mixing effect and the nested design of data, was applied to evaluate if significant differences on BAI between mixed-species and corresponding pure stands occurred:

$$BAI_{ij} = \beta_0 + \beta_1 \times Mix_{ij} + u_j + \varepsilon_{ij}$$

where  $BAI_{ij}$  is the mean of the basal area increment per tree  $i$  on triplet  $j$ ,  $\beta_0$  is the intercept,  $Mix_{ij}$  is the fixed effect describing the quantification of the mixing effect (expressed as % basal area) on tree BAI for tree  $i$  on triplet  $j$ ,  $u_j$  is the random effect for triplet  $j$  and  $\varepsilon_{ij}$  is the error term. Moreover, the following model was used to analyse the effect of both mixture and tree ring width (expressed as recruitment period) on wood quality (MOEd values), incorporating the triplet identifier as a random effect:

$$MOEd_{ij} = \beta_2 + \beta_3 \times Mix_{ij} + \beta_4 \times RP_{ij} + u_j + \varepsilon_{ij}$$

where  $MOEd_{ij}$  is the wood quality of tree  $i$  on triplet  $j$ ,  $RP_{ij}$  is the recruitment period of tree  $i$  on triplet  $j$ , examined as the main effect. For the linear mixed-effect model analysis, the nlme package for the R programming language [63] was used. In addition to the linear mixed-effect models, the Mann-Whitney Test for independent-sample ( $U$ -Test) was also used to compare the average MOEd values and the average BAI values between mixed-species and pure stands. More specifically, the  $U$ -test is a non-parametric test and requires no assumptions.

### 3. Results

Table 2 shows the main structural and dendrometric characteristics of the studied stands, while in Table 3, the age, the wood density, the acoustic velocity and the MOEd for the sampled trees are reported. Forest structure did not differ markedly among the studied stands. Analysis of variance (ANOVA) showed no significant differences among plots in stand density ( $F_{3/6} = 1.020$ ;  $p = 0.447$ ), tree DBH ( $F_{3/6} = 0.329$ ;  $p = 0.805$ ), basal area ( $F_{3/6} = 2.104$ ;  $p = 0.201$ ) and stand volume ( $F_{3/6} = 2.208$ ;  $p = 0.188$ ). The number of trees per hectare varied from 743 in the pure European beech plots to 873 in the mixed-species plots. The tree volume ranged between  $773 \text{ m}^3 \text{ ha}^{-1}$  in the pure European beech plots and  $876 \text{ m}^3 \text{ ha}^{-1}$  in the mixed-species plots.

**Table 2.** Structural traits obtained for the investigated triplets. Mean values and the related standard deviation (in bracket) are reported.

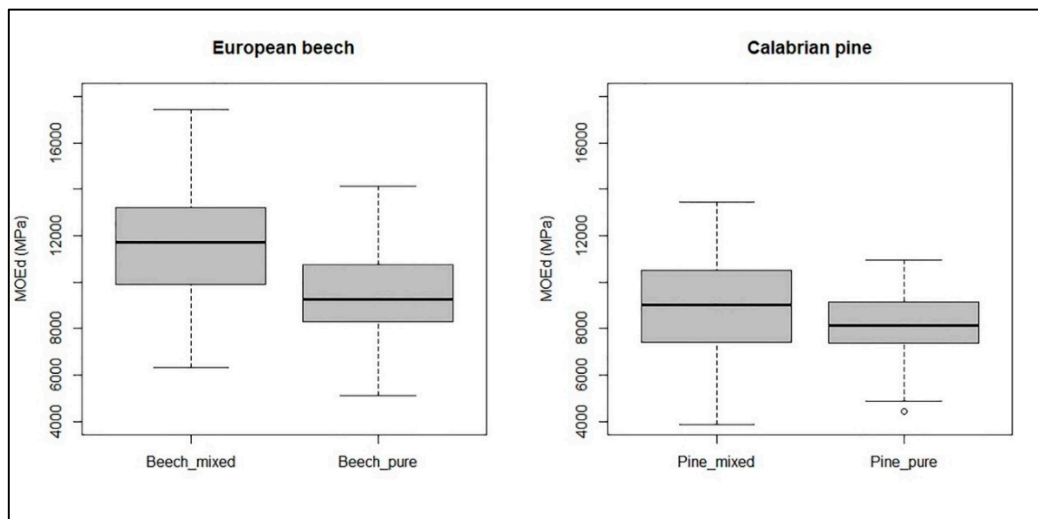
	Stand Density (N. Trees $\text{ha}^{-1}$ )	Tree DBH (cm)	Tree Height (m)	Basal Area ( $\text{m}^2 \text{ h}^{-1}$ )	Stand Volume ( $\text{m}^3 \text{ ha}^{-1}$ )
Beech pure	743 (155.7)	33.2 (2.8)	24.2 (2.2)	64.3 (4.6)	772.7 (41.5)
Pine pure	754 (96.3)	35.6 (4.4)	23.1 (0.8)	75.1 (10.4)	857.6 (160.9)
MBP-B	470 (75.9)	28.3 (2.3)	18.8 (1.3)	29.6 (6.3)	277.0 (31.1)
MBP-P	403 (74.1)	40.3 (9.6)	23.6 (5.1)	51.4 (14.1)	599.1 (90.7)

**Table 3.** Tree age, wood density, acoustic velocity, and MOEd values obtained for the two studied species in the pure and mixed-species stands (SD: standard deviation; MOEd: dynamic modulus of elasticity).

Stands	Tree Age (Years)		Wood Density ( $\text{kg m}^{-3}$ )		Wave Velocity ( $\text{m s}^{-1}$ )		MOEd (MPa)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Beech pure	69	41	658	28.4	3841.7	382.4	9523.2	1738.1
Pine pure	97	38	562	27.6	3823.4	427.5	8056.6	1358.2
MBP-B	127	33	653	30.1	4253.0	349.3	11583.0	2212.6
MBP-P	103	21	555	25.2	4066.4	370.6	8999.8	2132.6

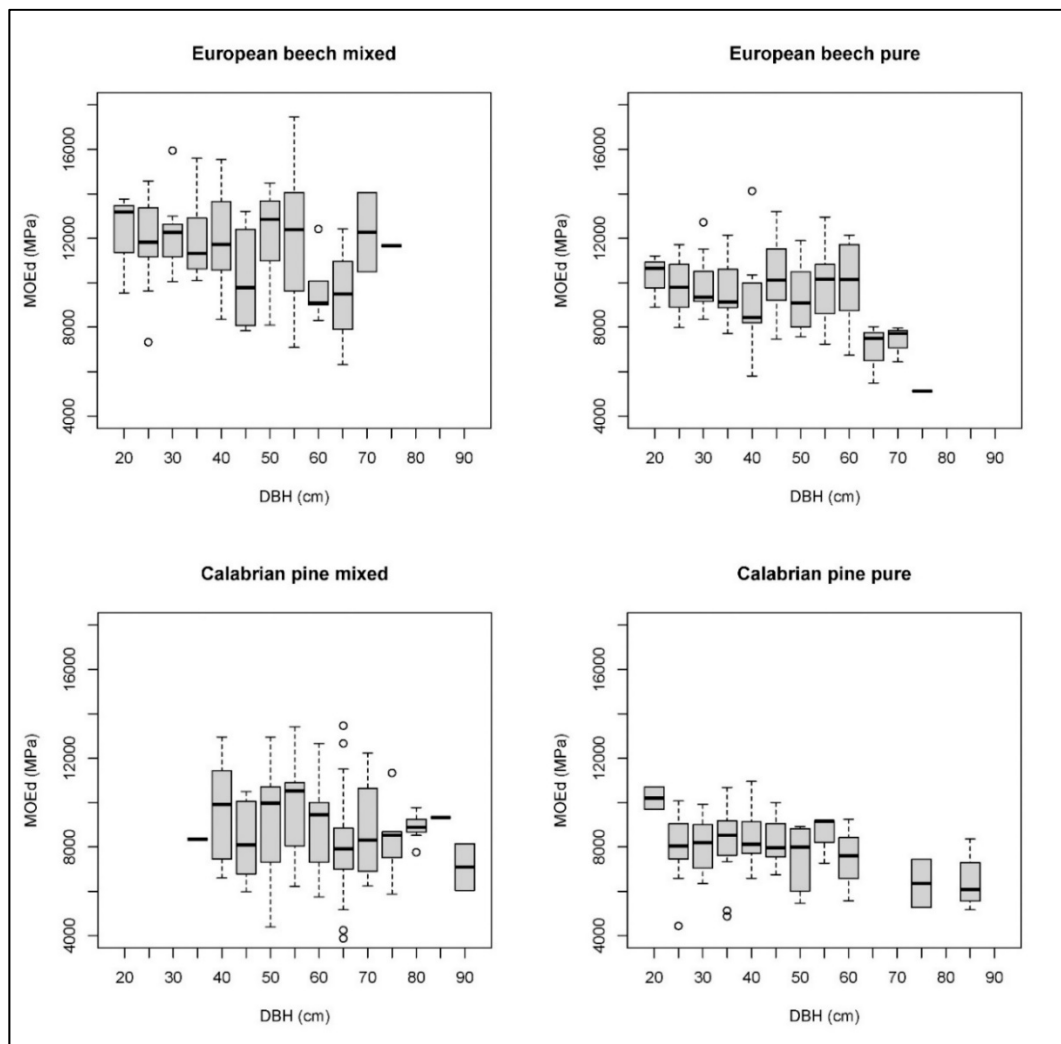
Tree age differed between the pure European beech plots (on average 69 years) and the European beech trees sampled in the mixed-species plots (on average 127 years) (Table 3). By contrast, Calabrian pines occurring in the pure and mixed-species plots revealed no significant differences in tree age (on average 100 years).

For both tree species, MOEd values were significantly higher in MBP than in BP and PP, as confirmed by the Mann-Whitney test applied for independent-samples (Figure 1). MOEd was 21.6% and 10.7% higher in MBP than in BP and PP, respectively. Further, considering the different diameter classes investigated, MOEd values were always higher in MBP than in BP and PP.



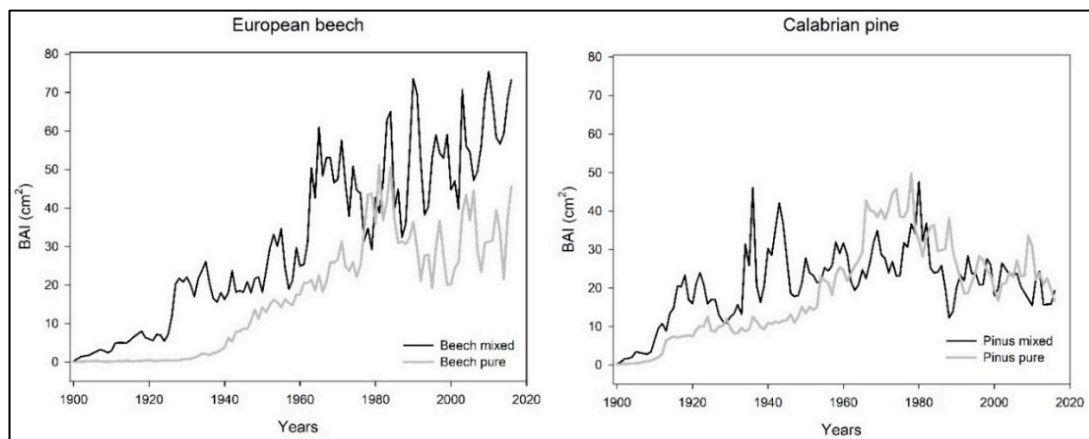
**Figure 1.** MOEd values in the pure and mixed-species stands for European beech (Mann-Whitney Test,  $Z = -6.491, p < 0.001$ ) and Calabrian Pine (Mann-Whitney Test,  $Z = -3.134, p < 0.010$ ).

Analysis of variance (ANOVA) showed a significant effect of the diameter classes on MOEd for BP and PP. As the diameter classes are not independent, the Kruskal–Wallis test was also used [64], which confirmed the significant effect of the diameter classes on MOEd. MOEd decreased as tree DBH increased, with significant differences observed between the smallest and the largest diameter classes. On the contrary, no significant differences were observed in MBP (Figure 2). The mixture of species had the effect of aligning MOEd values, both for European beech and Calabrian pine, making wood quality more uniform for each diameter class. In contrast, in the pure stands, MOEd values were significantly lower than in MBP, also varying significantly as tree DBH increased.



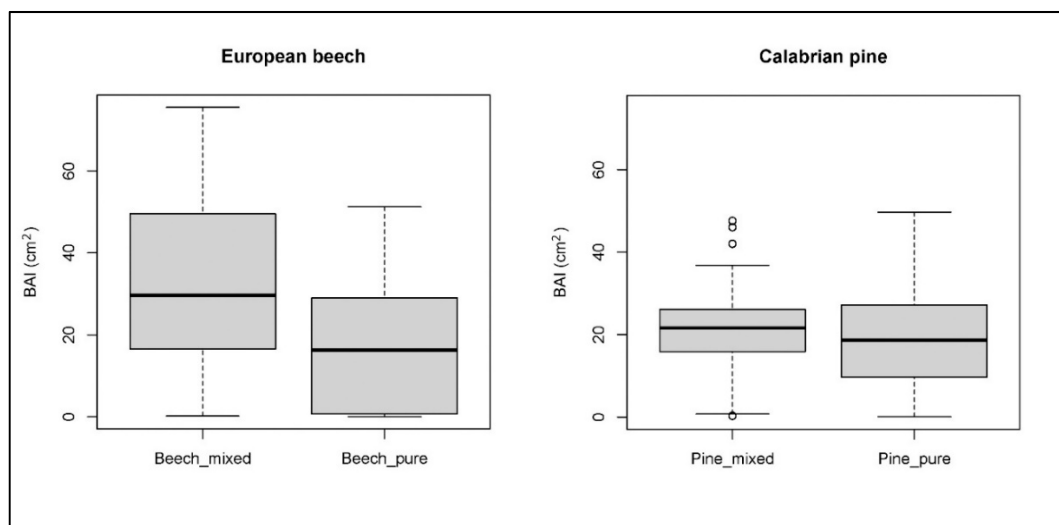
**Figure 2.** Dynamic modulus of elasticity (MOEd) in relation to the diameter classes for European beech and Calabrian pine growing in the pure and mixed-species stands. European beech in the mixed-species stand:  $F_{12;18} = 1.255$ ,  $p < 0.322$ ; for European beech in the pure stand:  $F_{12;18} = 2.461$ ,  $p < 0.050$ ; Calabrian pine in the mixed-species stand:  $F_{12;18} = 0.774$ ,  $p < 0.669$ ; Calabrian pine in the pure stand:  $F_{11;19} = 2.621$ ,  $p < 0.050$ .

Figure 3 shows the BAI values obtained for European beech and Calabrian pine. In general, BAI increased over time (at least up to a determined year) in both species. Overall, trees revealed higher BAI in MBP than in BP and PP. However, until 1980, BAI values of European beech growing in mixture were always higher than in BP. Later, a similar trend was observed, until 1990. In the last period (1990–2016), BAI values were again higher in MBP. In the period 1900–2016, BAI always increased in MBP, while it gradually decreased in BP, from 1990. For Calabrian pine, BAI values were higher in MBP than in PP, considering the period 1900–1960. Later, for about 20 years (1960–1980), an opposite trend was observed, with a higher BAI in PP. Furthermore, for 1980–2016, a consistent decrease of BAI values was observed for Calabrian pine, both in MBP and PP.



**Figure 3.** BAI values for European beech and Calabria pine growing in the pure and mixed-species stands. Values were considered starting from 1900.

Figure 4 reports both the variability and the average of BAI values for European beech and Calabrian pine growing in the pure and mixed-species stands. For European beech, the BAI variability was higher in MBP, while for Calabrian pine in PP. European beech growing in mixture had a significantly higher BAI values than in BP (+65%, 30.6 vs. 18.5 cm<sup>2</sup>, on average,  $p$ -value < 0.001). Yet, Calabrian pine growing in mixture revealed higher BAI values than in PP, although not significantly (+11%, 21.1 vs. 19.1 cm<sup>2</sup>, on average,  $p$ -value = 0.0563).



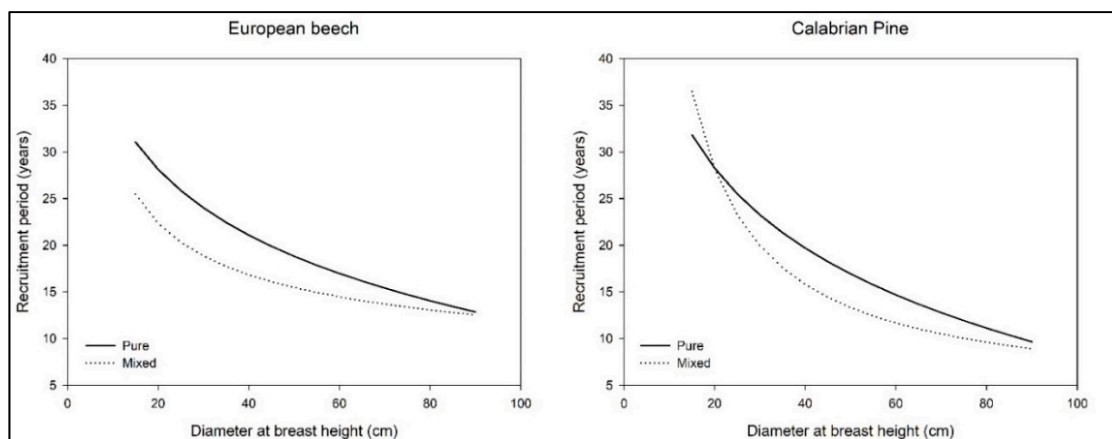
**Figure 4.** BAI values (mean values) in the pure and mixed-species stands for European beech (linear mixed-effect,  $p < 0.05$ ,  $R^2 = 0.437$ ; Mann-Whitney Test,  $Z = -4.345$ ,  $p < 0.0001$ ) and Calabrian pine (linear mixed-effect,  $p = 0.271$ ,  $R^2 = 0.078$ ; Mann-Whitney Test,  $Z = -1.928$ ,  $p = 0.0563$ ).

In Table 4, results obtained through the application of the linear mixed model are shown. The site identifier was considered as a random effect. The mixture significantly influenced European beech ( $p = 0.015$ ), but not Calabrian pine ( $p = 0.601$ ).

**Table 4.** Values achieved with the application of the linear mixed-effect model, considering the “triplet” as random effect. The influences of the fixed effects (BA%, RP) on the response variables “basal area increment” (BAI) and “dynamic modulus of elasticity” (MOEd) were examined. Significant variables are reported in bold.

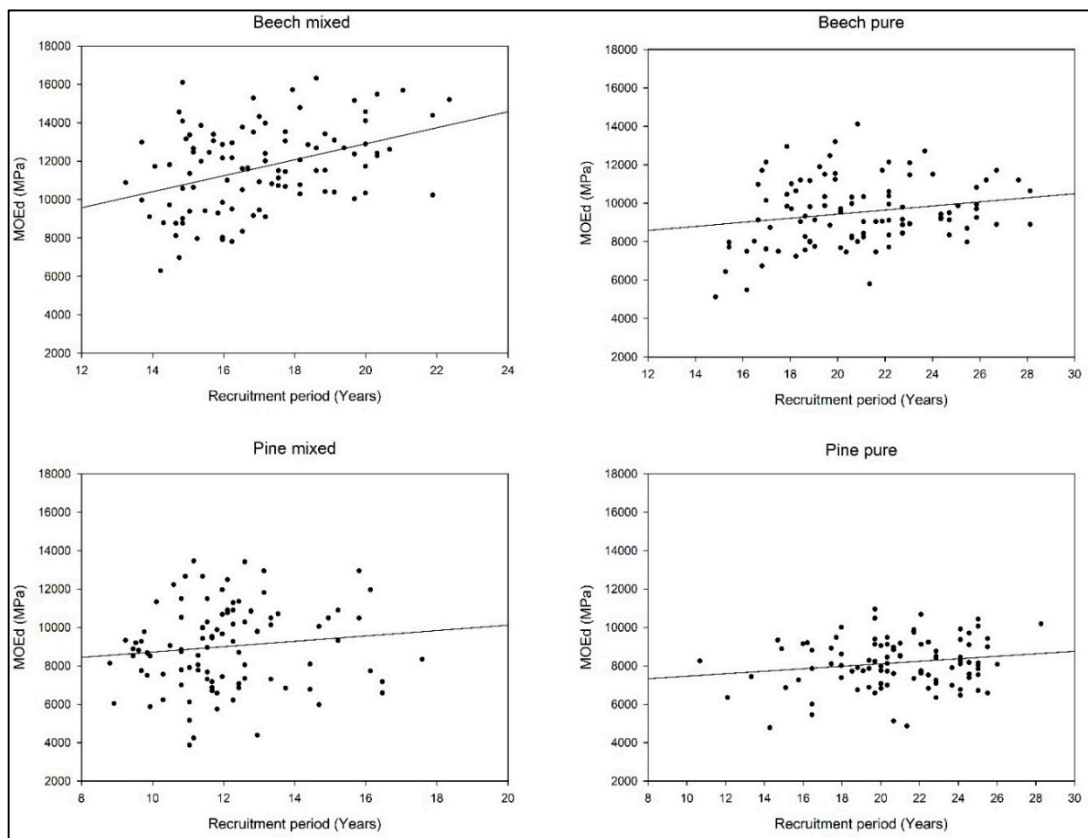
Model	Value	<i>t</i> -Value	<i>p</i> -Value	<i>R</i> <sup>2</sup>
European beech (BAI)				0.502
Intercept	17.623	7.720	<0.0001	
<b>Mix (BA)</b>	<b>0.358</b>	<b>4.047</b>	<b>0.0155</b>	
Calabrian pine (BAI)				0.015
Intercept	19.299	8.126	<0.0001	
Mix (BA)	0.028	0.567	0.6009	
European beech (MOEd)				0.278
Intercept	5114.401	4.191	0.0000	
<b>RP</b>	<b>210.252</b>	<b>4.119</b>	<b>0.0001</b>	
<b>Mix (BA)</b>	<b>76.434</b>	<b>3.353</b>	<b>0.0285</b>	
Calabrian pine (MOEd)				0.045
Intercept	6487.034	6.291	<0.0001	
RP	83.52	1.833	0.0684	
Mix (BA)	23.23	2.079	0.1061	

Figure 5 shows the values of the recruitment period (RP) for European beech and Calabrian pine, which invariably decreased as DBH increased. For European beech, RP was lower in MBP than in BP, though with lessening differences as DBH increased. Calabrian pine growing in PP had, for the first diameter classes, a slightly lower RP than in MBP, at least for the first diameter classes. Then, the trend was the opposite and the differences tended to increase, though not for the DBH of about 90 cm.



**Figure 5.** Recruitment period obtained for European beech and Calabrian pine growing in the pure and mixed-species stands. It indicates the number of years needed to pass from a diameter class  $x_i$  to the largest class  $x_i + 5$  cm.

Finally, in Figure 6, variations of MOEd as RP changes are shown. In each stand, MOEd tended to rise as RP increased, even if it revealed higher values in MBP than in BP and PP. In addition, the relationship between MOEd and RP was stronger in MBP, for both species. However, the analyses of the linear mixed-effects model underlined that only for European beech, RP ( $p < 0.0001$ ) and the mixing effect ( $p = 0.0285$ ) had a significant role, explaining the largest proportion of MOEd variation (Table 3). On the contrary, for Calabrian pine, RP ( $p = 0.0684$ ) and the mixing effect ( $p = 0.1061$ ) had marginal effects on MOEd.



**Figure 6.** Dynamic modulus of elasticity (MOEd) in relation to the recruitment period for European beech and Calabrian pine growing in the pure and mixed-species stands.

#### 4. Discussion

Results demonstrated how the mixture effect influenced both wood quality and tree ring widths. In both the pure and mixed-species stands, MOEd values were above the minimum quality threshold (MOEd > 9000 MPa) [65]. However, in the mixed-species plots, MOEd values were always higher than in the corresponding pure plots. This difference was more evident for European beech (11583 vs. 9523) than for Calabrian pine (8999 vs. 8056). Tree age differed between European beech trees sampled in the pure and mixed species plots, which might have played a role in determining differences in MOEd values. In the case of Calabrian pine, the differences in MOEd values are less evident, though significant. As a matter of fact, tree age did not differ between trees sampled in the pure and mixed-species plots.

Eventually, effects on MOEd exerted by the other parameters related to the stand structure (stand density, basal area, stand volume) could be excluded, since the parameters did not differ significantly between the pure and mixed-species stands. Several studies showed that, considering other variables being equal (stand density, stand volume, etc.), the mixture effect could have a role in improving the resistance and resilience of trees in comparison with the corresponding monocultures [21–24]. Yet, the mixed-species stands could also be more productive than the corresponding monocultures [26].

Therefore, even with some limitations, a mixture of European beech and Calabrian pine might have a positive effect on MOEd, not only at the stand level, but also considering the different diameter classes. In fact, in the mixed stands, the MOEd values were similar for all the diameter classes, in both species. On the contrary, in the pure stands, we observed a decrease in wood quality as the tree DBH increased. A combination of a light demanding tree species with one more shade tolerant was probably the foundation of these results. In other studies, mixed-species stands were found to show higher light interception and light-use efficiency in comparison with monocultures [10,66–68]. Promoting the



coexistence of these two species in the present environmental conditions might improve the quality of wood materials, regardless of the size of trees from which the assortments are obtained.

The MOEd values, strongly related to wood density and acoustic velocity, indicated an overall higher mechanical stability attained in the mixed-species stands. In fact, wood density is correlated with timber strength [69], hardness and abrasiveness [48]. Therefore, mixing these species might provide higher mechanical resistance to natural disturbances, such as windstorms, and higher carbon sequestration potential in these Mediterranean mountain forest ecosystems. It must be pointed out that Pretzsch and Rais [49] observed that the wood strength and stiffness could be lower in complex forests than in homogeneous monocultures, where tree size and shape development progress more continuously. Yet, Torquato et al. [70], in black spruce forests in Canada, detected lower strength and stiffness properties in complex stands.

Growing in mixtures induced an increase in tree biomass production, particularly for European beech, while differences between the pure and mixed-species stands were not significant for Calabrian pine. In European beech, although environmental conditions did not differ between stands, BAI was significantly higher in mixture than in monoculture. However, differences between the pure and mixed-species stands in tree age might also have affected BAI trends. The identification of growth trends and attribution of their drivers are not easy tasks, and require long-term and spatially-representative experiments to control the effect of tree size and age, avoiding sampling biases at the various scales. Indeed, heterogeneous crown structures and the tree size of mixed-species stands might facilitate the penetration of light into the lower canopy layers [10]. In the studied stands, European beech could take advantage of growing underneath the relatively transparent canopy of Calabrian pine. On the other hand, European beech in pure and dense stands develops homogeneous canopy cover, having high shade tolerance and large canopy expansion. Indeed, European beech growing in monocultures showed low self-tolerance [71,72], resulting in severe intraspecific competition due to high lateral canopy expansion [73]. Moreover, other studies reported beneficial effects on European beech productivity from growing in mixture [74,75]. Condes et al. [76] reported that the productivity of pine-beech admixtures was generally greater than in the corresponding pure stands. In light of this, admixture of European beech with Calabrian pine might, therefore, reduce competition or even increase facilitation processes in this Mediterranean mountain environment. Nevertheless, Conte et al. [16] observed higher productivity in the pure than mixed-species stands of European beech and Scots pine, in Alpine environmental conditions. These discrepancies suggest caution in generalizing the positive effects on European beech productivity from growing admixed with pine species.

However, the complexity of the species interactions, which depends on stand development stage, stand density and site conditions [26], suggests caution in generalizing these results, since other studies reported opposite patterns [77]. Equal productivity at the stand level might not necessarily indicate a neutral behaviour of the two species co-occurring in the mixed-species stands. In fact, species-specific reactions, at individual or stand level, might counteract and cancel each other with respect to the stand level productivity [74]. Behind overyielding or underyielding of mixed-species in comparison with nearby pure stands, as revealed in this study for Calabrian pine and European beech, there is always a modified supply and uptake, or different use-efficiency, of available resources [24,26,78]. Zhang et al. [21] reported that beneficial effects of admixing provided an overall 25% increase in productivity across forest types and a 12% increase at European scale in Scots pine—European beech mixtures [10]. Nevertheless, the mechanisms that might promote complementarity effects, leading to increased productivity in pine-beech mixtures, are poorly understood, despite the frequent occurrence and economic importance of these forest types [10].

Values of BAI in Calabrian pine and European beech mixtures, of both species, were generally greater than in the corresponding pure stands, although significant only in the case of European beech. European beech, especially in the mixed-species stands, had a constantly increasing BAI in the investigated time-span, although alternating years of little stem radial growth and years of great stem radial growth. On the contrary, Calabrian pine revealed a decrease in BAI values in the last 30–40 years.



Several studies reported that the inter-annual tree growth variability and its dependence on climatic conditions might be modulated by species composition [4,79–81]. A positive effect of species diversity on stand productivity, due to complementarity effects, might result in a greater size heterogeneity, with unknown consequences on the provision of goods and services in pure vs. mixed-species forests. A reduction in size asymmetry and growth inequality for European beech in mixture with Scots pine was related to the complementary light ecology of the associated species [10].

At the stand level, light absorption of admixed light demanding and shade tolerant species might benefit from light-related interactions, including canopy structure, stand density, tree size, crown architecture, and allometric relationships [82,83]. Nevertheless, in the present Mediterranean environment, although light-related interactions might contribute to the mixing effect on tree growth for Calabrian pine, water- and/or nutrient-related interactions might dominate in the mixing effect on tree growth for European beech [84]. Especially for European beech, we showed that the variability of BAI was higher in the mixed-species vs. the pure stands. Although this variability might have a minor role in determining the strength and stiffness of structural timber [49], it might still affect wood properties, such as the dimensional stability. Nevertheless, we may confirm that (i) wood quality was higher in the mixed-species than pure stands, (ii) wood quality was dependent on tree growth patterns and that (iii) the longer a tree took to pass from one diameter class to the next, the better was the wood quality. However, Genet et al. [85] stated that the way in which tree ring widths and ring wood density are related to each other would depend on whether the tree is a conifer, ring-porous hardwood, or diffuse-porous hardwood species.

We found a positive relationship between final growth time and MOEd, in both species. However, while for European beech MOEd was significantly dependent on tree growth (expressed as recruitment period), this relationship was not significant for Calabrian pine. In these relationships, MOEd was higher in the mixed-species than pure stands, for both species. Again, this might depend on species-specific growth patterns, as well as on technological wood features. However, it must be pointed out that wood quality of coniferous trees, in comparison with broadleaved species, might be strongly influenced by forest management practices. In fact, several studies on conifers [59,86–90], including Calabrian pine [44], showed a reduction in wood quality with increasing spacing and thinning.

Admixture of Calabrian pine and European beech might improve adaptation to rainy winters and dry summers of the Mediterranean climate, increasing both tree growth and wood quality, especially for European beech. Several studies showed that mixed-species forests might be more productive and resistant to disturbances, including drought, than corresponding pure stands [4,79], though contrasting evidence was also reported [14,16]. In particular, European beech populations from marginal ecological conditions were found more resistant to drought than those from the core of the distribution range [91–93], and their admixture with co-occurring drought-tolerant conifers might serve as benchmark for selecting resilient tree species combinations. Additional insight into the effect of tree species mixture on wood quality is required to support the entire wood supply chain, from the integration of wood quality in forest inventories to silvicultural guidelines for decision support tools. In fact, although structure and function of mixed-species stands are relevant for their role as supporting services in Mediterranean mountain forests, such as biodiversity conservation and soil protection, the consequence of structural heterogeneity in admixture on wood quality requires greater consideration in the future.

## 5. Conclusions

In the present study, the admixture of Calabrian pine and European beech increased stand productivity, particularly for European beech, and improved wood quality. Nevertheless, caution is still needed in drawing general conclusions on the mixture effect on wood quality and stand productivity, in marginal environmental conditions. Nevertheless, European beech and Calabrian pine co-occurring in forest stands of Southern Italy should be managed with the aim of improving the overall quality of wood, which could be promoted by mixing these species. Although any generalization could

be misleading, the admixture of tree species in these harsh environments might better maintain forest stability, ensuring also woody products of better quality. These results, though related to marginal environmental conditions, could be significant to implement and support climate-smart measures for managing Mediterranean mountain forests.

**Author Contributions:** Conceptualization, D.R., P.A.M., G.M. and F.L.; Data curation, D.R. and G.M.; Formal analysis, D.R., P.A.M., G.M., G.Z., R.T. and F.L.; Investigation, D.R. and G.M.; Methodology, D.R., P.A.M., R.T., and F.L.; Resources, R.T. and G.Z.; Writing—original draft, D.R., P.A.M., R.T. and F.L.; Writing—review & editing, P.A.M., R.T. and F.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Aspromonte National Park.

**Acknowledgments:** We are grateful to the Aspromonte National Park for the support given to realize this study. The research is linked to activities conducted within the COST (European Cooperation in Science and Technology) Action CLIMO (Climate-Smart Forestry in Mountain Regions-CA15226) financially supported by the EU Framework Programme for Research and Innovation HORIZON 2020, and the *Progetto bilaterale di Grande Rilevanza Italy-Sweden* “Natural hazards in future forests: how to inform climate change adaptation”.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Gamfeldt, L.; Snäll, T.; Bagchi, R.; Jonsson, M.; Gustafsson, L.; Kjellander, P.; Ruiz-Jaen, M.C.; Fröberg, M.; Stendahl, J.; Philipson, C.D.; et al. Higher levels of multiple ecosystem services are found in forests with more tree species. *Nat. Commun.* **2013**, *4*, 1340. [[CrossRef](#)] [[PubMed](#)]
2. van der Plas, F.; Manning, P.; Soliveres, S.; Allan, E.; Scherer-Lorenzen, M.; Verheyen, K.; Wirth, C.; Zavala, M.A.; Ampoorter, E.; Baeten, L.; et al. Biotic homogenization can decrease landscape-scale forest multifunctionality. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 3557–3562. [[CrossRef](#)] [[PubMed](#)]
3. Cudlín, P.; Klopčič, M.; Tognetti, R.; Máliš, F.; Alados, C.L.; Bebi, P.; Grunewald, K.; Zhiyanski, M.; Andonowski, V.; La Porta, N.; et al. Frans Emil Wielgolaski Drivers of treeline shift in different European mountains. *Clim. Res.* **2017**, *73*, 135–150. [[CrossRef](#)]
4. Pretzsch, H.; Bielak, K.; Bruchwald, A.; Dieler, J.; Dudzinska, M.; Erhart, H.P.; Jensen, A.M.; Johannsen, V.K.; Kohnle, U.; Nagel, J.; et al. Mischung und Produktivität von Waldbeständen. Ergebnisse langfristiger ertragskundlicher Versuche. *Allgemeine Forst-und Jagdzeitung* **2013**, *184*, 177–196.
5. Yachi, S.; Loreau, M. Does complementary resource use enhance ecosystem functioning? A model of light competition in plant communities. *Ecol. Lett.* **2007**, *10*, 54–62. [[CrossRef](#)]
6. Piotto, D. A meta-analysis comparing tree growth in monocultures and mixed plantations. *For. Ecol. Manag.* **2008**, *255*, 781–786. [[CrossRef](#)]
7. Morin, X.; Fahse, L.; Scherer-Lorenzen, M.; Bugmann, H. Tree species richness promotes productivity in temperate forests through strong complementarity between species. *Ecol. Lett.* **2011**, *14*, 1211–1219. [[CrossRef](#)]
8. Paquette, A.; Messier, C. The effect of biodiversity on tree productivity: From temperate to boreal forests. *Glob. Ecol. Biogeogr.* **2011**, *20*, 170–180. [[CrossRef](#)]
9. Pretzsch, H.; Schütze, G.; Uhl, E. Resistance of European tree species to drought stress in mixed versus pure forests: Evidence of stress release by inter-specific facilitation. *Plant Biol.* **2013**, *15*, 483–495. [[CrossRef](#)]
10. Pretzsch, H.; Schütze, G. Effect of tree species mixing on the size structure, density and yield forest stands. *Eur. J. For. Res.* **2015**, *135*, 1–22. [[CrossRef](#)]
11. Jucker, T.; Bouriaud, O.; Avacaritei, D.; Coomes, D.A. Stabilizing effects of diversity on aboveground wood production in forest ecosystems: Linking patterns and processes. *Ecol. Lett.* **2014**, *17*, 1560–1569. [[CrossRef](#)] [[PubMed](#)]
12. Metz, J.; Annighofer, P.; Schall, P.; Zimmermann, J.; Kahl, T.; Schulze, E.D. Site-adapted admixed tree species reduce drought susceptibility of mature European beech. *Glob. Chang. Biol.* **2016**, *22*, 903–920. [[CrossRef](#)] [[PubMed](#)]
13. Liang, J.; Crowther, T.W.; Picard, N.; Wiser, S.; Zhou, M.; Alberti, G.; Schulze, E.D.; McGuire, A.D.; Bozzato, F.; Pretzsch, H.; et al. Positive biodiversity–productivity relationship predominant in global forests. *Science* **2016**, *354*, 196. [[CrossRef](#)] [[PubMed](#)]

14. Grossiord, C.; Granier, A.; Gessler, A.; Jucker, T.; Bonal, D. Does drought influence the relationship between biodiversity and ecosystem functioning in boreal forests? *Ecosystems* **2014**, *17*, 394–404. [[CrossRef](#)]
15. Merlin, M.; Perot, T.; Perret, S.; Korboulewsky, N.; Vallet, P. Effects of stand composition and tree size on resistance and resilience to drought in sessile oak and Scots pine. *For. Ecol. Manag.* **2015**, *339*, 22–33. [[CrossRef](#)]
16. Conte, E.; Lombardi, F.; Battipaglia, G.; Palombo, C.; Altieri, S.; La Porta, N.; Marchetti, M.; Tognetti, R. Growth dynamics, climate sensitivity and water use efficiency in pure vs. mixed pine and beech stands in Trentino (Italy). *For. Ecol. Manag.* **2018**, *409*, 707–718. [[CrossRef](#)]
17. Gebauer, T.; Horna, V.; Leuschner, C. Canopy transpiration of pure and mixed forest stands with variable abundance of European beech. *J. Hydrol.* **2012**, *442*, 2–14. [[CrossRef](#)]
18. IPCC. Meeting report of the intergovernmental panel on climate change expert meeting on mitigation, sustainability and climate stabilization scenarios. In *IPCC Working Group III Technical Support Unit*; Shukla, P.R.J., Skea, R., van Diemen, K., Calvin, Ø., Christophersen, F., Creutzig, J., Eds.; Imperial College London: London, UK, 2017.
19. Hanewinkel, M.; Cullmann, D.; Schelhaas, M.J.; Nabuurs, G.J.; Zimmermann, N.E. Climate change may cause severe loss in economic value of European forestland. *Nat. Clim. Chang.* **2013**, *3*, 204–207. [[CrossRef](#)]
20. Altieri, V.; De Franco, S.; Lombardi, F.; Marziliano, P.A.; Menguzzato, G.; Porto, P. The role of silvicultural systems and forest types in preventing soil erosion processes in mountain forests: A methodological approach using cesium-137 measurements. *J. Soils Sediments* **2018**, *18*, 1–10. [[CrossRef](#)]
21. Zhang, Y.; Chen, H.Y.H.; Reich, P.B. Forest productivity increases with evenness, species richness and trait variation: A global meta-analysis. *J. Ecol.* **2012**, *100*, 742–749. [[CrossRef](#)]
22. Kanowski, J.; Catterall, C.P.; Wardell-Johnson, G.W. Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. *For. Ecol. Manag.* **2005**, *208*, 359–372. [[CrossRef](#)]
23. Petit, B.; Montagnini, F. Growth in pure and mixed plantations of tree species used in reforesting rural areas of the humid region of Costa Rica, Central America. *For. Ecol. Manag.* **2006**, *233*, 338–343. [[CrossRef](#)]
24. Richards, A.E.; Forrester, D.I.; Bauhus, J.; Scherer-Lorenzen, M. The influence of mixed tree plantations on the nutrition of individual species: A review. *Tree Physiol.* **2010**, *30*, 1192–1208. [[CrossRef](#)]
25. Bielak, K.; Dudzinska, M.; Pretzsch, H. Mixed stands of Scots pine (*Pinus sylvestris* L.) and Norway spruce [*Picea abies* (L.) Karst] can be more productive than monocultures. Evidence from over 100 years of observation of long-term experiments. *For. Syst.* **2014**, *23*, 573. [[CrossRef](#)]
26. Forrester, D.I. The spatial and temporal dynamics of species interactions in mixed-species forests: From pattern to process. *For. Ecol. Manag.* **2014**, *312*, 282–292. [[CrossRef](#)]
27. Petráš, R.; Mecko, J.; Bošela, M.; Šebeň, V. Wood quality and value production in mixed fir-spruce-beech stands: Long-term research in the Western Carpathians. *For. J.* **2016**, *62*, 98–104. [[CrossRef](#)]
28. Magin, R. Ertragskundliche Untersuchungen in montanen Mischwäldern. *Forstwissenschaftliches Centralblatt* **1954**, *73*, 103–113. [[CrossRef](#)]
29. Kennel, R. Untersuchungen über die Leistung von Fichte und Buche im Rein- und Mischbestand. *Sauerländer* **1965**, *136*, 149–161.
30. Kennel, R. Soziale Stellung, Nachbarschaft und Zuwachs. *Forstwissenschaftliches Centralblatt* **1966**, *85*, 193–204. [[CrossRef](#)]
31. Hausser, K.; Troeger, R. Beitrag zur Frage der Massen und Wertleistung gepflanzter Weisstannen und Fichtenbestände auf gleichen Standorten. *Allgemeine Forst- und Jagdzeitung* **1967**, *138*, 150–157.
32. Mitscherlich, G. Ertragskundlich-ökologische Untersuchungen im Rein- und Mischbestand. *Mitteilungen der Forstlichen Bundes-Versuchsanstalt* **1967**, *77*, 9–35.
33. Hink, V. Das Wachstum von Fichte und Tanne auf den wichtigsten Standortseinheiten des Einzelwuchsbezirks “Flächenschwarzwald” (Südwestfalen-Hohenzollern). *Allgemeine Forst- und Jagdzeitung* **1972**, *143*, 80–85.
34. Mettin, C. Betriebswirtschaftliche und ökologische Zusammenhänge zwischen Standortskraft und Leistung in Fichtenreinbeständen und Fichten Buchen-Mischbeständen. *Allgemeine Forst- und Jagdzeitung* **1985**, *40*, 803–810.
35. Kramer, H. *Waldwachstumslehre (Forest Growth and Yield Science)*; Paul Parey: Hamburg, Germany, 1988; p. 374. (In German)
36. Pretzsch, H. *Forest Dynamics, Growth and Yield: From Measurement to Model*; Springer: Berlin, Germany, 2010.

37. Saha, S.; Kuehne, C.; Kohnle, U.; Brang, P.; Ehring, A.; Geisel, J.; Leder, B.; Muth, M.; Petersen, R.; Peter, J.; et al. Growth and quality of young oaks (*Quercus robur* and *Quercus petraea*) grown in cluster plantings in central Europe: A weighted meta-analysis. *For. Ecol. Manag.* **2012**, *283*, 106–118. [[CrossRef](#)]
38. Liu, C.L.C.; Kuchma, O.; Krutovsky, K.V. Mixed species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Glob. Ecol. Conserv.* **2018**, *15*, e00419. [[CrossRef](#)]
39. Chomel, M.; DesRochers, A.; Baldy, V.; Larchevêque, M.; Gauquelin, T. Non-additive effects of mixing hybrid poplar and white spruce on aboveground and soil carbon storage in boreal plantations. *For. Ecol. Manag.* **2014**, *328*, 292–299. [[CrossRef](#)]
40. Battipaglia, G.; Pelleri, F.; Lombardi, F.; Altieri, S.; Vitone, A.; Conte, E.; Tognetti, R. Effects of associating *Quercus robur* L. and *Alnus cordata* Loisel. on plantation productivity and water use efficiency. *For. Ecol. Manag.* **2017**, *391*, 106–114. [[CrossRef](#)]
41. Kelty, M.J. The role of species mixtures in plantation forestry. *For. Ecol. Manag.* **2006**, *233*, 195–204. [[CrossRef](#)]
42. Machado, J.S.; Louzada, J.L.; Santos, A.J.A.; Nunes, L.; Anjos, O.; Rodrigues, J.; Simoes, R.M.S.; Pereira, H. Variation of wood density and mechanical properties of blackwood (*Acacia melanoxylon* r. Br.). *Mater. Des.* **2014**, *56*, 975–980. [[CrossRef](#)]
43. Pretzsch, H.; Schütze, G. Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: Evidence on stand level and explanation on individual tree level. *Eur. J. For. Res.* **2009**, *128*, 183–204. [[CrossRef](#)]
44. Russo, D.; Marziliano, P.A.; Macri, G.; Proto, A.R.; Zimbalatti, G.; Lombardi, F. Does thinning intensity affect wood quality? An analysis of Calabrian Pine in Southern Italy using a non-destructive acoustic method. *Forests* **2019**, *30*, 303. [[CrossRef](#)]
45. Guntekin, G.; Emiroglu, Z.G.; Yolmaz, T. Prediction of bending properties for Turkish red pine (*Pinus brutia* Ten.) Lumber using stress wave method. *Bioresources* **2013**, *8*, 231–237. [[CrossRef](#)]
46. Teder, M.; Pilt, K.; Miljan, M.; Lainurm, M.; Kruuda, R. Overview of some non-destructive methods for in-situ assessment of structural timber. In Proceedings of the 3rd International Conference Civil Engineering, Jelgava, Latvia, 12–13 May 2011.
47. Wessels, C.B.; Malan, F.S.; Rypstra, T. A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. *Eur. J. For. Res.* **2011**, *130*, 881–893. [[CrossRef](#)]
48. Bacher, M.; Krosek, S. Bending and tension strength classes in European standards. *Annals of Warsaw University of Life Sciences—SGGW. For. Wood Tech.* **2014**, *88*, 14–22.
49. Pretzsch, H.; Rais, A. Wood quality in complex forests versus even-aged monocultures: Review and perspectives. *Wood Sci. Technol.* **2016**, *50*, 845–880. [[CrossRef](#)]
50. Rais, A.; Van de Kuilen, J.W.G. Critical section effect during derivation of settings for grading machines based on dynamic modulus of elasticity. *Wood Mater. Sci. Eng.* **2015**, *4*, 189–196. [[CrossRef](#)]
51. FAO. World Reference Base for Soil Resources. In *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports, No. 106; FAO: Roma, Italy, 2014.
52. Ciancio, O.; Iovino, F.; Menguzzato, G.; Nicolaci, A.; Nocentini, S. Structure and growth of a small group selection forest of Calabrian pine in Southern Italy: A hypothesis for continuous cover forestry based on traditional silviculture. *For. Ecol. Manag.* **2006**, *224*, 229–234. [[CrossRef](#)]
53. Tabacchi, G.; Di Cosmo, L.; Gasparini, P. Aboveground tree volume and phytomass prediction equations for forest species in Italy. *Eur. J. For. Res.* **2011**, *130*, 911–934. [[CrossRef](#)]
54. Holmes, R.L. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* **1983**, *43*, 69–78.
55. Wang, X. Acoustic measurements on trees and logs: A review and analysis. *Wood Sci. Technol.* **2013**, *47*, 965–975. [[CrossRef](#)]
56. Vanninen, P.; Ylitalo, H.; Sievanen, R.; Makela, A. Effect of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). *Trees* **1996**, *10*, 231–238. [[CrossRef](#)]
57. Vargas-Hernandez, J.; Adams, W.T. Genetic relationships between wood density components and cambial growth rhythm in young coastal Douglas-fir. *Can. J. For. Res.* **1994**, *24*, 1871–1876. [[CrossRef](#)]
58. Zhembo, L.; Yixing, L.; Haipeng, Y.; Junqi, Y. Measurement of the dynamic modulus of elasticity of wood panels. *Front. For. China* **2006**, *1*, 425–430.



59. Todaro, L.; Macchioni, N. Wood properties of young Douglas-fir in Southern Italy: Results over a 12-year post-thinning period. *Eur. J. For. Res.* **2011**, *130*, 251–261. [[CrossRef](#)]
60. Zhang, H.; Wang, X.; Su, J. Experimental Investigation of Stress Wave Propagation in Standing Trees. *Holzforschung* **2011**, *65*, 743–748. [[CrossRef](#)]
61. Krajnc, L.; Farrelly, N.; Harte, A.M. Evaluating Timber Quality in Larger-Diameter Standing Trees: Rethinking the Use of Acoustic Velocity. *Holzforschung* **2019**, *73*, 797–806. [[CrossRef](#)]
62. Marziliano, P.A.; Menguzzato, G.; Scuderi, A.; Corona, P. Simplified methods to inventory the current annual increment of forest standing volume. *iForest* **2012**, *5*, 276–282. [[CrossRef](#)]
63. Team, R.C. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2016.
64. Zar, J.H. *Biostatistical Analysis*, 4th ed.; Prentice Hall: Upper Saddle River, NJ, USA, 1999.
65. Detters, A.; Cowell, C.; McKeown, L.; Howard, P. *Evaluation of Current Rigging and Dismantling Practices Used in Arboriculture*; The Health and Safety Executive: London, UK; The Forestry Commission: Edinburgh, UK, 2008; p. 355.
66. Binkley, D.; Dunkin, K.A.; DeBell, D.; Ryan, M.G. Production and nutrient cycling in mixed plantations of eucalyptus and albizia in Hawaii. *For. Sci.* **1992**, *38*, 393–408.
67. Kelty, M.J. Comparative productivity of monocultures and mixed-species stands. In *The Ecology and Silviculture of Mixed-Species Forests*; Springer: Dordrecht, The Netherlands, 1992; pp. 125–141.
68. Forrester, D.I.; Lancaster, K.; Collopy, J.J.; Warren, C.R.; Tausz, M. Photosynthetic capacity of *Eucalyptus globulus* is higher when grown in mixture with *Acacia mearnsii*. *Trees* **2012**, *26*, 1203–1213. [[CrossRef](#)]
69. Saranpää, P. Wood density and growth. In *Wood Quality and Its Biological Basis Blackwell*; Biological Sciences Series; Barnett, J.R., Jeronimidis, G., Eds.; CRC Press: Oxford, FL, USA, 2003; pp. 87–113.
70. Torquato, L.P.; Auty, D.; Herández, R.E.; Duchesne, I.; Pothier, D.; Achim, A. Black spruce trees from fire-origin stands have higher wood mechanical properties than those from older, irregular stands. *Can. J. For. Res.* **2014**, *44*, 118–127. [[CrossRef](#)]
71. Metz, J.Ô.; Seidel, D.; Schall, P.; Scheffer, D.; Schulze, E.D.; Ammer, C. Crown modeling by terrestrial laser scanning as an approach to assess the effect of aboveground intra- and interspecific competition on tree growth. *For. Ecol. Manag.* **2013**, *310*, 275–288. [[CrossRef](#)]
72. Pretzsch, H.; Biber, P. A re-evaluation of Reineke's rule and stand density index. *For. Sci.* **2005**, *51*, 304–320.
73. Pretzsch, H. Species-specific allometric scaling under self-thinning: Evidence from long-term plots in forest stands. *Oecologia* **2006**, *146*, 572–583. [[CrossRef](#)] [[PubMed](#)]
74. Pretzsch, H.; Block, J.; Dieler, J.; Dong, P.H.; Kohnle, U.; Nagel, J.; Spellmann, H.; Zingg, A. Comparison between the productivity of pure and mixed stands of Norway spruce and European beech along an ecological gradient. *Ann. For. Sci.* **2010**, *67*, 712. [[CrossRef](#)]
75. Pretzsch, H.; Bielak, K.; Block, J.; Bruchwald, A.; Dieler, J.; Ehrhart, H.P.; Kohnle, U.; Nagel, J.; Spellmann, H.; Zasada, M.; et al. Productivity of mixed versus pure stands of oak (*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L.) and European beech (*Fagus sylvatica* L.) along an ecological gradient. *Eur. J. For. Res.* **2013**, *132*, 263–280. [[CrossRef](#)]
76. Condés, S.; del Río, M.; Sterba, H. Mixing effect on volume growth of *Fagus sylvatica* and *Pinus sylvestris* is modulated by stand density. *For. Ecol. Manag.* **2013**, *292*, 86–95. [[CrossRef](#)]
77. Zeller, L.; Ammer, C.; Annighöfer, P.; Biber, P.; Marshall, J.; Schütze, G.; del Río Gaztelurrutia, M.; Pretzsch, H. Tree ring wood density of Scots pine and European beech lower in mixed-species stands compared with monocultures. *For. Ecol. Manag.* **2017**, *400*, 363–374. [[CrossRef](#)]
78. Binkley, D.; Stape, J.L.; Ryan, M.G. Thinking about efficiency of resource use in forests. *For. Ecol. Manag.* **2004**, *193*, 5–16. [[CrossRef](#)]
79. Lebourgeois, F.; Gomez, N.; Pinto, P.; Mérian, P. Mixed stands reduce *Abies alba* tree-ring sensitivity to summer drought in the Vosges mountains, western Europe. *For. Ecol. Manag.* **2013**, *303*, 61–71. [[CrossRef](#)]
80. Del Río, M.D.; Schütze, G.; Pretzsch, H. Temporal variation of competition and facilitation in mixed species forests in Central Europe. *Plant Biol.* **2014**, *16*, 166–176. [[CrossRef](#)]
81. Del Río, M.; Pretzsch, H.; Ruíz-Peinado, R.; Ampoorter, E.; Annighöfer, P.; Barbeito, I.; Bielak, K.; Brazaitis, G.; Coll, L.; Drössler, L. Species interactions increase the temporal stability of community productivity in *Pinus sylvestris*-*Fagus sylvatica* mixtures across Europe. *J. Ecol.* **2017**, *105*, 1032–1043. [[CrossRef](#)]

82. Ellenberg, H.; Leuschner, C. *Vegetation Mitteleuropas Mit den Alpen in Ökologischer, Dynamischer und Historischer Sicht*; Eugen Ulmer Stuttgart: Nürtingen, Germany, 2010.
83. Pretzsch, H. The Effect of Tree Crown Allometry on Community Dynamics in Mixed-Species Stands versus Monocultures. A Review and Perspectives for Modeling and Silvicultural Regulation. *Forests* **2019**, *10*, 810. [[CrossRef](#)]
84. Forrester, D.I.; Ammer, C.; Annighöfer, P.J.; Barbeito, I.; Bielak, K.; Bravo-Oviedo, A.; Coll, L.; del Río, M.; Drössler, L.; Heym, M.; et al. Effects of crown architecture and stand structure on light absorption in mixed and monospecific *Fagus sylvatica* and *Pinus sylvestris* forests along a productivity and climate gradient through Europe. *J. Ecol.* **2018**, *106*, 746–760. [[CrossRef](#)]
85. Genet, A.; Auty, D.; Achim, A.; Bernier, M.; Pothier, D.; Cogliastro, A. Consequences of faster growth for wood density in northern red oak (*Quercus rubra* Liebl.). *Forestry* **2012**, *86*, 99–110. [[CrossRef](#)]
86. Grammel, R. Zusammenhänge zwischen Wachstumsbedingungen und holztechnologischen Eigenschaften der Fichte. *For. Cent.* **1990**, *109*, 119–129. [[CrossRef](#)]
87. Brazier, J.D.; Mobbs, I.D. The influence of planting distance on structural wood yields of unthinned Sitka spruce. *Forestry* **1993**, *66*, 333–352. [[CrossRef](#)]
88. Larocque, G.R.; Marshall, P. Wood relative density development in red pine (*Pinus resinosa* Ait.) stands as affected by different initial spacings. *For. Sci.* **1995**, *41*, 709–728.
89. Zhang, S.Y.; Chauret, G.; Swift, D.E.; Duchesne, I. Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. *Can. J. For.* **2006**, *36*, 945–952. [[CrossRef](#)]
90. Moore, J.R.; Cown, D.J.; McKinley, R.B.; Sabatia, C.O. Effects of stand density and seedlot on three wood properties of young radiata pine grown at a dry-land site in New Zealand. *N. Z. J. For. Sci.* **2015**, *45*, 209. [[CrossRef](#)]
91. Tognetti, R.; Michelozzi, M.; Borghetti, M. The response of European beech (*Fagus sylvatica* L.) seedlings from two Italian populations to drought and recovery. *Trees* **1995**, *9*, 348–354. [[CrossRef](#)]
92. Bolte, A.; Czajkowski, T.; Coccozza, C.; Tognetti, R.; de Miguel, M.; Pšidová, E.; Ditmarová, L.; Dinca, L.; Delzon, S.; Cochard, H.; et al. Desiccation and mortality dynamics in seedlings of different European beech (*Fagus sylvatica* L.) populations under extreme drought conditions. *Front. Plant Sci.* **2016**, *7*, 751. [[CrossRef](#)] [[PubMed](#)]
93. Coccozza, C.; de Miguel, M.; Pšidová, E.; Ditmarová, L.; Marino, S.; Maiuro, L.; Alvino, A.; Czajkowski, T.; Bolte, A.; Tognetti, R. Variation in ecophysiological traits and drought tolerance of beech (*Fagus sylvatica* L.) seedlings from different populations. *Front. Plant Sci.* **2016**, *7*, 886. [[CrossRef](#)] [[PubMed](#)]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).