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Salvatore Francesco Papandrea

Innovative processes for the development of the Forest-Wood Supply Chain in Calabria region

PH.D. THESIS

Tutor
Prof. Giuseppe Zimbalatti

Co-Tutor
Dott. Andrea Rosario Proto

Ph.D. Coordinator
Prof. Leonardo Schena

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Abstract

More than a third of Italy is covered by arboreal and shrub vegetation, equivalent to 35% of the national surface. Out of all the regions of Italy, several regions in South Italy have the largest percentage of forest. In this area, delineated geographically as southern Italy, woodlands are very important, not only in terms of forest production, but also for the variety of typical landscapes that they form. Their economic potential is considerable due to the favourable seasonal conditions, which prolong the vegetative time, consequently increasing productivity levels. In Southern Italy, Calabrian 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. In fact, forests and wood represent a basis for economic, environmental and social stability in rural areas and wood harvesting has always represented one of the most important management interventions for the future of forests. Additionally, several techniques have been developed during the last fifty years to increase operator productivity, work qualifications and occupational safety. Technologically speaking, the first phase (forests) of the forest wood supply chain forms a series of production processes that transform natural resources from forests into products and services. The timber production process takes place through different production phases. Dealing with the wood forest supply chain in a universal sense does not allow us to focus on the weak or strong links in the chain. The aspects of the supply chain are really broad, starting from the supply of the wood resource to the quality of the finished product sold to the final consumer, and to be deepened, one needs to focus on each of these aspects individually, without forgetting the importance of their cohesion in a large solid chain that embraces the culture, the environment, the economy, of the Calabrian forests. This Ph.D. research has set out to evaluate the supply chain in order to provide information on the current reality that characterizes the forestry sector of the Calabria Region and propose potential innovative developments. In particular, several studies have been conducted, distinguished three activities, to investigate three aspects of the Wood Supply Chain to determine: *i*) productivity and cost analysis of forest operations sites in different areas of Bulgaria (some data were collected during the period abroad) and with different levels of mechanization;

ii) ergonomic condition in forest operations through the determination of significant differences in terms of forest operator exposure to noise and hand-arm vibration due to the use of chainsaws and the study of working postures during the measurement of forest assortments; *iii)* wood quality through the development of Non-Destructive Technologies (NDT) capable of predicting the intrinsic properties of wood from individual standing trees to the final product and assessing the quality of wood for stands and forests.

The result of first activity have shown that a good organization on-site, in particular, planning an optimal road network to reduce the extraction distance, managing the arrangement of the wood assortments already during felling, using innovative machines, can limit the time consumption related to the extraction operations, during the total time of the work cycle. In particular, it has been observed how productivity increases thanks to the use of innovative forestry machinery. The results obtained from the study performed on postures during wood measurements demonstrate that updated technology is needed, and can help improve ergonomic conditions, in many forestry applications, including wood measurement. Regarding the determination of the significant differences in terms of forest operator exposure to noise and hand-arm vibrations due to the use of chainsaws, the results obtained, demonstrate the correct maintenance of chainsaws over time has an important role in exposure to noise and vibrations by the forestry operator, especially for small agroforestry companies that occasionally use these dated tools.

About the third activity, the results of the studies carried out, showed that the non-destructive methods (NDT) applied are valid both for identifying different defects in a tree trunk, including ring shake, without affecting its biological activity, overcoming the difficulties of prediction using only the visual inspection, which to estimate some mechanical characteristics of the wood tissue such as the dynamic modulus of elasticity (MOEd) and therefore, the prediction for the static MOE in poplar wood.

Riassunto

I dati presentati dalla recente pubblicazione dell'Inventario Nazionale delle Foreste e dei Serbatoi di Carbonio (IFNC, 2015) confermano che la Calabria è una regione a tipica vocazione forestale ed in particolare il suo coefficiente di boscosità risulta sensibilmente superiore a quello nazionale. In particolare, il processo produttivo denominato "Filiera Foresta-Legno" riveste un ruolo di notevole importanza per la regione. Purtroppo, però numerosi sono gli ostacoli che rendono gli anelli di questa filiera deboli. In aggiunta, gli aspetti da considerare sono davvero ampi, a partire dall'approvvigionamento della risorsa legno fino alla qualità del prodotto finito venduto al consumatore finale. Tutti questi aspetti presi singolarmente svolgono un ruolo fondamentale creando una forte coesione in una grande filiera solida che abbraccia la cultura, l'ambiente, l'economia partendo dalle foreste calabresi. Questo dottorato di ricerca si è proposto di valutare la filiera del legno al fine di fornire informazioni sulla realtà attuale che caratterizza il settore forestale della Regione Calabria e proporre potenziali sviluppi innovativi da adottare. In particolare, sono stati condotti diversi studi, distinti in tre attività, per indagare alcuni aspetti della filiera Foresta-Legno e quindi determinare: i) l'analisi della produttività e dei costi dei cantieri forestali in diverse aree della Bulgaria (alcuni dati sono stati raccolti durante il periodo all'estero) e con diversi livelli di meccanizzazione; ii) le condizioni ergonomiche nelle utilizzazioni forestali, valutando l'esposizione dell'operatore forestale al rumore e alle vibrazioni mano-braccio dovute all'uso di motoseghe e lo studio delle posture di lavoro durante la misurazione degli assortimenti forestali; iii) la qualità del legno attraverso l'impiego di tecnologie non distruttive (NDT) in grado di prevedere le proprietà intrinseche del legno dall'albero in piedi fino al prodotto finale e monitorando la qualità del legno lungo le diverse fasi della filiera. I risultati della prima attività hanno dimostrato che una buona gestione del cantiere forestale, che tenga conto della pianificazione ottimale della viabilità, della disposizione degli assortimenti legnosi e dell'utilizzo appropriato di macchine innovative, può limitare il consumo di tempo relativo alle operazioni di esbosco, durante il tempo totale del ciclo di lavoro e quindi aumentare la produttività. I risultati ottenuti dallo studio effettuato sulle posture durante le misurazioni del legno dimostrano che è necessaria una

tecnologia aggiornata, che può contribuire a migliorare le condizioni ergonomiche, in molte applicazioni forestali, compresa la misurazione degli assortimenti legnosi. Per quanto riguarda la valutazione delle differenze in termini di esposizione dell'operatore forestale a rumore e vibrazioni mano-braccio dovute all'utilizzo di motoseghe, i risultati ottenuti, dimostrano che la corretta manutenzione nel tempo delle motoseghe ha un ruolo importante nell'esposizione a rumore e vibrazioni da parte l'operatore forestale, soprattutto per le piccole aziende agroforestali che saltuariamente utilizzano questi datati strumenti. Per quanto riguarda la terza attività, i risultati degli studi effettuati, hanno dimostrato che i metodi non distruttivi (NDT) applicati, sono validi sia per identificare diversi difetti del tessuto legnoso senza intaccarne l'attività biologica della pianta, superando le difficoltà di previsione poste dall'utilizzo della sola ispezione visiva, che per stimare alcune caratteristiche meccaniche del tessuto legnoso come il modulo dinamico di elasticità (MOEd) e quindi, la previsione del MOE statico del legno.

Keywords: Forest Operations; Non-Destructive Testing; Postural Analysis; Noise; Vibration; Wood Technology

1. General Introduction

1.1 The current forest situation in Italy

Forests play an essential role in ensuring global natural and environmental balances and in contributing to the satisfaction of the needs of human race: in order that forests to “count” in the political and economic choices and strategies of the country, it is necessary that, first, the forests “count”. Forests represent the ecosystems richest in animal and plant biodiversity and are able to perform irreplaceable services: they provide an important contribution to mitigating the effects of climate change through the subtraction of carbon dioxide present in excess of the atmosphere, characterize the water cycle by influencing evaporation, absorption and regimation, guarantee the purification of the air and the emission of the oxygen we breathe, they favor the consolidation of soils and slopes, they contribute to the contrast of desertification phenomena. In addition, they represent the vital habitat for many other species, plants, and animals, and generate a further series of positive externalities, both in terms of the production of renewable raw materials such as wood and products of the undergrowth, and in terms of fundamental intangible services such as the tourist-recreational fruition, the characterization of the landscape and the preservation of traditional, cultural and, sometimes, even spiritual values of the territories. By subtracting from the atmosphere and storing greenhouse gases, particularly CO2, forests contribute to mitigating the effects of climate change and regulating the climate. In fact, like the whole plant kingdom, they represent a formidable biological machine that captures carbon from the atmosphere, stores it in its fibers and keeps it blocked for even very long times: a cubic meter of wood contains about 260 kg of carbon, equal to about half of its dry weight, the result of the absorption of about a ton of carbon dioxide.

The Italian forestry heritage is made up, overall, of 10,982,013 ha, of which 9,165,505 ha of forest and 1,816,508 ha of other wooded lands (provisional results of the National Inventory of Forests and Carbon Tanks (INFC, 2015). The forest areas, therefore, cover 36.4% of the national territory. In some Italian Regions and Autonomous Provinces, forests occupy about 50% or more of the regional surface (RAF, 2017-2018). The comparison of the surface estimates produced by the three national forest inventories made in Italy (1985, 2005, and 2015) indicates a significant increase in the forest area in the last century, with a slight slowdown in the last decade. The expansion of the forest was mainly caused by the abandonment of territories that have become marginal for agriculture and the reduction in the use of pastures for livestock activities, and occurred simultaneously with a gradual decrease in forest uses (RAF, 2017-2018; Marchetti et al. 2018; ISPRA, 2019; Gasparini and Marchetti, 2019). The annual increase in the total forest area (Forests + Other Wooded Lands) for the 1985-2005 and 2005-2015 intervals is respectively 0.3% and 0.2% of the national area. In particular, the annual increase in the forest was 77,960 ha in the period 1985-2005 and 52,856 ha in the period 2005-2015, and affects, with varying intensity, all the Italian regions (SFN, 2020).

The natural reconstitution and expansion of the forest have been accompanied in recent decades by particular attention to the conservation and enhancement of the naturalistic aspects. Italy is one of the European countries with the highest incidence of forests with naturalistic constraints; to date, over 27% of Italian forests are subject to particular protection regimes: from the integral reserves of national and regional parks to the areas included in the European Natura 2000 network (Maesano et al. 2014; European Commission, 2015). Since 1923, most of the Italian forests (currently 86.7%) have been subject to the hydrogeological risks which recognizes that forests have an important role in water management and therefore imposes regulations and all management methods. Furthermore, since 1985, 100% of forests (a unique case in Europe) are also subject to landscape restrictions (Marchetti et al. 2018).

Calabria is among the most forested southern Italy regions. In fact, it has a woodiness index of 44.5%, exceeding the national one by 8%.

Evaluated this immense woodland patrimony, the enhancement of the woods is still low with a wood harvest far below the possibilities and with the use of wood not sufficiently anchored to artisanal and quality productions. Although in Italy forest resources represent an important productive and employment reality for the country and offer ample opportunities for growth and development, today the Italian wood industry is a leader in Europe, but with the supply of raw materials from abroad, in fact, most of the timber needs are covered by wood imports from other countries.

This is due to the fact that, despite the increase in forest areas, there has not been an adequate increase in investments in management, use and production in the sector. The forest-wood supply chain presents numerous opportunities for growth, especially upstream of the supply chain itself, for companies that carry out silvicultural activities ensuring, in addition to wood production, the management and continuous maintenance of the territory (Piano della Filiera Legno 2012-14).

Italy is one of the most important producers and exporters of furniture and has a consolidated production capacity in the paper and packaging sector, all economic activities consistent with the guiding principles of the “circular bio-economy” (Hetemäki et al. 2017), which the European Union (EU) has fully adhered to its development strategy to 2030. To these large-scale processes must be added the positive trend of the timber construction market. Italy has reached a record level on a European scale in the recycling of wood products at the end of the cycle, so much so that it has become a net exporter of these products. In fact, if the import is excluded, the Italian industrial production of finished wood products uses more material from the final phases of the supply chain (recycling and reuse) than from primary forest products.

However, the low capacity of the industrial wood sector without a national plan of “forest-wood product” has determiend a strong dependence on the import of timber and semi-finished wood products from European and non-European countries. In fact, Italy has become the second net importer of wood products in Europe (after the United Kingdom) (Marchetti et al. 2018).

The forestry sector is often limited to the production of wood for energy purposes, while the management of forest stands hardly sees the implementation of targeted interventions towards the production of wood assortments most requested by the first and second transformation sectors of the forest-wood supply chain. This is also accompanied by a lack of knowledge of the vegetative state of stands, for many of which the silvicultural treatments and interventions prescribed by good government practice have not been foreseen for some time. It is for this reason that many of these stands, even if inserted in a highly valued stationary context, are in precarious management conditions and show the need for urgent interventions (Ventura and Romano, 2000).

The interventions of forest use represent the moment of synthesis of correct silvicultural management applied on a specific forest surface. The increase in complexity in forest systems and the improvement of retractable wood assortments are the main objectives of interventions in the woods where the production function is recognized. Only through correct and multifunctional management of the forest, can all the functions and components (economic, protective, environmental and recreational) that the forest heritage performs, also and above all for future generations, be guaranteed at the same time (Proto et al. 2014).

1.2 Forest-Wood Supply Chain

Forestry as an industry is not intended for itself. It represents several parts of a complex forest-wood chain. Technologically speaking, the forestry part of the forest wood supply chain forms a series of production processes that transform natural resources from forests into products and services. The timber production process takes place through different production phases. Production processes vary in different environments and have evolved over time in different directions. Different equipment and machines are required in the process of carrying out technological procedures, which enable the implementation of a certain procedure. Production processes also vary by raw material (maybe products or semi-finished products) in which they take place.

Forest-wood supply chain deals with processes within the chain, starting from the management of the new forest to the valorisation of the wood product; covering forest organization, logging and transport, and forest industry to end-use (Vötter, 2009), but each provider can take independent decisions. Entrepreneurs often have to decide which type of supply chain to employ for a certain operation. In recent years, new technologies and methods for the utilization of wood have been suggested and 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 incremental innovations that improve the existing systems by enhancing the efficiency of their resources or reducing their costs in gradual steps.

In Italy, the forest-wood supply chain is divided into four sectors:

1. FOREST PROPERTY composed of private, public (municipalities, regions, state), communion rules family members
2. FORESTRY ENTERPRISES
3. FIRST PROCESS or sawmills
4. SECOND/THIRD WORKS (carpentry, joinery, etc.)

In the first ring of the supply chain, i.e. the forest property, we are confronted with the procurement of raw materials, technically speaking of the log. The properties must therefore secure the supply of raw materials, in terms of volume and quality. The criticalities of this ring are multiple, being multiple players that make it up: partial planning of surfaces, disinterest of the average private owner, very high land fragmentation, accessibility of the lots (forest roads), bureaucracy, etc.

The second ring is made up of foresters firms, responsible for felling e sometimes the transport of logs. Also, this is a very diverse sector, with the presence of a few firms specialized in forestry activities and many mixed realities between farms and artisans companies who carry out multiple activities such as earthmoving, snow clearing, etc. An unskilled but lively sector. The third ring, the first transformation (sawmills), is currently the weakest part of the supply chain. The business of these companies is sawing roundwood and seasoning of the planks/beams. The fourth ring, the companies of second/third transformation is composed of carpentry, carpenters (door and window fitters and floor fitters) e furniture factories. This is the link in the chain plus solid and healthy.

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 or service to the marketplace that the customer is willing to pay for. For decades, in fact, the wood products industry has been doing strenuous efforts to improve the productivity, efficiency and cost-effectiveness of its operations, including forestry, harvesting, transportation, wood processing and the manufacturing of end wood products and building components. Intense efforts have focused on minimizing individual costs links (process steps or units) in the process chain (Hansen and Juslin, 2011), thus incrementally improving the productivity and efficiency of the units (Larsson et al. 2016). As the wood supply chain is a complex and highly dynamic network due to unpredictable simultaneous interactions, it hardly can be solved optimally. In practice, coordinated processes are applied to cope with this complexity, but fail frequently when unexpected risks occur, or changes have to be implemented. This leads to an inefficient supply chain. A fundamental supply chain management principle is to emphasize the overall performance of the supply chain in order to compete with other supply chains (Haartveit et al. 2004; Westlund and Furness-Lindén, 2010). Accordingly, the attention focuses on the wood supply chain connecting forest owners and forest-based industries.

Forest-wood supply chain (FWSC) (Figure 1) applies the concepts of logistics and supply chain management to the field of forestry, and in particular to the area logging and transport operation. FWSC can be seen as a set of processes by which forest resources are converted into products and services. FWSC deal 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 in single processes but they are linked together and interact with each other, creating an entire and full system to supply wood from forest to sawmill in an expected way.

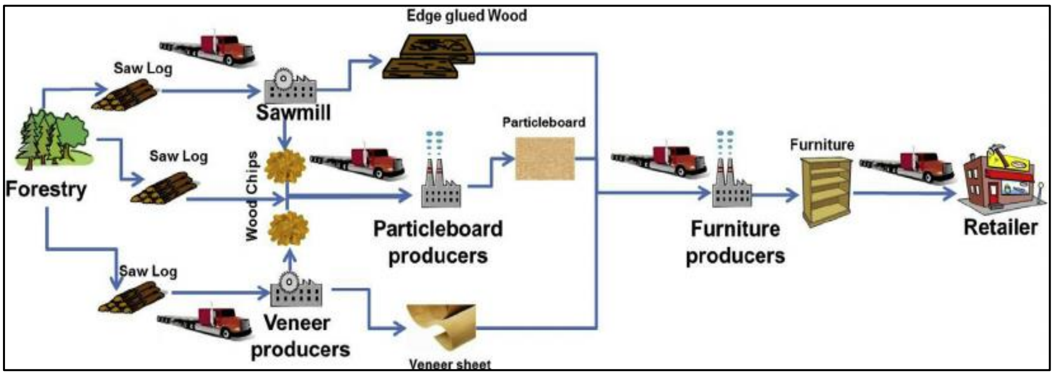

Figure 1 - Forest Wood Supply Chain

Depending on a number of factors such as the level of harvesting and trasport industry development in a country, forest and terrain conditions, 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 forest wood supply chain is a complex process. In fact, each provider involved in the wood supply chain can take indipendet decision.

2. State of the Art

2.1 Forests and Logging Operations in Calabria Region

Calabria is a region with a typical forest vocation and in particular his woodiness coefficient is significantly higher than the national one (Brunori, 2007).

Calabria is one of the most interesting Italian regions in terms of forest for the potential and diversification of wood production and, also, for the Mediterranean specificity of some natural formations. The third Italian national forest inventory (INFC, 2015) is currently being drawn up, which will update the forest statistics by providing detailed information on regional realities, but based on the data published in the second Italian national forest inventory (INFC, 2005), the Calabria region, compared to a territorial area of 1,511,000 hectares (Iovino et al. 2017), has a forest area of 612,934 hectares and a woodiness index of 40.6%. A considerable share (54%) of the regional forestry assets, equal to 332,829 hectares (22.03% of the total regional area), falls within protected areas. This surface characterized by multiple forest species and woods inserted in different geo-morphological contexts, different climatic conditions, characterized by the action and use of man over time, also according to local customs and traditions, is divided as follows (Calabria Region 2007):

- National Parks: 246,759 hectares;
- Regional parks: 17,687 hectares;
- State reserves: 1,896 hectares;
- Regional state-owned areas: 26,608 hectares;
- Regional reserves: 5,253 hectares;
- SIC, SIN and SIR: 34,626 hectares.

Considering the data provided by the Forest Plan of the Calabria Region 2007 - 2013, the forested area in Calabria is divided by property categories into:

- Private, which owns 50.59% of the regional surface;

- Public, which owns 34.74% of the regional surface;
- Unclassified, which includes 14.68% of the regional surface.

By type of crop, the wooded areas are divided into:

- High woods, which make up 56% of the regional surface;
- Coppices, which make up 27% of the regional surface
- Mixed, which make up 2% of the regional surface;
- Unclassified which represent 12% of the regional surface;
- Not defined which represent 2% of the regional surface.

However, it emerged from some provisional data from the latest inventory (INFC, 2015) that the Calabrian forest area has increased, bringing the forest index to 44.5%, exceeding the national average by 8%.

This heritage positively carries out various functions: from higher quality wood production to be used in construction and processing industries, to biomass and waste from forest uses for energy production, from non-wood forest products to the supply of a whole series of goods and services that have become increasingly important in a context of sustainable forest management (GFS), that is, forest management that maintains a whole plurality of characteristics and attributes such as biodiversity, productivity, capacity for renewal, vitality and potential to fulfil, now and in the future, to relevant ecological, economic and social functions at local, national and global levels.

From the data reported by the 2007-2013 Regional Forest Plan, they estimate the cormometric mass that can be used annually by the forests of the Region to be approximately 1-1.5 million m^3, compared to 2.5 million m^3 of current increase relating to high forests only (Tabacchi et al. 2007). According to data published by Iovino (2013) in the decade 2001-2010, the wood harvest was equal to only 25% of the annual increase. In the face of this immense patrimony, the enhancement of the woods is still low with a wood harvest far below the possibilities and with the use of wood not sufficiently anchored to artisanal and quality productions.

It should also be noted in this regard that in 2011 about 730 forest companies and about 1,840 processing companies were operating in Calabria (Proto et al. 2011). The gap existing between the supply of wood supplied annually by forest companies and the needs of raw materials by processing companies is often bridged by imports of timber coming, above all, from Eastern European countries (Proto and Zimbalatti, 2008).

In order to make useful indications about the systems used for forest use, it is necessary to consider the main stationary characteristics in which companies are placed in Calabria. 52% of the wooded area is between the second and third gradient, while slope values of less than 20% are found in about 88,000 hectares of forest. As for the accident of the Calabrian forests, it is noted that 57% of the wooded areas are not rough, while 43% of the surface varies between the rugged and the very rugged. Finally, according to the degree of accessibility of forest areas, i.e. physical access to the forest and ease of access, most of the surface is accessible (88%). The territory is characterized by a wide network of natural forest tracks, especially in areas where the land is prevalent and where in the past there have been repeating and forest reconstruction financed by the 1st and 2nd Calabrian Special Laws. Unfortunately, these road networks are not always easily accessible due to lack of maintenance (Barreca et al. 2008). In Calabria, climatic conditions, which are certainly not prohibitive during the winter season, encourage businesses not to do any forestry activities during that time of the year for only 2 or 3 weeks.

Forests and wood products provide a basis for economic, environmental and social sustainability in rural areas and wood harvesting has long been one of the most important forms of forest management. Various harvesting methods can be used depending on forest site-specific conditions and degrees of mechanization and appropriate mechanization levels depend on several factors. In Italy, wherever terrain characteristics permit, chainsaws have been replaced with alternative highly mechanized systems, especially for specialized forest plantation harvesting, such as poplar (Spinelli and Magagnotti, 2011) and eucalyptus (Picchio et al. 2012). but in mountainous areas such as the Calabria Region, and where numerous environmental protection restrictions exist, conventional and traditional mechanization is used (Baraldi and Cavalli, 2008; Zimbalatti and Proto, 2009; Picchio et al. 2016; Proto et al. 2017; Iranparast Bodaghi et al. 2018). Although in recent times significant forestry use innovations have become available (Cavalli, 2008b), the majority of Italian’s private and public forests are still being harvested with traditional methods, i.e., motor-manual felling (chainsaw) (Brachetti Montorselli et al. 2010) and low mechanized extraction methods (mules and/or agricultural tractors) (Picchio et al. 2011). The choice of machinery and methods used depends on factors such as harvest type, environmental constraints, slope and roughness terrain classification, machine availability and harvesting costs. This is because each harvesting system has its limitions and each machine has technical characteristics which rule out its use in certain circumstances. In southern Italy limited harvested area volume prevails in small-scale forestry and ground-based extraction is still the most common harvesting technique. Specifically, 60% of southern Italian forests are located on 20-60% gradients, restricting harvesting systems to small-scale forestry action (Nakahata et al. 2014; Proto et al. 2018b) such as motor-manual harvesting and low-cost equipment (Johansson 1997; Ozturk and Senturk 2010; Jourgholami 2014; Proto et al. 2016a; Koutsianitis and Tsioras 2017)

The three main wood harvesting systems are: full-tree (FT), tree-length (TL), and cut-to-length (CTL). Anyway, the choice of a harvesting method depends on the final product required and can be divided into the following groups, sorted to relevance and level of diffusion:

- motor-manual FT/TL harvesting: felling and processing with a chainsaw, and skidding with a farm tractor and winch or grapple;
- motor-manual CTL harvesting: felling and processing with a chainsaw, and skidding with a farm tractor and bin or trailer;
- partially mechanized FT/TL harvesting: felling and processing with a chainsaw, and skidding with a skidder or cable crane;
- partially mechanized CTL harvesting: felling and processing with a chainsaw and skidding with a forwarder.

During the ‘90s the most common working system in Calabria was considered as traditional and at the beginning of an early stage of mechanization (Hippoliti, 1997). It was based mainly on farm tractors, sometimes with specific forest attachments like winches, hydraulic cranes, log grapples but also, the use of animals for gathering and yarding was a widely used technique, due to the site features, the characteristics of the propriety, the small dimensions of many enterprises, scant knowledge of modern machinery, and the scarcity of studies related to the use of modern machinery.

Despite the motor-manual operations are still frequently applied in steep terrain and the farm tractor equipped with forestry winches, pliers, trailers or dumpsters are still today the most common machinery for cutting and extracting timber (Verani and Sperandio, 2003; Proto et al. 2020), currently, there are numerous highly specialized machines for forest exploitation and can be traced to the use of the skidder, forwarder, and cable crane where the orography of the Calabrian forests are well suited to their use. Skidders, cable cranes and forwarders are used where farm tractors are limited by terrain steepness and roughness and to guarantee more productivity and safety with respect to traditional extraction methods.

During the last years, the technological gap between means and methods applied in the Apennines and Alps areas is considerably shortened, thanks to the firms which want to be competitive in local markets, and also thanks to the recent boost initiatives connected to the rural development politics (Moscatelli et al. 2007).

In Eastern Europe as well as in Calabria, abiotic and biotic factors cause significant damage to forests and in these conditions, timber recovery operations become very difficult especially in sensitive areas such as natural parks (national and regional). Therefore, in recent decades a common way to minimize these events by forest management is salvage logging. Salvage logging can be described as the harvesting of dead, damaged, or infested trees, aiming to recover the maximum value prior to the wood's deterioration (Stokes et al. 1989). Such operations require supplementary concerns to plan and adapt the harvesting system and safety to the site-specific characteristics and degree of damage (Kramer et al. 2014; Cadei et al. 2020). When salvage logging is in question, the most suitable harvesting solutions are those guaranteeing the safety of the operators while yielding acceptable productivities and costs (Kärhä et al. 2018; Oprea 2008). The problem is more challenging when these disturbances occur in sensitive areas, because the interventions must be consistent with the natural disturbance regime, which is known to contribute to biodiversity, while salvage logging may alter it (Lindenmayer et al. 2012) by causing changes in the structure, soil, microclimatic, and vegetation conditions in the harvested areas (Wermelinger et al. 2017). Still, salvage logging is a management option which is used in many European national parks (Michalová et al. 2017).

2.2 Ergonomic Conditions in Forest Operations

Occupational safety and health change through time due to technological and social development. It is an obligation of scientific research to impartially and critically examine these changes and propose measures to reduce negative impacts on people. The aim of each society and individual must be to preserve work as a basic right and need of every human being, as through work achieve fulfilment at a personal and social level. However, work should have no negative impacts on workers' health, and it should provide them with a dignified life in old age. Within this context, ergonomics as a science and a profession adjusts work to workers so as to reduce the difficulty and harmfulness of work by providing adequate work efficiency, which is reflected in a reduced level of illnesses or injuries at work. Thus, a commitment of the ergonomics society is to provide ergonomic knowledge and tools in a form useful for decision-makers who require assistance (Brewer and Hsiang, 2002).

Regardless of the introduction of modern methods of harvesting and production, forest work is considered one of the most dangerous industrial activities with a high share of lethal accidents and injuries (EU-OSHA, 2008; Adams et al. 2014). Due to the natural environment, heavy loads and frequent use of manual tools and machines, workers are exposed to physical, physiological and environmental factors that result in various illnesses, related in particular to muscles, skeleton, nerves and vascular system, and impairment of hearing (Bovenzi, 2008; Fonseca et al. 2015, Proto and Zimbalatti 2015).

2.2.1 Postural Assessment

In Europe, musculoskeletal disorders (MSD) are common work-related problems. Almost 24% of all European workers reports suffering from backache and 22% complain about muscular pains. Moreover, almost 2/3 of workers in Europe report being exposed to repetitive hand-arm movements and 1/4 to vibrations: these are significant risk factors for developing WRULD (Work Related neck and Upper Limb Disorders - European Agency, 2008). Most work-related MSD and WRULD are cumulative disorders, resulting from repeated exposure to high or low intensity loads, repetitive movements and vibrating tools utilisation over a long period of time: however, MSD and WRULD can also be acute traumas, such as fractures, that occur during an accident. Different groups of factors may contribute to the development of these pathologies, including physical or biomechanical factors and organisational and psychosocial factors (Waters, 2004). In Italy, technopathies of the musculoskeletal system and connective tissue represent 2/3 of the total number of occupational diseases; the repetitiveness of the work affects 64% of the confirmed cases of injuries to the upper limbs and the lifting of a load affects 55% of the cases of back pathologies. Of the total diseases reported in 2019, out of over 15,000 cases, approximately 75% concern males. The sectors most at risk are crafts (28.5), agriculture (26.7), industry (23.5), services (18.7) and Pa (2.9), from the analysis of the INAIL data in Italy during the period 2020-2022.

With the development of mechanical harvesting, the work transferred from outdoors to a cabin thus reducing the physical difficulty of work and exposure to most environmental risk factors. An increased human/machine interaction (Burman and Löfgren, 2007) and the change of work from “doing to thinking” (Hollnagel and Woods, 2005) caused the focal points of accidents to change (Axelsson, 1998) and new injuries (Repetitive strain injuries - Axelsson and Pontén, 1990) as well as new, cognitive risk factors to occur. As a consequence, it appears that, in mechanical harvesting, the traditional ergonomic paradigm “less is better” should be replaced by »more can be better«, since reduced physical activity also has harmful impacts on health. To comprehensively improve the situation of occupational safety and health in the field of forestry, the rooted culture of “can do” must be replaced by “can do safely”, which requires changes in the entire chain of wood production (Adams et al. 2014).

Notwithstanding the mechanized wood production expanding to the fields where the work was executed in a traditional way, e.g., using chainsaw and cable skidder, traditional harvesting technologies remain applicable in difficult working conditions (e.g., co-natural, mostly deciduous forests) and private small-scale forests. Work technology used, out-of-date work equipment, non-use of personal protection equipment and lack of knowledge and experience cause poorer occupational safety and health of private forest owners than is the case with professional workers (EU-OSHA, 2008).

Constant social and technological changes have also an impact on forest use and the importance of its functions, i.e. on forest production and consequently occupational safety and health.

2.2.2 Vibration and Noise Measurements

Work in the forest brings significant pressure on forestry workers, and it is considered one of the most dangerous industrial activities (EU-OSHA 2016, Yovi et al. 2019). A more detailed analysis of accidents in the forestry sector has shown that the work on wood utilization is far more dangerous than other forestry operations. Workers in the felling and processing of wood assortments are exposed to significant vibration levels because they use mechanized means of work from different manufacturers, with different mass and power of propulsion engines, and that are expected to meet the defined working norm which is related to the operation, method, stand conditions and work-related parameters. The main causes that influence on vibration levels of chainsaws are mainly dynamic forces from the motor, sawing modes, unbalanced moving parts, shocks in gears, bearings and other mechanisms and also in the interaction between the operator, the machine and the wood being processed (UNI EN ISO 11681-1:2011). Workers whose hands are regularly exposed to higher-intensity vibrations transmitted through the palms and fingers can suffer damage with a number of consequences commonly referred to as the “hand-arm vibration syndrome” (Kacian, 1999). The use of chainsaws has been connected to a large number of ergonomic threats. Forest workers are affected by exhaust gas (Alander et al. 2005; Magnusson and Nilsson, 2011), wood dust (Puntaric et al. 2005) and poor body posture causing lower back injuries (Hagen et al. 1998). However, the two most frequently documented threats during motor manual felling include exposure to noise and vibration. Extensive research has been done with regard to the measurement of the vibration during working with chainsaws (Pitts, 2004; Poje et al. 2019; Papandrea et al. 2022), the effect of technological developments on the mitigation of hand-arm vibration (HAV), the prevalence of vibration-induced white finger (VWF) a vascular disorder (Bovenzi, 2008; Bovenzi et al. 2008), and musculoskeletal disorders due to HAV (Bovenzi et al. 1991; Koskimies et al. 1992).

Vibration-induced white finger (VWF) (Figure 2) is a secondary form of Raynaud’s phenomenon occurring in professional users of vibratory tools. VWF is characterised by episodes of finger blanching attacks usually triggered by exposure to cold. The prognosis of VWF is still uncertain.

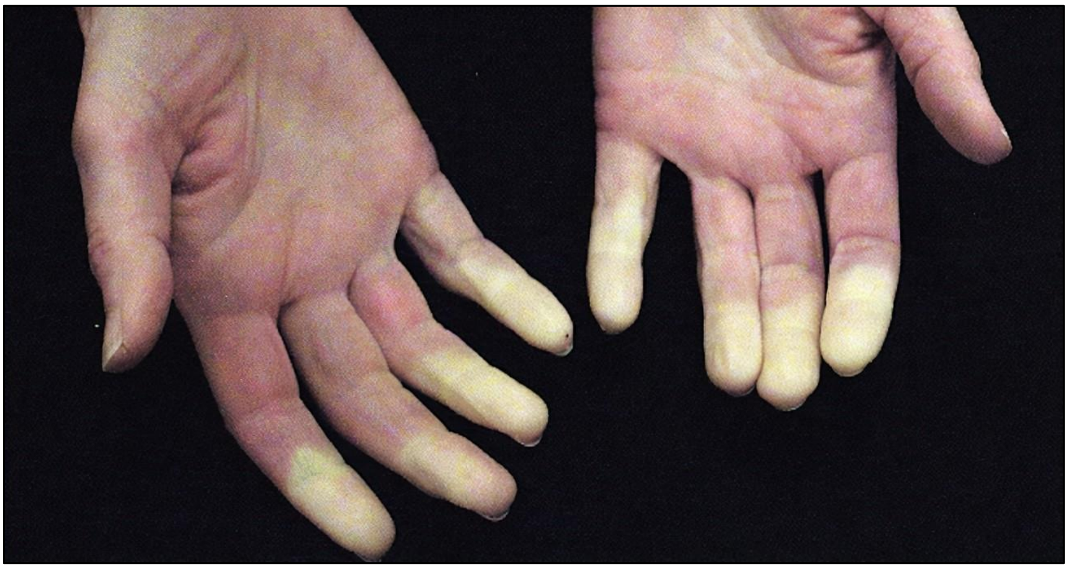

Figure 2 - Vibration-induced white finger (VWF) secondary form of Raynaud's phenomenon.

Continued use of vibratory tools is associated with a deterioration of vasospastic symptoms and an unfavourable prognosis for VWF workers. On the other hand, there is clinical and epidemiological evidence for an improvement of VWF after reduction or cessation of exposure to hand-transmitted vibration (HTV) (Koskimies et al. 1992; Bovenzi et al. 2000). For instance, the introduction of anti-vibration (AV) chainsaws (Figure 3) in forestry work has been associated with a decrease in the prevalence and incidence of VWF among users. Some authors, however, have reported that vibration from AV chainsaws can still induce damage to the vasoconstrictor mechanisms in finger circulation (Sutinen et al. 2006; Bovenzi 2008)

Figure 3 - Anti-Vibration (AV) system in chainsaw

Occupational noise (Bolaji et al. 2018) is defined as sound pressure perceived by the human ear as an undesirable sound with different frequencies, intensities, and phases. According to EU Directive 2003/10/EC, the noise maximum exposure threshold is equal to 87 dB(A) considered as the time-weighted average value of noise exposure levels for a nominal eight-hour working day. Exposure to noise is an important and preventable cause of hearing loss (Dobie. 2008), and can be caused by short exposures to extremely high sound levels or by repeated exposures to moderate levels (Neri et al. 2018). High-intensity sound can negatively affect hearing capability with a temporary or permanent loss of sensitivity and acuity (Fonseca et al. 2015).

The damage caused by noise depends on the entity of the sound level, i.e. on the sound energy, on the duration of exposure and on the sensitivity of the worker's ear (frequency of the sound energy). The main types of damage are:

- hearing problems: hypoacusis, i.e., partial loss of the sense of hearing, up to the limit of hearing loss;
- effects on other sense organs: since the ear is the seat of the sense of balance, the noise could cause dizziness and nausea;

- Physiological effects: tiredness, sleep disturbances, migraine, dizziness, anaemia, neurovegetative disorders, acceleration of heartbeat and breathing, and changes in blood pressure.

Forest logging involves the use of various noise-producing equipment, which may be harmful to the hearing capabilities of operators in the immediate area. Two common operations found in forest logging are felling (tree cutting) and tree transportation. These operations involve using an array of different heavy machinery, including tree cutters, skidders for tree trunks transporting to loading areas, loaders for loading tree trunks onto trucks, and chainsaws for cutting limbs of trees. Most of this equipment is noise-producing and could be hazardous to operators' hearing (Taoda et al. 1998).

2.3 Wood Technology and Non-destructive Testing

Wood is the material obtained from the stems of plants, in particular from trees but also from shrubs. Trees are characterized by having stems and branches that grow concentrically towards the exterior from year to year and from having fabrics essentially composed of cellulose (38-50%), hemicellulose (23-32%), lignin (15-25%) and extractives (1-8%). From a botanical point of view, the wood species are divided into Conifers (pine, fir, larch, cypress, etc) and deciduous Hardwoods (oak, beech, ash, alder, chestnut, etc). Conifers have a simpler structure, mainly composed of a single type of cell called tracheids. Deciduous is characterized by two types of cells: elongated cells, along the direction of the trunk, and radial cells. Wood is a natural material with good beauty aspects and superior formability which has been used as an engineering and construction material and also used for interior and exterior decoration (Hoseinzadeh et al. 2019). Moreover, wood has a good weight ratio and acoustic properties (Ateş et al. 2010) and despite of its great benefits, wood also suffers a number of disadvantages, for instance, wood is damaged when exposed to environmental conditions as a function of sunlight, humidity, wind and microorganisms (Hoseinzadeh et al. 2019). The industrial system draws technical, logistic and economic advantages in using raw materials of known and constant quality.

This condition, which normally occurs in many industrial sectors, is not the norm for the forest-wood chain since the raw material used, precisely wood, has a very high intrinsic variability due to biological origin. In addition to the high variability between botanical genera and between woody species of commercial interest, there are significant differences in the characteristics of the wood linked to the production areas and management techniques.

Furthermore, even in the context of defined origins, a drift over time has become evident, causing changes in the characteristics of the wood and in the quality.

The contribution of research to increase and rationalize the correct and sustainable use of wood consists, among other things, in characterizing the raw material by enhancing the characteristics of the different species, origins and quality. As sylviculture aims to guarantee and perpetuate the productivity of forest stands, the commercial volume of trees, and their ecological sustainability, wood-based products are the principal economical source used to realize these purposes. Therefore, wood quality represents a primary objective for the entire wood supply chain. Several authors have focused their studies on wood qualities and properties, paying attention to various aspects, such as the influence of forest stand characteristics on physical, mechanical, and chemical wood characteristics (Todaro and Macchioni, 2011; Marini et al. 2021), or the practical wood implications derived from quality characteristics. Other researchers have investigated the potential of various methods and techniques of wood quality evaluation (Bonifazi et al. 2015; Proto et al. 2017b). Wood quality can be defined as a set of characteristics that make woody materials economically valuable for their end uses. For several years, researchers in wood processing industries have been constantly looking for ways to increase the value and quantity of their products (Borz et al. 2021); therefore, assessing wood quality has become an important practice for forest operations (Jozsa and Middleton 1994).

Wood quality can be described by many characteristics, and according to the classical meaning, it is related to the final use of wood affected by tree phenotype, like stem shape and bearing, stem curvature crown shape development as well as number and size of branches. From a technological point of view, wood quality is related to wood defects but also to some physical and mechanical parameters, like wood density, shrinkage, and mechanical properties (Romagnoli et al. 2004).

Measurements of wood mechanical properties are crucial in assessing the overall relative strengths (i.e., resistance to fracture) of different wood products, and in their propensity to deform under load. Such measurements also give good predictability into how well a particular wood (tree species) might perform its mechanical functions within the living plant, a topic of increasing significance as biotechnological manipulations of wood formation continue to be explored. The woody stem must, of course, also be able to meet mechanical requirements of support, while supporting its major purpose, the photosynthetic canopy that collects solar radiation for photosynthesis. Mechanical properties are directly linked to both wood anatomy and types of wood cell wall polymers present. Thus, the measurement of such properties provides very useful information with regard to performance differences within and among different species, and as an indication of how wood materials respond to, and are affected by, various physical forces. The primary mechanical properties of interest are those of both strength and stiffness, which reflect load-bearing capacity at fracture and deformability under load, respectively. These, in turn, reflect the properties of the wood cell wall biopolymers, their morphological arrangements, and their general cell wall types. Loads are thus typically placed on wood materials in tension, compression, shear, or flexure modes, with the properties of each varying with the loading mode. In pure tension and compression loading, the stiffness is gauged in terms of Young's modulus (E), whereas in flexure mode the property measured is the modulus of elasticity (MOE). To evaluate/compare strength properties, however, stress must be taken into consideration, this being the load per unit area of a material sample. While strength values simply represent the maximum stress supported by a material in either tension or compression, the modulus of rupture (MOR) represents the maximum stress value that a material can support under, for example, a bending load. As the stress varies throughout a wooden beam in the flexure mode, the MOR has maximum values at the outer surfaces (Kiaei et al. 2011; Romagnoli and Spina, 2013).

To date, the study of the mechanical characteristics of wood requires tests in which the appropriately shaped wooden samples (called specimens) are subjected to stresses oriented according to the single main anatomical directions, obviously, these stresses lead to the destruction of the samples used. This, together with the complicated preparation according to the European regulations of the samples to be tested, is currently a drawback to be taken into consideration. For this reason, the research world is moving towards the use of non-destructive testing (NDT) or semi-destructive testing (SDT). These methods do not affect the properties of the tested samples. They allow the estimation of the parameters of the wood without reducing the value of the object tested (Vössing and Niederleithinger, 2018).

2.3.1 Non-destructive testing technique to determine wood quality

The estimate of the woody assortments that can be retraced from a specific stand represents an important moment in which the real productive value of a forest is quantified. The most common non-destructive analysis techniques are mainly based on the visual characterization of the assortments with the identification of some requirements required by the reference standards: minimum length, growth rate, presence and measurement of defects. The steps for standing classification include the measurement of the portion of the working drum, the observation of the characteristics of the drum that can favour or hinder the processing and finally the assignment of the drum to a quality class. Classifying the timber means dividing the roundwood into homogeneous classes of belonging, according to the characteristics detected (size, diameter) and in relation to defects and anomalies (knots, chives, cracks, etc.) It is therefore evident the need to demonstrate the product potential right from the standing trees in order to justify and plan the cultivation interventions during the shift. In particular, on valuable woody productions, valid support for the choice of plants to be used can be achieved through a series of portable scientific equipment.

Non-destructive testing can be divided into global techniques (ultrasound waves, stress waves, and resonance) and local techniques (probing, coring, and drilling).

Acoustic instruments usually measure the wave velocity or the speed of sound in wood. There are two methods of the acoustic wave in wood assessment: ultrasonic and stress waves. The major difference between them is the ultrasonic wave is generated with sound pulses of known frequency, while the stress wave does not. In principle, the wave velocity is much faster in wood than in air as in a solid medium, it depends on the type of wave and the elasticity and density of the material (Pollard and Harris, 1968). In different internal conditions, that is, sound, the decay of trees often results in a modified propagation velocity of the acoustic wave (Wang, 2013). Hence, the time of flight of the acoustic wave, together with the prior knowledge of the logs, provides internal information about them. Ultrasonic pulses are generated by a transmitting transducer. The wave is in excess of 20 kHz, and above the range of human hearing. The frequency of the ultrasonic signal must be low to have penetrating energy, but this results in decreased resolution and, in some instances, the wavelength of the signal may be large that regions of different wood densities may be obscured (Socco et al. 2004). The development of tree decay analysis has been started based on single path ultrasonic waves. In the early 1990s, ultrasound decay detectors (UDD) have been commercially available. Among them, Arborsonic Decay Detector (ADD) is one of the UDD implementations, it is portable and delivers an ultrasound pulse of 77 kHz, which according to the operational guide traverses a tree of any species at a relatively constant speed of approximately 2000 ms^{-1} but the maximum tree diameter required is 1.4 m (Wade, 1975). The UDD operates using a transducer (which sends the signal) and a receiver (that receives the signal) on opposite sides of the tree. The time required for the wave to travel between them is measured, and if the structure is not intact, or decayed, it takes longer to travel through the nearest path of sound wood. Increasing amounts of decay correspond to longer time intervals (Kazemi-Najafi et al. 2009). The problem with this approach is that there is no way to determine if a longer time condition is caused by a void, or if there is bad transducer-to-wood contact. Recognizing this problem, the earlier investigations were able to detect tree decay using UDDs by conducting their experiments either stripping bark or the transducers were magnetically attached to a nail that was tapped into the xylem to provide good contact to the wood (Ahmad et al. 2012; Xu et al. 2000). This process causes wounds in trees that serve as entry points for spores and inserts. Besides, it was reported that ultrasonic velocity measurements alone are unlikely to provide sufficient information to distinguish wood decay from a void, or either of those from the cell wall degradation, furthermore the technique seems to be species dependent. The ultrasonic technique has been attracting attention and two improvements have been carried out: the UDD tools can record time-domain and frequency-domain waveforms, and the use of uses smaller, pointed and more conical transducers with bark penetration capability to minimize tree wounds (Divos and Szalai, 2002). A stress wave is a sound wave produced manually, in a complex mixture of frequencies. Instead of using sensors to generate waves, in the stress wave approach, raw data is the sound of a hammer tapping on one pin to each pin that are inserted into the xylem (Gilbert and Smiley, 2004). This technique requires minimally invasive, as pins are inserted a few millimetres into the xylem. Similar to the ultrasonic wave approach, detecting decay using the stress wave method is based on the observation that wave travels slower in decayed wood than in sound wood and for this reason, stress wave transmission time increases dramatically in decayed areas (Wang et al. 2007), and internal defects can be detected by the time difference between the measured value and the reference value (Pellerin and Ross, 2002). Several commercial stress wave testing tools are available to conduct single path stress wave measurements in wood. In the later phase, some equipment (e.g., Fakopp Arbosonic 3D; Picus; Arbotom) (Figure 4) have been developed to conduct multipath stress wave measurements on trees and construct tomograms of tree cross sections. By using multiple transducers, stress wave computed tomography technology has been developed, where an increase in the number of installed transducers and higher frequency can give more accurate information on decays (Wang et al. 2007).

Figure 4 - Acustic Tomography (Fakopp enterprise)

The drilling resistance test was conducted using an IML-Resi PD400 (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany) resistograph equipped with a 400-mm-long and 3-mm-thick steel drill (tip diameter 3 mm, shaft diameter 1.5 mm). Drilling resistance tools such as the IML-Resi PD400 Resistograph (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany) which consists of a power drill unit, a small-diameter spade-type drill bit and an electronic device that can be connected to the serial interface input of any standard personal computer. The method is based on measuring the drilling resistance along a small needle path when a needle is driven into a tree with a constant force (Szewczyk and Wasik, 2018). This system produces a chart showing the relative resistance over the needle's travel path. Areas of sound wood have varying levels of resistance, whereas voids and areas of decay show no resistance, so the user can determine areas of low, mild and high decay levels. During the drilling measurement process, the relative drilling resistance, feeding force and speed parameters can be continuously measured as a function of the drill bit's position along the drilling path (Papandrea et al. 2022b). The test results were transmitted to a computer and processed with dedicated software (Figure 5).

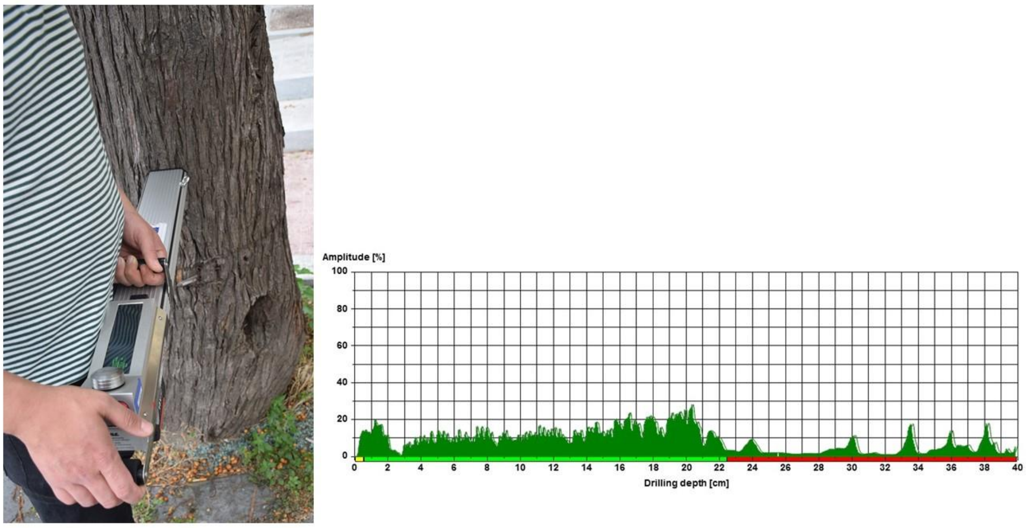

Figure 5 - IML-Resi PD400 Resistograph (Left); Test results processed with dedicated software (Right).

The former techniques are mainly focused on the estimation of static modulus of elasticity (MOE) and bending strength (fm, formerly referred to as MOR) (Jayne, 1959; Auty and Achim, 2008; Íñiguez-González et al. 2019), and the latter on estimation of density (Llana et al. 2018; Fundova et al. 2019; Martínez et al. 2020). It is also common to combine different non-destructive techniques for better estimation results (Divós and Tanaka, 1997; Vössing and Niederleithinger, 2018). Currently, worldwide 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 - from the assessment of standing trees to in-place structures (Brayshaw et al. 2009). Non-destructive testing has the potential to provide low-cost timber quality assessment, which could be used in the forest to segregate logs into different end-use categories. The estimation of mechanical properties of timber from standing trees or green logs has many benefits for growers and processors, as decisions taken at an early stage can result in cost savings (Llana et al. 2020).

The most common non-destructive testing technique used on standing trees for mechanical properties estimation is based on the measurement of stress wave velocity (Wessels et al. 2011). In fact, among the parameters that express the quality of wood, the determination of the velocity is the easiest and quickest (Divos, 2010).

3. Study's objectives

A typical supply chain for wood and wood-based products includes the forest operations, transport of raw material, processing, and further distribution to a secondary processing unit, or wholesale and retail facilities.

As can be seen from the title of this Ph.D. research, the main objective has been to optimize and enhance the wood forestry chain in Calabria. As part of the recent National Operational Program (PON - ALFORLAB), several researchers have focused their attention on the Wood Supply Chain in Calabria. According to the stakeholders, the attention paid by these researchers (Paletto et al. 2017; Proto et al. 2017, 2018; Iovino et al. 2017; Sperandio et al. 2017; Puletti et al. 2017) has revealed what are the critical points of the wood forest supply chain in Calabria and in particular the major criticalities were found:

- Lack of improvement in the level of mechanization in the procurement of wood;
- Failure to improve the safety of forest workers
- Lack of economic exploitation of wood products

Starting from these considerations, this research doctorate has set out to evaluate the supply chain according to these three critical points found, in order to provide information on the current reality that characterizes the forestry sector of the Calabria Region.

Dealing with the wood forest supply chain in a universal sense does not allow us to focus on the weak or strong links in the chain. The aspects of the supply chain are really broad, starting from the supply of the wood resource to the quality of the finished product sold to the final consumer, and to be deepened, one needs to focus on each of these aspects individually, without forgetting the importance of their cohesion in a large solid chain that embraces the culture, the environment, the economy, of the Calabrian forests.

Significant effort has been devoted to developing environmentally friendly, but also economically productive and in compliance with workplace safety regulations forestry for future generations; in particular, several studies have been conducted, distinguished three activities, to investigate three aspects of the Wood Supply Chain to determine:

- Productivity and cost analysis of forest operations sites in different areas of Bulgaria (some data were collected during the period abroad) and with different levels of mechanization (First Activity);
- Ergonomic condition in Forest Operations through the determination of significant differences in terms of forest operator exposure to noise and hand-arm vibration due to the use of chainsaws and the study of working postures during the measurement of forest assortments (Second Activity);
- Wood quality through the development of Non-Destructive Technologies capable of predicting the intrinsic properties of wood from individual standing trees to the final product and assessing the quality of wood for stands and forests (Third Activity);

4. Results organization

In order to guarantee a logical flow of topics linked to the forest wood supply chain, the thesis is developed of ten scientific papers coming from my PhD research, split into three main activities.

<u>First activity</u>

Various harvesting methods can be used depending on forest site-specific conditions and degrees of mechanization and appropriate mechanization levels depend on several factors. Although in recent times significant forestry use innovations have become available (Cavalli, 2008), the majority of Italy's and Calabria's private and public forests are still being harvested with traditional methods, i.e., motor-manual felling (chainsaw) (Brachetti Montorselli et al. 2010) and low mechanized methods. They are based mainly on farm tractors, sometimes equipped with specific forest-related attachments (winches, hydraulic cranes, log grapples, etc.). This level of mechanization of forest resource extraction is due to the features of the forest sites, the characteristics of the forest properties, and the small dimensions of many forest enterprises. The level of mechanization in harvesting is low: the most common harvesting method can be described as being at an early stage of mechanization (Proto et al. 2014).

The first activity, composed of five scientific articles, refers to the study of the productivity and costs of various forestry sites, some of which were analyzed during the period abroad (Bulgaria). Countries such as Bulgaria and Romania present a territory very similar to the Calabrian panorama, in terms of orography and management of forest uses. However, in recent years, the technological innovation of the forestry sector in Eastern Europe has certainly been improved compared to the context of Southern Italy. The importance of this activity was to evaluate the management of forest operations, in various sites, with different traditional and innovative logging systems and different levels of forest mechanization. This passage was useful for understanding, from a future perspective, whether the knowledge and technologies of Eastern Europe, applied to the well-established forest utilization sector, could be transferred and will give a positive contribution in terms of economic and environmental, in the panorama Calabrian.

Second activity

Forest work is considered one of the most dangerous industrial activities with a high share of lethal accidents and injuries (EU-OSHA 2008, Adams et al. 2014). Due to the natural environment, heavy loads and frequent use of manual tools and machines, workers are exposed to physical, physiological, and environmental factors that result in various illnesses, related in particular to muscles, skeleton, nerves and vascular system and impairment of hearing (Bovenzi, 2008; Fonseca et al. 2015).

The second activity, composed of two articles, is related to the determination of ergonomic conditions in forestry operations. In particular, the research carried out concerned: the determination of significant differences in terms of forest operator exposure to noise and hand-arm vibration due to the use of chainsaws; the study of working postures during the measurement of forest assortments by comparing three different measurement options, i.e., say traditional measurement, scanning from a smartphone, and scanning from a commercial laser scanner.

Third activity

From a technological point of view, wood quality is related to wood defects but also to some physical and mechanical parameters, like wood density, shrinkage, and mechanical properties (Romagnoli et al. 2014; Romagnoli and Spina, 2013). Some of these properties can be estimated non-destructively from the standing tree. The estimate of the woody assortments that can be retraced from a specific stand represents an important moment in which the real productive value of a forest is quantified. In particular, on valuable woody productions, valid support for the choice of plants to be used can be achieved through a series of portable scientific equipment.

The third activity, composed of three articles, is related to the assessment of wood quality through the development of non-destructive technologies able to predict the intrinsic properties of wood from individual trees to the final product and evaluate the quality of wood for stands and forests. In particular, the research concerned the use of different non-destructive instruments on Chestnut wood to evaluate the possibility of the presence of ring shake in standing trees, a first methodological approach to determine the precision of four different non-destructive methods in detecting and quantifying the decay in Mindi Tree, and finally, a study was performed to determine the predictive accuracy of non-destructive analysis of the dynamic modulus of elasticity (MOEd) in standing trees and trunks of a 22-year Poplar clone, and to examine the relationship with the static modulus of elasticity (MOEs) in sawn specimens.

4.1 Papers details

Below are the details of the papers divided by group, highlighting each document its status and its location in terms of bibliometric indexes.

Activity 1: Forests and logging operations

- Stoilov S, Proto AR*, Angelov G, **Papandrea SF**, Borz SA (2021) Evaluation of salvage logging productivity and costs in the sensitive forests of Bulgaria. *Forests*, *12*(3), 309. https://doi.org/10.3390/f12030309

  Journal bibliometric classification: Forests: IF 3,28; category forestry JIF quartile Q1.

  Salvatore Francesco Papandrea role and contribution in this paper: Writing original draft preparation.

- Stanimir Stoilov, **Salvatore F. Papandrea***, Georgi Angelov, Delyan Oslekov, Giuseppe Zimbalatti, Andrea R. Proto. PENDING PUBLICATION. Productivity analysis and costs of wheel cable skidder during salvage logging in European beech stand.

  Journal bibliometric classification: Journal of Agricultural Engineering (JAE): IF 1,72; category Mechanical Engineering JIF quartile Q3.

  Salvatore Francesco Papandrea role and contribution in this paper: Corresponding author, Data curation, Writing original draft preparation, Writing review and editing, Supervision.

- **Salvatore F. Papandrea**, Stanimir Stoilov, Georgi Angelov, Tanya Panicharova, Piotr S. Mederski*, Andrea R. Proto (2023) Modelling productivity and estimating costs of processor tower yarder in shelterwood cutting of pine stand.

  Forests 2023, 14 (2), 195 https://doi.org/10.3390/f14020195

  Journal bibliometric classification: Forests: IF 3,28; category forestry JIF quartile Q1.

  Salvatore Francesco Papandrea role and contribution in this paper: Conceptualisation, Methods, Writing original draft preparation, Writing review and editing.

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- **Salvatore F. Papandrea**, Stanimir Stoilov, Pavel Nichev, Georgi Angelov, Maria Francesca Cataldo* Andrea R. Proto. UNDER REVIEW. Effect of the Different Concentration of Assortments on Forwarder Productivity and Costs in Coniferous Forests.
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Activity 2: Ergonomic conditions in Forest Operations

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Activity 3: Wood Technology and Non-destructive testing

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  Salvatore Francesco Papandrea role and contribution in this paper: Methodology, Investigation, Software, Formal analysis, Writing original draft.

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4.2 Forests and Logging Operations

Article 1
Evaluation of Salvage Logging Productivity and Costs in Sensitive Forests of Bulgaria

Stanimir Stoilov[1], Andrea R. Proto2[*], Georgi Angelov[1], Salvatore F. Papandrea[2], Stelian A. Borz[3]

[1]University of Forestry, Department of Technologies and Mechanization of Forestry, Kliment Ohridski Blvd. 10, 1756, Sofia, Bulgaria; stoilovs@ltu.bg (S.S.); ggangelov@ltu.bg (G.A.)

[2]Mediterranean University of Reggio Calabria, Department of AGRARIA, Feo di Vito snc, 89122, Reggio Calabria, Italy; salvatore.papandrea@unnirc.it (S.F.P.)

[3]Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Şirul Beethoven 1, 500123, Brasov, Romania; stelian.borz@unitbv.ro (S.A.B.)

[*]Correspondence: andrea.proto@unirc.it; Tel.: +39-(0)965-169-4275

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Article

Evaluation of Salvage Logging Productivity and Costs in the Sensitive Forests of Bulgaria

Stanimir Stoilov [1], Andrea R. Proto [2,*], Georgi Angelov [1], Salvatore F. Papandrea [2] and Stelian Alexandru Borz [3]

[1] Department of Technologies and Mechanization of Forestry, University of Forestry, Kliment Ohridski Blvd. 10, 1756 Sofia, Bulgaria; stoilovs@ltu.bg (S.S.); ggangelov@ltu.bg (G.A.)
[2] Department of AGRARIA, Mediterranean University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy; salvatore.papandrea@unirc.it
[3] Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Şirul Beethoven 1, 500123 Brasov, Romania; stelian.borz@unitbv.ro
* Correspondence: andrea.proto@unirc.it; Tel.: +39-(0)965-169-4275

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Abstract: Steep terrain harvesting can only be implemented by a limited set of operational alternatives; therefore, it is important to be efficient in such conditions, in order to avoid incurring high costs. Harvesting abiotically-disturbed forests (salvage harvests caused by wet snow), which is becoming common these days, can significantly impact the operational efficiency of extraction operations. This study was implemented in order to evaluate the performance of truck-mounted uphill cable yarding operations in salvage logging deployed in coniferous stands. A time study was used to estimate the productivity and yarding costs, and predictive models were developed in order to relate the time consumption and productivity to the relevant operational factors, including the degree of wood damage. The average operational conditions were characterized by an extraction distance of 101 m and a lateral yarding distance of 18 m, resulting in a productivity rate of 20.1 $m^3 h^{-1}$. In response to different kind of delays, the productivity rate decreased to 12.8 $m^3 h^{-1}$. Under the prevailing conditions, lateral yarding accounted for 32% of the gross work cycle time, and for 50% of the delay-free work cycle time of the machine. Decreasing the lateral yarding distance and increasing the payload volume to the maximum capacity of the machine would eventually lead to a yarding productivity of close to 30 m^3 per SMH (scheduled machine hour). The calculation of the gross costs of uphill yarding showed that the labor costs (35.7%) were slightly higher than the fixed costs (32.9%), and twice as high compared to the variable costs (17.7%). The remote control of the carriage, mechanical slack-pulling mechanisms, and radio-controlled chokers are just some of the improvements that would have led to increments in operational efficiency.

Keywords: steep terrain; windbreak; windthrow; Natura 2000; cable yarder; performance

1. Introduction

Abiotic and biotic factors are causing important damage in European forests, and windstorms are the dominant factor causing them [1]. Such forest disturbances are becoming common due to the current trends in the climate, and their severity has increased in many forest ecosystems, including those in the Northern Hemisphere [2]. For instance, wet snow and ice cause damage to forests by bending or breaking the tree branches and tops. This happens when the weight of frozen precipitation exceeds the buckling load of the tree part bearing the load. In such circumstances, bending can occur, and it can result in permanent internal wood damage without any external exhibition of such damage. When they are left in forests, broken and uprooted trees favor insect outbreaks. A common way to minimize these effects by forest management is salvage logging [2], an activity that gained considerable interest and importance in those cases when disturbances occur in sensitive forest areas, and which is needed in recovering the economic value of timber in damaged forests, even in those locations which otherwise are spared from regular logging [3,4].

Salvage logging can be described as the harvesting of dead, damaged, or infested trees, aiming to recover the maximum value prior to the wood's deterioration [5]. Such operations require supplementary concerns to plan and adapt the harvesting system and safety to the site-specific characteristics and degree of damage [6–8]. When salvage logging is in question, the most suitable harvesting solutions are those guaranteeing the safety of the operators while yielding acceptable productivities and costs [3,8]. The problem is more challenging when these disturbances occur in sensitive areas, because the interventions must be consistent with the natural disturbance regime [9,10], which is known to contribute to biodiversity [11], while salvage logging may alter it [12] by causing changes in the structure, soil, microclimatic, and vegetation conditions in the harvested areas [13]. Still, salvage logging is a management option which is used in many European national parks [14,15].

Among the existing protected areas, the Natura 2000 network was established with the purpose of preserving Europe's most valuable and threatened species and habitats [16]. Currently, it protects approximately 18% of the European Union's land [17]; in these areas, it is of fundamental importance to regulate human-caused disturbance so as not to alter the natural conditions and to preserve the habitats, including by the correct implementation of the salvage logging operations. In fact, in several sensitive areas, such operations are not implemented, or are limited due to ecological reasons [18,19]. In addition, the economic factors may prohibit such operations, making them unfeasible due to low timber prices, causing situations in which the damaged timber is often left in the forests [20,21]. These reasons have led, in some regions, to a decrease in the implementation of salvage logging operations [22].

As an option, ground-based harvesting systems require a dense extraction infrastructure which may generate increased costs when they are developed in steep terrain. For slopes of 40% or higher, cable extraction is expected to cause less environmental impact compared to ground-based systems [23,24]. In addition, it is a desirable alternative to ground-based equipment when dealing with sensitive sites [25]. As such, cable yarding causes the least damage to soil [8], and minimizes the impact in environmentally sensitive areas. Hence, it could support biodiversity goals, and could be integrated into ecosystem management plans [26,27], based also on its competitiveness in terms of CO_2 emissions [28] and on its potential of using gravity [29] compared to other partly- or fully-mechanized ground-based harvesting systems. In fact, the natural level of biodiversity can be preserved by avoiding soil disturbance, which is enabled by the use of the suspended transportation of wood, enabling cable logging operations to preserve the succession of species that depend on undisturbed soil [2,30,31]. In the past, cable yarders were considered to be more complex and expensive than ground-based harvesting, mainly due to their purchasing costs and challenging setup operations, making cable-yarding operations more costly. Fortunately, most of the modern yarders are referred to as mobile equipment integrating a steel tower [8], making them less resource-intensive in setup and dismantling operations [32,33]. On steep terrain, they were found to be a more efficient alternative to building an extensive [34,35], costly [23], and environmentally-damaging [36,37] network of skidding roads. During the last few decades, different yarder models have been used in those conditions in which the terrain prohibits the use of other timber extraction equipment [38,39].

The current knowledge on the performance of salvage logging is mainly based on studies which have been carried out in order to evaluate it for harvesters, forwarders, and skidders. Dvôrák et al. [40] found that the time consumption of harvesting broken stems increased by 33% in Norway spruce forests affected by windthrow compared to regular operational conditions. Brzózko et al. [41] suggested that the productivity of operations in wind-damaged forests is 40–60% lower compared to normal conditions. Bodaghi et al. [42] evaluated the productivity of skidding operations deployed in wind-damage forests for skidders and farm tractors. Borz et al. [43] developed a survey on the skidding performance in difficult conditions characterized by low access and wind-damaged forests. Cadei et al. [7] evaluated the forwarding productivity in salvage logging deployed in the difficult terrain of the Italian Alps, in a forest area affected by windthrow caused by the Vaia storm. Kärhä et al. [3] carried out a comparative study and analyzed the productivity of a harvester–forwarder system in salvage operations deployed in Finnish windfallen forests. Câkša [44] evaluated the influence of sawlog volume production on the recovered timber assortments, in order to provide the information necessary to support salvage logging decisions. However, no studies have been identified to address the problem of cable yarding salvage logging operations. For this reason, this paper aimed at filling the knowledge gap related to cable yarding productivity in salvage operations. Based on the above, the objectives of this research were: (*i*) to evaluate the influence of selected operational factors on time consumption by a statistical modeling approach, and (*ii*) to improve our understanding on the operational efficiency of mobile cable-yarders in the salvage logging of coniferous stands. The efficiency improvement concerned the analysis of the time consumption, productivity, and costs, as these performance metrics are useful to integrate cable yarding operations in order to achieve the economic and environmental efficiency of timber harvesting in forests disturbed by abiotic factors.

2. Materials and Methods

Most Bulgarian forests (approximately 60%) are located in mountainous areas, on steep slopes and complex terrain configurations, while 23.6% of the national territory is protected within the framework of the Natura 2000 network. Bulgaria is not affected by Atlantic storms, but snow-breaks, wind-blows, and forest fires occur frequently; the statistical data indicates that traces of natural catastrophes/disturbances may be found on about 3% of the Bulgarian forest land [39].

2.1. Description of the Site and Yarding Setup

The study was carried out in the Sredna Gora Mountains (42°37′47.71′′ N–24°22′58.76′′ E), near the city of Koprivshtitsa, Sofia Province, Central Bulgaria (Figure 1). A description of the forest site and the operational characteristics is given in Table 1.

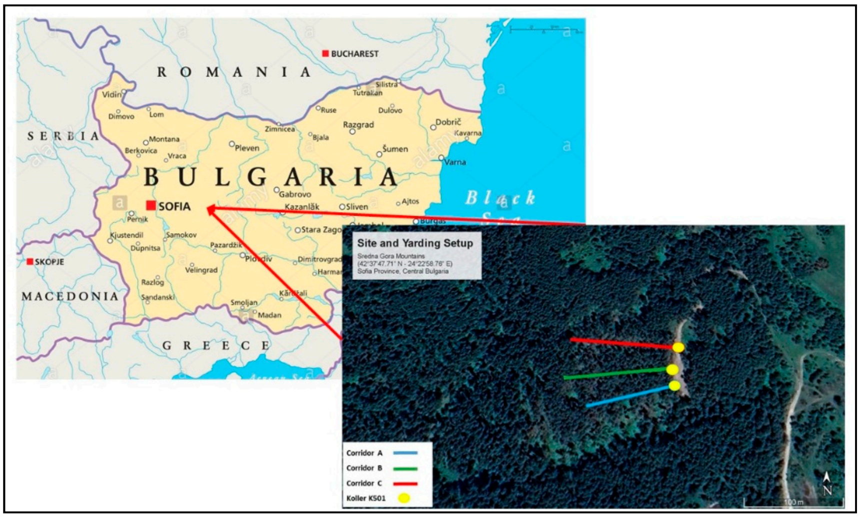

Figure 1. Site map of the study and the schematic layout of the corridors during the cable-yarding operations.

The forest chosen for the study is a part of the Natura 2000 network, designated by the function codes BG 0002054 and BG 0001389, listed under the Birds and the Habitats Directives, respectively. The type of habitat, by its code, is 91CA Rila-Rhodope and Balkan Mts. Scots pine forests. Such forests are dominated by *Pinus sylvestris* L., on mountain slopes with sun exposure, mainly on silicate and (more limitedly) on calcareous terrains.

They have a diverse structure and rich species composition. The participation of other tree species, in different proportions, is a sign of the dynamic status of a large part of the pine forests. This is why cable yarding was used as a more environmentally-friendly extraction solution while the studied forest was affected by wet snow and subsequent windbreaks and windthrow. Broken and uprooted trees are commonly described to generate additional difficulties for felling and extraction, mainly due to the fact that they are subjected to intense and complex tensions within the wood [8]. This makes both the tasks of identifying and taking safe positions by the workers, as well as for the cuts to be performed, more challenging because of the potential hazards.

Table 1. Characteristics of the test site.

Site	Kriva reka, subcompartment 9019-a1
Elevation	1200 m asl
Protection function/designation	Natura 2000: BG 0001389, BG 0002054, habitat 91CA
Species composition	Scots pine (*Pinus sylvestris* L.)
Stand age (years)	40
Stand type by age	Even-aged
Stand density (trees ha^{-1})	1784
Logging operation	Salvage cutting after wet snow, windbreaks and windthrow damage
Average tree height (m)	15
Average DBH of tree (cm)	24
Site volume (m^3 over bark)	540
Removal volume (m^3 over bark)	175
Altitudinal difference between the corridor endpoints (m)	45
Average sag (m)	12
Average lateral yarding distance (m)	17.8

Three yarding corridors (A, B, and C) were designated on terrain slopes of 18° (32%) on corridor A, 16° (29%) on corridor B, and 14° (25%) on corridor C; each corridor had a length of approximately 200 m. Most of the damaged trees were located on the site specific to corridor A. The field observations were designed to cover the minimum required number of 30 complete yarding work cycles (turns) on each corridor [45]. The extraction was performed in the uphill direction, and the trees were manually felled. A single-span layout was rigged on each corridor, and the proportion of undamaged standing trees was 50%. A total number of 892 trees were removed from the stand, out of which 64 were removed from the cable yarding corridors. The removed trees were distributed as follows: 437 trees (about 49%) on the site of corridor A, 277 trees (31%) on the site of corridor B, and the remaining of 178 trees (20%) on the site of corridor C. The classification of the damaged trees was performed according to the system described by Kärhä [3]; accordingly, the types of damage corresponded to code 1A—uprooted whole tree with stump, code 1B—hang-up whole tree, code 1C—uprooted and broken tree with separate butt and top sections, and code 1D—broken tree section. The damaged trees coded by 1A were dominant in the site corresponding to corridor A, while in the sites of corridors B and C, the dominant damage type was 1D.

2.2. Description of the Cable Yarder Unit and Work Team

The study was performed on a Koller K501 truck-mounted tower yarder (Table 2–Figure 2). The work team consisted of the yarder operator, a second worker who unhooked, delimbed, and bucked the trees, and a choker-setter at the yarding site. The workers were 35 to 45 years old, and all of them had an extensive experience of cable yarding operations. They were informed in advance on the study objectives and the intended use of the data, and they agreed to be observed. The observed yarder was designed for uphill extraction. It was a powerful machine, and it was mainly used in selective cuts and for other common wood harvesting operations. During the observed operations, it was equipped with a SKA 2.5 (KOLLER Forsttechnik GmbH, Schwoich, Austria) carriage that supports payloads of up to 2.5 t. The mass (9800 kg) was distributed on the rear axle of a Mercedes-Benz truck equipped with special reinforced frames. The logs were yarded laterally to the carriage using the power of the mainline winch and active skyline clamps.

Table 2. Technical characteristics of the cable crane.

Parameter	Value
Skyline capacity 600 m, ø 24 mm	120 kN (tension section)
Mainline 600 m, ø 14 mm	43 kN (average drum)
Guylines	4 × 75 m^2, ø 16 mm/2 × 15 m^2 (extension)
Foldable telescopic tower, height	13.5 m
Power station	Autonomous engine and hydrostatic transmission
Engine power	250 kW (340 HP)
Skyline	Manually actuated band brake
Mainline	Hydraulically actuated band brake
Operation	Hydro-mechanical/electro-hydraulic single lever operation with dead-man's control
Carriage	Koller SKA-2.5, manual slack-pulling carriage
Choker system	Bardon choker
Lifting moment	270 kNm
Carrier	6 × 4 Mercedes-Benz truck

Figure 2. Koller K501 yarder during the operations: (**a**) view from the landing site; (**b**) view from the lateral yarding.

2.3. Time Study

An elemental time study was carried out in order to estimate the time consumption and productivity of the cable yarder in the observed conditions. The elemental composition of a work cycle was assumed to be that described in the related scientific literature [35,46,47], and the operational variables were accounted for in order to check their effect on the variation of the work cycle time. Each yarding work cycle was individually timed by a stopwatch (Hanhart® Stratos 2) to account for the scheduled machine hours (SMH). Following the field observations, the productive time was separated from the delay time, and the time shares and harvesting productivity were estimated based on a productive machine hours (PMH) approach. The yarding distance and the terrain slope were measured by a professional laser range-finder (Bushnell® V5). The payload volume was estimated by measuring the length and the mid-length diameter of all of the logs from each load. Six work elements were separated and taken into account in order to estimate the work cycle time [48]; they were similar to those described by Proto et al. [24,35,49]:

1. Carriage outhaul (CO) begins when the operator is ready to move the empty carriage from the landing out to the stump, and ends when the choker-setter touches the chokers.
2. Lateral outhaul (LO) begins at the end of carriage outhaul, and ends when the choker-setter has completed the hooking of the chokers and signals to begin yarding.
3. Lateral inhaul (LI) and hook begins at the end of the hook up, and ends when the turn is pulled up to the carriage and the carriage begins to move up the corridor.
4. Carriage inhaul (CI) begins at the end of the lateral inhaul, and ends when the load has reached the deck where it can be directly unhooked at the landing.
5. Unhook (U) begins at the end of the carriage inhaul, and ends when the chokers have returned to the carriage.
6. Delay time (D) includes the rest, personal delays, organizational delays, service, and repair.

2.4. Economic Evaluation

The objective of developing hourly costs for the yarder and operators (machine rate) should be to achieve a value that is the most accurate, standing for a good representation of the work performed under the existing operating conditions and the accounting system in use. The machine rate includes cost categories such as the fixed, operating (variable), and labor costs. The machine costs were estimated using the COST model proposed by Ackerman et al. [50]. The hourly costs were reported by considering the productive machine hours (excluding delays) as well as the scheduled machine hours. The investment in machine purchasing and salaries required by the cost calculations were obtained from catalogues and accounting records. The wages were set at 37.87 € SMH^{-1}, and they included all indirect salary costs. The fuel consumption was measured by the commonly used method of refilling to full. The machine's salvage value was set at 10%, and the Value Added Tax (VAT) was excluded from the calculations. The economic evaluation was based on the assumption that the company worked for 200 days in the year, and the depreciation period was set at 10 years.

2.5. Data Analysis

The prediction of the work cycle time and productivity were performed by statistical modeling, which involved the use of regression analysis. The variables used as predictors were the yarding distance (L, m), lateral yarding distance (l, m), payload per cycle (Q, m^3), terrain slope angle (i, °), and the number of trees per payload (n). In addition, the tree damage type (dt) was used as an indicator (dummy) variable to enhance the discrimination of the time prediction models. The models describing the time consumption and productivity were defined in Equations (1) and (2):

$$T_{net} = f\ (L,\ l,\ Q,\ i,\ dt) \quad (1)$$

$$P_{PMH} = \frac{3600\ Q}{T_{net}} \quad (2)$$

where T_{net} = the productive time separated from the delay time, and P_{PMH} = the harvesting productivity based on a productive machine hours approach.

The preliminary statistical steps consisted of the exclusion of outliers, and a correlation analysis which was run for the predictors in order to check their appropriateness in the models. The correlation analysis was based on a threshold set at 0.75 for the correlation coefficient to exclude predictors based on a pair-by-pair comparison. The reason for this approach was the avoidance of an artificial inflation of the determination coefficients in the developed models, which is an approach which has been used in similar studies. Then, the main descriptive statistics were estimated, and least-square multiple linear regression was used by a stepwise backward approach to develop predictive models of the time consumption and productivity as a function of the predictors kept in the analysis. The predictive models were developed using a confidence threshold set at 95% ($\alpha = 0.05$) by assuming a probability of $p < 0.05$. Under these assumptions, the predictors are significant for a given model when $p < 0.05$, i.e., there is a strong presumption against the neutral hypothesis. The software used to process and analyze the data was Statistica 8 (StatSoft Inc., Tulsa, OK, USA).

3. Results

The field observations covered, in total, 14 h, and within this time, the cable crane completed 30 cycles for each corridor. Under the studied conditions, the largest share (33%) of the delay-free work cycle time was spent during the lateral outhaul and hooking, with some differences that were characteristic to each corridor (A, 28%; B, 36%; C, 24%), followed by the lateral inhaul (17% in general, and 14, 18, and 15% for corridors A, B and C, respectively). These shares were related to the work deployed on moderately steep terrain, as well as to the specific distribution of crossed, thrown, and broken trees. The work elements of the carriage outhaul, unhooking, and carriage inhaul accounted for shares of 19%, 18%, and 13%, respectively. Regarding the total scheduled time, delays accounted for the most time: 46% for site A, 31% for site B, and 47% for site C. For comparison, Huyler and Ledoux [48] found a time share of approximately 35% for delays caused by operational, mechanical, and non-productive time on steep slopes of approximately 40–50% in the US Northeast. In this study, the delay time recorded at each site was related mainly to the operation of the yarder. In fact, the processing of the yarded trees into logs was a work task performed by the worker who unhooked, delimbed, and bucked the trees, whereas the yarder operator piled the logs by hydraulic crane on landing, during which the yarding work was interrupted. The lateral outhaul and hook accounted for about 15% (site A), 25% (site B), and 13% (site C), respectively. According to Dimitrov [51], in order to increase the productivity of tower yarders operated in Southwest Bulgaria, the time consumption for lateral outhaul (28%), inhaul (21%), and unhook (13%), as well as the ineffective time covering the spare and delays of workers (16%) should be minimized.

The remaining work elements had an approximately equal share in the time consumption. The carriage outhaul accounted for 12% (11, 12, and 13% in corridors A, B and C, respectively), unhook accounted for 12% (11, 11, and 12%), and lateral inhaul accounted for 11% (8, 13, and 8%); the carriage inhaul accounted the smallest time share, which was 8% (9, 8 and 8%). The work tasks related to the lateral yarding (the lateral pull of the main line, the chocking, and the extraction of the load to carriage) accounted for 32% of the gross study time (21, 38, and 21% for corridors A, B, and C, respectively), and for 50% (general), 42% (A), 54% (B), and 39% (C) of the delay-free work cycle time. Due to the short yarding distance, moderate terrain slope, and small loads per turn (2.2 trees and 1.1 m^3, on average), where the latter did not load the carriage at its full capacity, the lateral yarding distance had a high impact on the work cycle time. Also, it is worthwhile to note that the running time of the empty carriage was longer compared to the loaded running, a fact that was controlled by the operator of the yarder, and which depended on the operator's availability for certain tasks. The yarding productivity for an average yarding distance of 100.7 m and for an average lateral yarding distance of 17.8 m, excluding and including the delays, was estimated at 20.1 and 12.8 $m^3 h^{-1}$, respectively. The increase of the lateral and corridor extraction distances resulted in significant variations of the work cycle time. The results indicate a good efficiency of the extraction system, but there are many organisational issues which could be addressed in order to fully utilize the potential of the tested cable yarding system [49]. If the remote control of the carriage had been available, it could have been controlled by the choker-setter. Another option to reduce the choker-setter's fatigue and to decrease the time for the lateral outhaul and hook would have been to use a carriage equipped with a mechanical slack-pulling device. Tables 3 and 4 and Figure 3 show the main descriptive statistics related to the time consumption and yarding distances, which are given at the site and corridor level.

Table 3. Descriptive statistics of the time consumption and operational distances.

Yarding Time Consumption Variables	Cycle Time, s			Distance, m		
	Mean Value ± St. Dev.	Min	Max	Mean Value ± St. Dev.	Min	Max
Carriage Outhaul	**39.5 ± 10.0**	**22**	**70**	**100.7± 31.8**	**60**	**130**
Corridor A	39.5 ± 10.2	22	70	96 ± 31.2	60	130
Corridor B	39.5 ± 10.3	22	70	96 ± 31.2	60	130
Corridor C	39.6 ± 9.6	22	60	108.4 ± 28.7	60	130
Lateral outhaul and hook	**69.2 ± 51.8**	**20**	**200**	**17.8 ± 11.3**	**9**	**42**
Corridor A	83.0 ± 58.6	20	200	20.8 ± 12.8	9	42
Corridor B	36.5 ± 25.3	20	180	14.7 ± 4.1	7	22
Corridor C	44.0 ± 25.3	20	120	12.1 ± 2.5	9	19
Lateral inhaul	**36.0± 25.3**	**15**	**100**	**17.8 ± 11.3**	**9**	**42**
Corridor A	41.5 ± 28.7	15	100	20.8 ± 12.8	9	42
Corridor B	41.3 ± 28.7	15	100	14.7 ± 4.1	7	22
Corridor C	27.7 ± 17.6	15	100	12.1 ± 2.5	9	19
Carriage Inhaul	**28.3± 7.2**	**15**	**45**	**100.7± 31.8**	**60**	**130**
Corridor A	33.5 ± 7.2	15	45	96 ± 31.2	60	130
Corridor B	26.6 ± 4.7	20	35	96 ± 31.2	60	130
Corridor C	24.8 ± 6.0	20	35	108.4 ± 28.7	60	130
Unhook	**38.3± 11.1**	**10**	**60**			
Corridor A	38.2 ± 11.1	10	60			
Corridor B	38.1 ± 11.3	10	60			
Corridor C	38.9 ± 11.1	10	60			
Delay	**120.0± 131.1**	**0**	**550**			
Corridor A	109.7 ± 131.1	0	525			
Corridor B	102.9 ± 127.8	0	525			
Corridor C	142.7 ± 136.8	0	550			
Total cycle time	**331.3± 120.9**	**151**	**715**			
Corridor A	345.4 ± 127.8	154	690			
Corridor B	331.6 ± 114.1	151	695			
Corridor C	317.4 ± 135.3	154	715			
Delay-free cycle time	**211.3 ± 77.5**	**135**	**430**			
Corridor A	235.7 ± 88.7	145	430			
Corridor B	228.7 ± 85.4	140	421			
Corridor C	317.4 ± 135.4	140	330			

The regression analysis used the time study data with the aim to develop prediction equations to estimate the yarding work cycle time. The significant variables, which were retained in the models, were the lateral yarding distance (l, m) and slope (i, °). The general regression equation for the delay-free cycle time T_{net} (s, seconds), which was developed in order to reflect the performance at the site level, along with its significant variables, are shown in Table 5. According to Equation (1), the minimum values of the delay-free cycle time (T_{net}, productive machine hours; PMH) may be reached when the lateral yarding distance (l, m) and the terrain slope (s, °) are small, in conjunction with damage type 1A (dt = 1). For such a case, it was easier to laterally yard the trees, because of the presence of fewer obstacles. The damage type *dt* = 2 (code 1D, broken tree section prevailed) involves lateral outhaul among the broken tree sections, which may stand as serious obstacles. Besides the general model, which enables a differentiation between the condition of the yarded trees, the equations in Table 6 show the cases specific to the three corridors, in which the lateral yarding distance *l* (m) was found to be the only significant variable affecting the variation of the delay-free work cycle time. As shown by the regression coefficients, the effect of the lateral yarding distance on the delay-free work cycle time was the strongest in the case of corridor B compared to the specifics of corridors A and C; this was due to the aforementioned operational conditions. As was provided for the same lateral yarding distance, the time needed to yard the trees would be significantly less in corridors A and C compared to corridor B.

Table 4. Payload and productivity metrics.

	Mean Value ± St. Dev.	Min	Max
Payload per cycle (site), m^3	**1.1 ± 0.38**	**0.4**	**1.8**
Corridor A	1.04 ± 0.38	0.5	1.8
Corridor B	1.05 ± 0.38	0.5	1.8
Corridor C	1.10 ± 0.30	0.4	1.6
Productivity (site), m^3 SMH^{-1}	**12.8 ± 6.40**	**4.47**	**29.45**
Corridor A	11.86 ± 6.11	4.47	29.45
Corridor B	12.45 ± 6.60	5.42	29.45
Corridor C	14.04 ± 6.40	4.97	24.51
Productivity (site), m^3 PMH^{-1}	**20.1 ± 9.9**	**5.42**	**43.2**
Corridor A	17.8 ± 9.4	6.35	43.20
Corridor B	18.49 ± 9.9	5.42	43.20
Corridor C	23.73 ± 9.5	7.83	41.10
Number of work cycles per SMH (site)	**10.86**	**5.03**	**23.84**
Corridor A	10.42	5.22	23.38
Corridor B	10.84	7.18	23.84
Corridor C	11.34	5.03	23.38

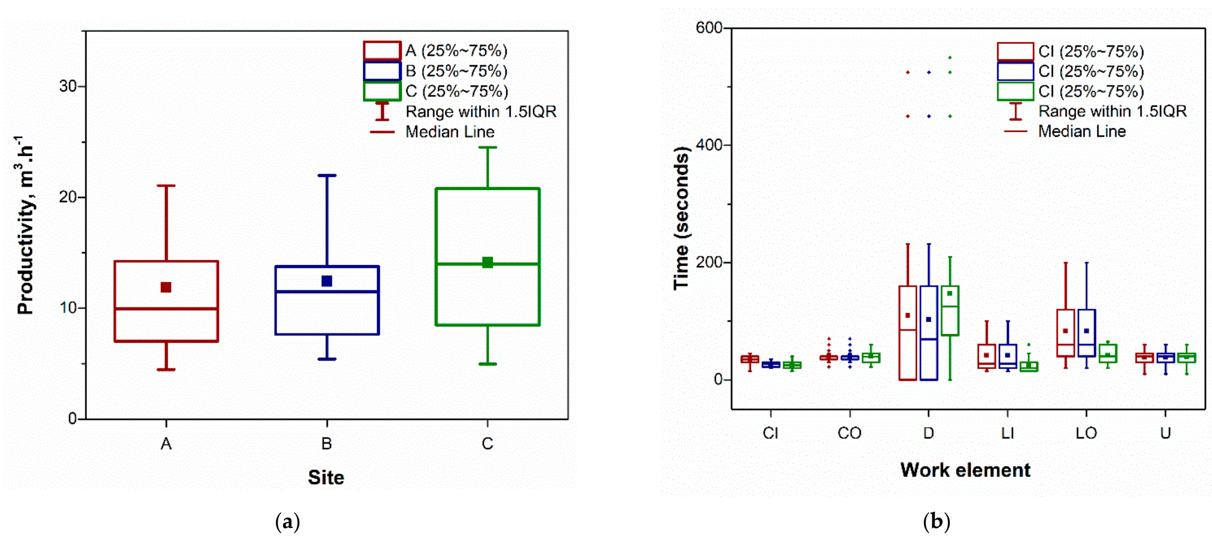

Figure 3. Summary statistics of the yarding productivity for the three corridors (**a**) and of the elemental time consumption (**b**). Legend: A, B, and C stand for corridors A, B and C; CI, CO, D, LI, LO and U work elements are defined in Section 2.3

Table 5. Summary of the work cycle time models at the site and corridor level.

Equations	F	$R^2_{adjusted}$	Std. Error	*p*-Value
$T_{net} = -0.575\ L + 5.193\ l + 17.017\ i + 23.972\ dt$	18.30	0.54	52.63	$p < 0.05$
$T_{net\_A} = 6.9005\ l$	50.17	0.87	34.46	$p < 0.05$
$T_{net\_B} = 15.2073\ l$	15.92	0.67	48.82	$p < 0.05$
$T_{net\_C} = 2.6206\ l$	2.85	0.20	32.93	$p < 0.05$

Table 6. Summary of the productivity models developed for the site and corridor conditions.

Equations	F	$R^2_{adjusted}$	Std. Error
$P_{PMH} = 34.61 - 0.34\ l + 17.46\ Q - 1.58\ i$, ($m^3\ h^{-1}$)	42.14	0.73	5.09
$P_{PMH\_A} = 14.20 + 0.08\ l + 3.48\ Q$, ($m^3\ h^{-1}$)	37.83	0.84	3.81
$P_{PMH\_B} = -0.71\ l + 12.42\ Q$, ($m^3\ h^{-1}$)	12.69	0.62	4.08
$P_{PMH\_C} = 18.83 - 1.13\ l + 9.02\ Q$, ($m^3\ h^{-1}$)	10.78	0.57	4.20
$P_{SMH} = 12.87\ Q$, ($m^3\ h^{-1}$)	15.69	0.50	4.53
$P_{SMH\_A} = 13.827\ Q$, ($m^3\ h^{-1}$)	9.60	0.54	4.13
$P_{SMH\_B} = -0.717\ l + 12.428\ Q$, ($m^3\ h^{-1}$)	12.69	0.62	4.08
$P_{SMH\_C} = 18.832 - 1.138\ l + 9.027\ Q$, ($m^3\ h^{-1}$)	10.78	0.57	4.20

The regression equations developed to describe the work cycle time including the delays (SMH) at the site and corridor (A, B, C) levels revealed no additional significant predictors, a fact that may be the effect of including the delays which are known to follow different statistical laws [52] and, therefore, to mask other important effects [53].

The variation of yarding productivity at the site level, which was estimated based on the delay-free time consumption, is given by the general regression equation reported in Table 6. Therefore, the factors that could contribute to the increment of the yarding productivity are the terrain slope and the lateral yarding distance l, by their minimization. In addition, the payload volume per work cycle (Q) should be increased in order to enable higher productivities. The control over these factors is difficult to attain by engineering, as they are frequently a reflection of the given operational conditions. In regard to the productivity being estimated based on the total time, the general regression equation of yarding productivity indicates that the productivity for the given conditions depends solely on the volume of the payload, because no other factors acted as significant predictors. However, at the corridor level, the situation changed in the sense that the lateral yarding distance became a significant predictor of the productivity for corridors B and C. The models given in Table 6 also indicate that by decreasing the lateral yarding distance l, and by increasing the payload volume Q, one can increase the yarding productivity per scheduled machine hour; however, the control issues on such an attempt are similar to those presented in the case of time consumption models. Productivity did not depend significantly on the damage type.

The hourly costs of the studied tower yarder, as well as the labor costs, are summarized in Table 7. As shown, the gross costs for uphill whole tree yarding were estimated at 120.17 € PMH (productive machine hour). In the structure of the gross costs, the fixed costs (34%) were slightly higher than the labor (31%) and variable costs (24%). Therefore, for the productive time of the machine, the extraction costs were estimated at 5.72 € per m^3. Different cost results were found by comparing the three different damage types. Corridor C, which was characterized by the damage code 1C, returned the lowest costs of wood harvesting, which were 25 and 22% lower compared to those of corridors A and B, respectively. In addition, an increase of the yarding productive time would lead to a decrease in the extraction costs, even though these costs are lower compared to those found for a similar machine operating on moderate slopes to extract resinous wood for an outhaul distance of 125 m and a lateral yarding distance of 7 m, i.e., conditions in which the costs ranged between 12.910 and 14.690 US $ per m^3 [54].

Table 7. Yarding costs (€) at the corridor level.

Costs Category	Costs per PMH	Costs per m^3	% of Total	Costs per m^3		
				Site A Code 1A	Site B Code 1B	Site C Code 1C
Fixed costs	40.38	1.91	33.46	2.27	2.18	1.70
Variable costs	29.05	1.40	24.45	1.63	1.57	1.22
Labor costs	37.87	1.80	31.38	2.13	2.05	1.60
Net costs (excluding profit)	107.30	5.11	89.29	6.03	5.80	4.52
Gross costs (including 12% profit)	120.17	5.72	100	6.75	6.50	5.06

4. Discussion

As reported by similar studies [23,35,40,46,50,55], the comparison of productivity and costs across different countries, highly variable personnel costs, and contrasting environmental conditions is difficult, despite the similarity of the machines used. As such, the particular condition of the forest stand examined in this study and the lack of similar studies in which the cable yarder was used for salvage logging did not allow for a complete and exhaustive comparative analysis of the results. However, the objectives of this study were to check and find ways of improving the performance of cable yarding in salvage logging operations. For the neighbor country of Bulgaria, Romania, which shares a similar economic context, Munteanu et al. [29] evaluated the operational costs at 7.4 € m^{-3} for the use of a gravity-driven Wyssen yarder. In their study, which was performed in a group shelterwood system by the use of a gravity-assisted downhill yarding, the extraction distance was 326 m, the lateral yarding distance was 43 m, and the payload per turn was 1.87 m^3. In the Italian Alps, Spinelli et al. [56] estimated the costs of timber extraction and processing in the range of 9 to 40 € m^{-3}. These previous studies proved that costs and productivity vary depending on the variables considered; in particular, the lateral yarding distance has an influence on productivity, while the costs are largely dependent on the productivity. Generally, the yarding productivity in this study was found to be higher than that reported by other studies on tower yarders [51,57,58]. Erber et al. [59] evaluated the performances of a Koller K507 in the conditions of Bavarian State Forests, and reported an average productivity of 10.1 m^3 h^{-1}, identifying the terrain slope, stand density and yarding direction as the significant independent variables explaining the performance of the machine. Dimitrov [51] estimated that the productivity of the studied yarder was of 3.22 m^3 h^{-1} in operational conditions characterized by a 33 m lateral yarding distance, and a 230 m outhaul distance, therefore the productivity figure estimated by him could be interpreted as moderate. Furthermore, our findings indicate higher productivities compared to those reported for Turkish coniferous forests, which were estimated at 6.6, 5.5, and 4.9 m^3 h^{-1}, for extraction distances of 100, 200, and 250 m, respectively [60]. Tavankar et al. [61] reported that the volume of the fallen trees, harvested selectively, was twice as low as that from the protected forest stands of the Hyrcanian forest of Iran, a fact that may affect the productivity of salvage logging compared to conventional logging. The machines from the Processor Tower Yarder (PTY) class were evaluated as highly productive during our study, and are recommended for use in coniferous forests in order to fully use their functionality potential [32]; for these machines, the productivity increment is supported by technical features such as those of enabling tree processing, sorting, and piling after load lowering and releasing [62–65]. In addition, the use of radio-controlled chokers may help to decrease the unhooking time consumption by the elimination of this manual task at landing, and it could be supported by a remote controller mounted in the yarder's cab [66], improving the operations safety. Furthermore, the results of this study provide evidence that cable yarding could be used effectively in salvage logging, complementing the commonly used harvesting systems, such as those including skidders [42]. In fact, nowadays, in steep terrain, there is no cost-efficient alternative to cable-based extraction. Schweier et al. [55] defined a winching distance of 50 m as the threshold value of winching operations performed by skidders. Higher productivities may support cost reduction when the extraction is carried out using a yarder. In particular, the costs analysis of this study produced values ranging from € 5.06 m^{-3} to € 6.75 m^{-3}, costs that are clearly lower than those of traditional ground-based salvage logging. The higher productivities and lower costs of this study may be related to the efficient forest operation planning during the cable yarder setup phase. The results confirmed that short operational distances influenced the productivity rate and, consequently, the operational cost. In addition, Bodaghi et al. [42] found no economic justification to harvest wind-fallen trees using ground-based wood extraction, due to lower productivities. As such, our opinions concur to consider the positive effects that salvage logging may have to overcome economic barriers; in fact, even if the salvage logging is frequently resource intensive in sensitive forest areas, these operations are important for the forests, as they can be used as a strategy to mitigate further damage outbreaks in coniferous forests [3]. In addition, some studies [67] have reported more conservative results on the impact of salvage logging, thereby supporting their implementation based on careful planning to protect the soil. The use of cable yarders holds the potential to reduce the damage and disturbances; in fact, if the operations are carefully planned and performed, then the resilience of seedlings and small trees is sustained [6]. In addition, there are several challenges to which the use of storm-damaged wood could respond, such as balancing the demand and supply of energy wood [13]. For other industrial purposes, the quality of such timber is in question, and should be researched further [68,69], and its use should also balance ecological, social, and economic needs [42].

5. Conclusions

Large-scale windstorms are increasingly frequent in European forests, and they may cause important losses, especially when they affect sensitive forests, for which there are problems related to the wood's recovery. This study was set up to evaluate the performance of wood extraction by tower yarders in such forests, by observing an operation done in the Bulgarian mountains. By its results, the study extended the existing knowledge on the productivity and costs of salvage logging operations. On the one hand, the damage type was found to produce significant variations in time consumption and productivity, mainly due to the amount of time needed to deal with different types of damaged trees. Similar to other findings, the limited payloads observed in this study have depended on the particular operational conditions, and not on the machine capacity. The preparation of the loads affected the efficiency of the extraction, in conjunction with delays, resulting in a decreasing trend of productivity, a situation for which better time management could be one of the improvement measures. Until extensive studies on the problem are developed, the results reported herein may be used as a baseline to plan and organize the production for similar operational conditions, because such information is needed at least to develop an equitable payment system for salvage logging operations. On the other hand, our findings complement the existing knowledge on the performance of salvage logging operations, which currently covers only ground-based harvesting systems.

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Abbreviations

The following abbreviations are used in this manuscript:

asl	above sea level
CI	carriage inhaul time
CO	carriage outhaul
CO	carriage outhaul time
D	delay time
DBH	diameter at breast height
LO	lateral outhaul time
PMH	productive machine hours
PTY	processor tower yarder
SMH	scheduled machine hour
TNET	delay-free cycle time
U	unhook time

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4.3 Forests and Logging Operations

Article 2
Productivity analysis and costs of wheel cable skidder during salvage logging in European beech stand

Stanimir Stoilov[1], Salvatore F. Papandrea[2*], Georgi Angelov[1], Delyan Oslekov[1], Giuseppe Zimbalatti2, and Andrea R. Proto[2]

[1]University of Forestry, Department of Technologies and Mechanization of Forestry, Kliment Ohridski Blvd. 10, 1756, Sofia, Bulgaria.

[2]Mediterranean University of Reggio Calabria, Department of AGRARIA, Feo di Vito snc, 89122, Reggio Calabria, Italy.

*__Correspondence:__ Salvatore Francesco Papandrea, Department of AGRARIA, *Mediterranean* University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy;

Email: salvatore.papandrea@unirc.it; ORCID: 0000-0002-2974-7760 Tel.: +39 (0)965-169-4202

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Productivity analysis and costs of wheel cable skidder during salvage logging in European beech stand

Stanimir Stoilov[1], Salvatore F. Papandrea[2*], Georgi Angelov[1], Delyan Oslekov[1], Giuseppe Zimbalatti[2], and Andrea R. Proto[2]

[1]University of Forestry, Department of Technologies and Mechanization of Forestry, Kliment Ohridski Blvd. 10, 1756, Sofia, Bulgaria.

[2]Mediterranean University of Reggio Calabria, Department of AGRARIA, Feo di Vito snc, 89122, Reggio Ca-labria, Italy.

***Correspondence:** Salvatore Francesco Papandrea, Department of AGRARIA, *Mediterranean* University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy;

Email: salvatore.papandrea@unirc.it;

ORCID: 0000-0002-2974-7760

Tel.: +39 (0)965-169-4202

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Abstract

The salvage logging is increasing in Central Europe because of the growth of severe meteorological events and timber harvesting in these conditions is challenging in terms of both productivity performances and safety of the operations. In recent years, with the increase of natural calamities several researchers studied machinery productivity performances regarding salvage logging carried out by ground-based systems. In fact, a common post-disturbance management approach is salvage logging which consists of the widespread removal of damaged trees. In this research, system productivity and the cost of salvage logging are analysed in European beech stand affected by wet snow. Accretion of heavy wet snow poses the greatest risk to forests in the Northern Hemisphere. This type of snow attaches more effectively to tree crowns and branches when temperatures are close to freezing point at the time of precipitation.

Trees may break or bend, and they may be uprooted when the soil is unfrozen. This study has been implemented in order to evaluate the productivity and cost effectiveness of extraction in salvage logging deployed with a skidder in beech stand affected by two different type of wet snow damages. The results show that the productivity of the four-wheel-drive cable skidder despite operating in salvage cutting with a removal intensity of 10% is 14.73 m^3•SMH^{-1}, similarly to skidder performances in "ordinary" cuttings. Skidder productive time was 86% from scheduled time, whereas the delays are due to organizational reasons, mechanical delays, and those due to adverse weather conditions. The mean travel speed of the cable skidder obtained in this study is close to the results obtained of other studies on similar machines. The costs per unit are lower compared to the effective cost consumptions for the other cable skidders and agricultural tractor, adapted for skidding operated in hardwood salvage logging. Therefore, under the given conditions, the operation of the four-wheel-drive cable skidder is viable from silvicultural, technical and economic point of view in the salvage operation logging.

Introduction

Severe natural disturbances are common in many forest ecosystems, particularly in the Northern Hemisphere (Thorn *et al.* 2017). Forest disturbances have caused noticeable damage to European forests over the last few decades (Schelhaas *et al.* 2003). Different abiotic and biotic disturbances are expected to become more common in the future due to a warming climate. In particular, ice-storms could trigger physical damage to forests and therefore significantly affect forest structures and functions (Carbaugh and Hensle 2005; Kramer *et al.* 2014; Zhu *et al.*, 2022). In detail, wet snow or ice causes bending or breakage branches and tree tops and this occurs when the weight of frozen precipitation exceeds the buckling load of the portion of the tree bearing the load (Stoilov *et al.*, 2021; Thorn *et al.*, 2017). In order to prevent biological diseases (fungi and insects) and to foster active forest restoration, forest managers apply salvage logging in affected stands with the intent of recovering maximum value prior to deterioration (Stokes *et al.* 1989). These interventions differ from the common planned logging activities, for the higher harvesting intensity (Cadei *et al.* 2021; Schmiegelow *et al.* 2006; Stoilov 2021) or for their higher difficulties founded during harvesting operations. For these reasons, post-disturbance salvage logging is becoming more predominant to recover economic value from timber in disturbed forests (Kärhä *et al.* 2018; Magagnotti *et al.* 2013), and this purpose motivated several studies in recent years to determine productivity models and cost assessments to support a correct decision in choosing between alternative wood harvesting systems. These aspects are particularly important in salvage logging, because of difficulties due to irregularly positioned fallen trees in forest areas, and due to particular aspects related to the absence of work planning (Bodaghi *et al.* 2018). These interventions required valid operational planning according to the characteristics of the site to assure high productivity and greater safety for forestry workers. According to the steep slope condition, low road density, and the structure and tree volume, ground-based systems are the main extraction methods for logs, which are felled and processed by chainsaws (Cataldo *et al.* 2020). This semi-mechanized system represents the most suitable technological solution on rapid post-disturbance wood harvesting. In particular, the productivity of logging machines depends on many factors such as forest disturbance types, logging intensity, the number of trees per hectare, machine type, tree size, terrain conditions, operator skills, silvicultural treatment, and distances between skid roads (Proto *et al.* 2016; 2018; Wang *et al.* 2004).

In recent years, with the increase of natural calamities several researchers studied machinery productivity performances regarding salvage logging carried out by ground-based systems, based mainly on adapted agricultural tractors with related logging equipment such as winches, as well as wheel cable skidders (Cadei *et al* 2020*;* Bodaghi *et al* 2018; Borz *et al* 2013) Compared to agricultural forestry tractors, skidders have greater mobility, and being specially built, they meet the ergonomic and safety standards imposed by the wood industry, for these reasons and not only, all over the world the skidder is one of the primary machines used for timber extraction operations (Georgiev and Stoilov 2007). The skidders may successfully replace modified farm tractors without requiring any substantial changes in the conventional harvesting methods (Proto *et al.*, 2018). Wheel cable skidders are used in many harvesting systems on slopes prohibitive for farm tractors due to their better longitudinal and lateral stability, mobility and long winch cable (80–100 m) giving a better opportunity to access to marked trees and enhanced productivity. Currently, there are a few studies on the work cycle, productivity rates and costs of cable skidders in salvage logging in different silvicultural systems, damage type, and terrain conditions. The influence of different operational and technical parameters in salvage logging were studied by Bodaghi *et al.* (2018) that monitored the productivity and costs of wheeled skidder and farm tractors under two different stand conditions. In Romanian Carpathians, Borz *et al.* (2013) evaluated the efficiency of two different skidder models during timber skidding in reduced accessibility conditions caused by wind-fallen trees. Such studies have been needed to evaluate the application of typical wheel cable skidders in salvage logging in sensitive sites from silvicultural, technical and economic point of view. However, the available knowledge when dealing with salvage logging is still limited in productivity and costs for different harvesting equipments, including the association between chainsaws and skidders, as different damage types (wind-storm, ice-storm, etc.). For this reason, the study aims to partially fill the lack of knowledge of skidder productivity in salvage logging operation working in two different type of damages caused by wet snow disturbance. The aims of the present study proposes (*i*) to determine productivity rates and extraction costs using conventional cable skidder in salvage cutting in deciduous stands, and (*ii*) to develop skidding time and productivity prediction models in European beech high forests damaged.

Material and Methods

Study site and work organisation

The study was carried out in Vitinya State Hunting Range, Sofia Province, located in Western Balkan Mountains, Bulgaria. Stand and operation characteristics are shown in Table 1. The wet snow disturbance damaged an European beech (*Fagus sylvatica,* Linnaeus, 1753) stand and the proportion of damaged trees respect the total number of trees was 10%. There were 981 damaged trees in the stand and the type of damages corresponded to code 1A Uprooted whole tree with stump (standing tree had lodged, felling a whole stem) and 1D Broken tree section (broken tree with a separate butt section or top broken sections) (Kärhä *et al.*, 2018). The stand was divided into two approximately equal parts (Figure 1): site A (upper part) with damages corresponding to code 1D and site B (lower part) with damages described with code 1A. Skidding direction was downhill and trees were motor-manually felled. The logs were transported by a wheel cable skidder as semi-suspended stem sections. The work team consisted of the skidder operator, a second worker who unhooked the stems at landing, and the other two workers were chainsaw operators at the cutting area. A chainsaw operator outhauls the main cable and hook the stem sections to it. The work team had at least 5 years of experience with logging and the age of the operators ranged between 35 and 55 years. An articulated four-wheel-drive TAF-690 PE (SC Irum SA, Reghin, Romania) double-drum cable skidder was used for the tests (Figure 2, Table 2).

Table 1. Characteristics of test site

Location	N 42.77810779; E 23.67989894
Elevation	1150 m asl
Function	Natura 2000: BG 0001043, habitat 9150 (Medio-European limestone beech forests of the Cephalanthero-Fagion)
Species composition	European beech (*Fagus sylvatica,* L) 100%
Stand age	90 years
Stand type	High natural forest
Total area	15.4 ha
Stand density	640 trees ha^{-1}
Relative stocking	0.7
Logging operation	Salvage cutting, removal intensity 10%
Average tree height	21 m
Average DBH of tree	26 cm
Average slope gradient	26° (49%)
Growing stock	298 $m^3 \cdot ha^{-1}$
Allowable cut	30 $m^3 ha^{-1}$, 64 trees$\cdot ha^{-1}$
Extraction direction	Flat and uphill
Average slope gradient of skidding road	4.72° (8.26%)

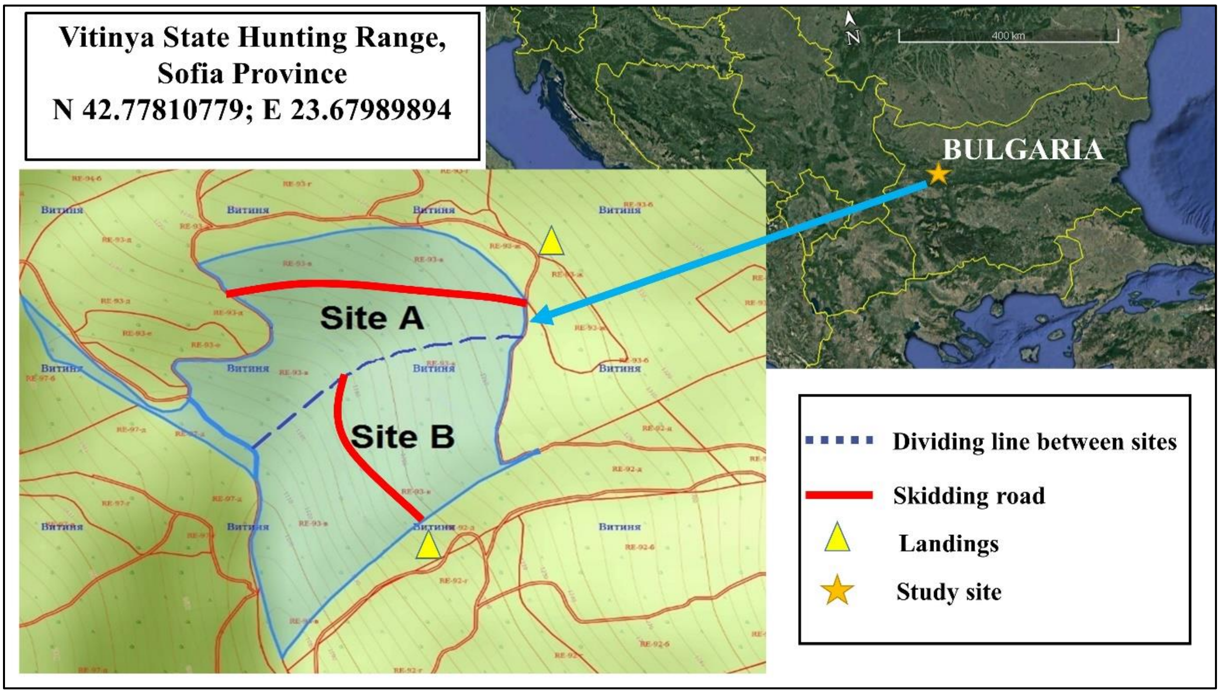

Figure 1. Stand map and schematic layout of sites and skidder roads

Figure 2. An overview of the test skidder

Table 2. Technical data of TAF 690 PE double-drum cable skidder

Parameter	Value
Engine	Perkins 1104D-44T
Engine power	70kW at 2300 rpm
Dimensions	
Length	5800 ± 50 mm
Width	2500 ± 50 mm
Height	2700 ± 50 mm
Wheel base	2830 ± 50 mm
Track	2050 ± 50 mm
Ground clearance	450 ± 20 mm
Blade width	2140 ± 50 mm
Shield width	2000 ± 50 mm
Weights	
Weight (with no load)	7500 kg
on the front axle	4285 kg
on the rear axle	3215 kg
Maximum permissible semi-suspended load	5000 kg
Maximum permissible load weight	9300 kg
Maneuverability	
Minimum turning radius	2.9 m
Turning angle of chassis	± 40°
Oscillation of front axle	± 12°
Winch	TA2 – AM
Cables, number/diameter	2/13 mm
Cable lenght	70 m
Tractive force	70 kN

Productivity study and costs

The time and motion study was conducted to estimate the duration of work elements and productivity of the cable skidder and field observations were carried out on 60 work cycles (turns). A work cycle was assumed to be composed of repetitive elements (Olsen *et al.*, 1998). The work cycle of skidder was composed of following repetitive elements:

- travel unloaded along skidding trail (UT);
- bunching – time for winching and gathering the tree load, including the time for maneuvers and choice of position. Bunching can be divides into maneuvering (M), outhaul of the main cable, hook (OH) and inhaul the load to the skidder (I);
- travel loaded along skidding trail (TL);
- unload of the stems (U);
- delays (D).

During the study the skidding distance, bunching distance and slope, as well as the volume of the stems were measured. Each work cycle was individually measured by astopwatch and productive time was separated from delay time. Skidding distance and slop gradient of skidding road were measured by GPS – receiver with Digital Terrain Model using GIS software. Bunching distances and terrain slopes were measured with a Nikon Forestry Pro II (Nikon Vision Co. Ltd, Tokyo, Japan) professional laser range-finder with clinometer. Load volume was determined by measuring the length and the mid-length diameter of all logs from each load. The machine costs were calculated using the COST model proposed by Ackerman *et al.* (2014). In order to calculate the production cost for 1 m^3 of timber, the cost analysis was based on the following parameters: the number of operators, the hourly cost of an operator, the hourly cost of machines, the volume of extracted timber, and the productive machine hours (excluding all delay times). The machine costs per hour were reported both as productive machine hours excluding delays and scheduled machine hours. The purchase prices and operator wages required by the cost calculations were obtained from accounting records (Borz *et al.* 2014). Diesel fuel consumption was calculated using diesel fuel consumption norms. A salvage value of 10% of the purchase price was assumed and the Value Added Tax (VAT) was excluded.

Cost calculations were based on the assumption that companies worked for 150 working days in the year and a depreciation period of 10 years. The extraction work amounts to 130–150 working days per year (20-21 working days per month), at an average of 6-7 scheduled working hours per day (assuming one to two hours spent on lunch, rest and other breaks). This yielded annual working times of 910–1050 SMHs with a 70% use coefficient (Proto *et al.* 2018; Spinelli and Magagnotti 2011).

Data analysis

Regression analysis was performed on the experimental data in order to develop prediction equations for estimating the work cycle time and productivity. Variables used in the modelling approach included skidding distance L, winching distance l, load volume per cycle V, slop gradient of skidding road s, the load's number of trees n. In addition, the tree damage type dt was used as an indicator (dummy) variable to enhance the discrimination of the time prediction models. Therefore, the models describing the time consumption and productivity were defined in Eq. (1), (2), (3), and (4):

$$T_{net} = f(L, l, V, n, i, dt), \tag{1}$$

$$T = f(L, l, V, n, i, dt), \tag{2}$$

$$P_{PMH} = \frac{3600.V}{T_{net}}, \tag{3}$$

$$P_{SMH} = \frac{3600.V}{T}, \tag{4}$$

where T_{net} and T are respectively the productive time separated from the delay time, and scheduled time, and P_{PMH} and P_{SMH} are respectively the productivity based on a productive machine hours and scheduled machine hours.

The confidence level used for regression analysis was 95% (α=0.05) and the assumed probability $p<0.05$. Independent variables are significant at $p<0.05$, i.e. strong presumption against neutral hypothesis. To process the experimental data the Statistica 8 (StatSoft Inc., Tulsa, OK, USA) software was used.

Results and Discussion

Elemental Time Study and Efficiency Analysis

At site A, the average skidding distance was 251m, the average distance of the outhaul of the main cable, hook and inhaul the load to the skidder was 13m and the average volume skidded per turn was 3.90 m^3. On site B, the average skidding distance was 277m, the average distance of the outhaul of the main cable, hook and inhaul the load to the skidder was 15m, and the volume skidder per turn was 3.98m^3. The extraction cycle time at site A with the winch was 970 s (± 363 SD), while at site B thecable skidder extraction cycle time was 1359 s (± 277 SD) (Table 3). Figure 3 shows the share of operations of the working cycle elements excluding and including delays of cable skidder. The largest share occupies the operation travel loaded (34% and 29% respectively, excluding and including delays), followed by the travel unloaded (29% and 25% respectively, excluding and including delays), load inhaul (17% and 15% respectively), outhaul and hook (14% and 12% respectively). The breakdown by main groups of operations in delay-free cycle time shows the predominance of the movement of the skidder with the largest share of 63%, followed by the bunching of the load (34%), and unload of the stem sections at landing (3%). Skidder productive time was 86% from scheduled time. The delays (14%) are due to organizational reasons (delays are due to waiting for the felling of trees in the cutting area) (4%), mechanical delays (4%), and those due to adverse weather conditions (rain, snow, thick fog) (6%).

Table 3. Descriptive statistics of time consumption and operational distances.

Variables	Duration, s			Distance, m		
	Mean value ± SD	**min**	**max**	**Mean value ± SD**	**min**	**max**
Travel unloaded (UT)	**261±105**	**111**	**502**	**264±103**	**60**	**450**
Site A	252±134	111	502	251±131	60	450
Site B	269±66	111	440	277±63	75	405
Maneuvering (M)	**22±9**	**10**	**35**			
Site A	23±8	10	35			
Site B	21±9	10	35			
Outhaul and hook (OH)	**118±42**	**54**	**193**	**14±4**	**8**	**22**
Site A	94±31	54	156	13±3	9	21
Site B	143±36	79	193	15±4	8	22
Load inhaul (I)	**206±116**	**65**	**465**	**14±4**	**8**	**22**
Site A	102±23	65	145	13±3	9	21
Site B	309±67	194	465	15±4	8	22
Travel loaded (TL)	**381±138**	**91**	**638**	**264**	**60**	**450**
Site A	318±139	91	512	251	60	450
Site B	443±108	133	638	277	75	405
Unloading (U)	**29±17**	**9**	**83**			
Site A	27±13	9	46			
Site B	32±20	9	83			
Delays (D)	**147±125**	**15**	**668**			
Site A	137±95	36	490			
Site B	158±149	9	668			
Total cycle time	**1164±375**	**406**	**1804**			
Site A	970±363	406	1548			
Site B	1359±277	633	1804			
Delay-free cycle time	**1017±323**	**370**	**1587**			
Site A	833±302	370	1294			
Site B	1201±225	559	1587			

* SD – standard deviation, PMH – productive machine hour, SMH – scheduled machine hour.

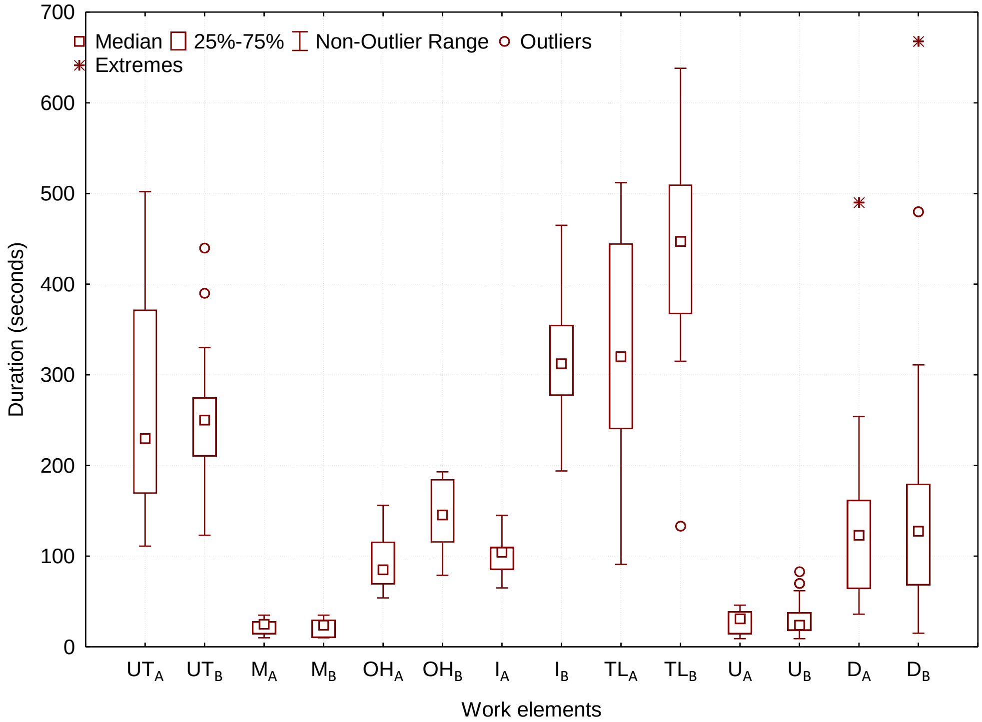

Figure 3. Summary statistics of the work elemental time of TAF 690 PE cable skidder

The regression analysis was done on the time-study data in order to develop prediction equations for estimating the skidder cycle time by excluding and including delays; in particular, the delay-free cycle time T_{net} regression equation obtained with significant variables given in equation (1). In Eq. (1) minimum duration of delay-free cycle time T_{net} can be achieved in case of short skidding distances, bunching distances and rather lighter damage type dt = 2 (code 1D, broken tree section prevailed), than the types of damage corresponded to code 1A—uprooted whole tree with stump (dt = 1). In sites A and B, Eq. (2) and Eq. (3), a reduction in delay-free cycle time can be expected by reducing the skidding and the winching distances, and in the first site this will also be achieved by reducing the volume of payload. The regression equations (4), (5), (6) for studied cable skidder cycle time including delays T is also presented in Table 4. Generally, the cable skidder cycle time including delays also depends only on damage type dt, skidding distance L and and winching distance l and its minimum duration may be attaining by minimizing the skidding and bunching distances. Damage type dt = 2, corresponding to code 1D (broken tree section prevailed), provides greater reduction of cycle time including delays than the types of damage corresponded to code 1A—uprooted whole tree with stump (*dt* = 1). The mean travel speed of the skidder is 2.90 $km{\cdot}h^{-1}$ (Table 5). The mean speeds with and without load are 2.49 $km{\cdot}h^{-1}$ and 3.62 $km{\cdot}h^{-1}$ respectively. For comparison, Orlovsky *et al.* (2020) pointed higher mean travel speed monitoring four LKT 81T wheel cable skidders (3.97 $km{\cdot}h^{-1}$) working on average 5.9 m^3 with a slop inclination of 35%. Spinelli and Magagnotti (2012) reported empty and loaded travel velocities of 96 kW agricultural tractor of 8.1 and 7.3 $km\ h^{-1}$ skidding on flat terrain (12%) and moving meanly 2.4 m^3 for each cycle. The mean travel speeds of the skidder in site A and site B are close in value. However, when the skidder is loaded, the speed in site B is lower respect to site A, the opposite is observed at the speed of unloaded skidder, where it is higher in site B, this trend is not due to the average slope of the skid track equal to 4.72° (8.26%), but is probably due to the different conformation of the roads in the two sites; in fact, site B has a greater number of hairpin bends that can affect speed of the unloaded skidder. Theoretically, the movement time of cable skidder could be reduced by increasing the travel velocity loaded and unloaded. Unfortunately, the terrain conditions practically do not afford significant increasing of travel velocity. The mean speed of a cycle load during winching was 0.09 $m{\cdot}s^{-1}$. Due to more obstacles, the speed of winching is more than twice lower in site B, where the damages are of code 1A.

Table 4. Summary of the work cycle time models

Equations		*F*	R^2	R^2_{adj}	Std. Error	*p*-Value
T_{net} =-3.49976·*dt*+0.03892·*L*+0.25665·*l*, min	(1)	179.65	0.95	0.95	1.23	$p < 0.05$
T_{net_A}=4.21+0.037·*L*+0.85·*V*-1.23·*l*, min	(2)	323.60	0.99	0.98	0.67	$p < 0.05$
T_{net_B}=0.042·*L*+0.34·*l*, min	(3)	39.33	0.89	0.87	1.36	$p < 0.05$
T = -3.00·*dt*+0.047·*L*+0.28·*l*, min	(4)	68.80	0.89	0.87	2.23	$p < 0.05$
T_A=0.045·*L*, min	(5)	35.91	0.97	0.87	1.17	$p < 0.05$
T_B=0.07·*L*+0.41·*l*, min	(6)	11.13	0.70	0.64	2.79	$p < 0.05$

Table 5. Payload, productivity and speed metrics.

Variables	Mean value ± SD	min	max
Load volume, m^3	**3.94±0.40**	**2.60**	**4.84**
Site A	3.90±0.60	2.60	4.84
Site B	3.98±1.00	2.70	4.80
Pieces number	**2.20±0.40**	**2.00**	**3.00**
Site A	2.10±**0.31**	2.00	3.00
Site B	2.30±0.47	2.00	3.00
Productivity, m^3·PMH^{-1}*	**15.73±6.43**	**8.87**	**31.98**
Site A	19.11±7.08	10.16	31.98
Site B	12.36±3.24	8.87	25.12
Productivity, m^3·SMH^{-1}*	**13.80±5.71**	**7.35**	**27.91**
Site A	16.57±6.38	9.00	27.91
Site B	11.04±3.13	7.35	22.18
Number of cycles per SMH*	**3.58±5.57**	**2.00**	**8.87**
Site A	4.39±6.39	2.33	8.87
Site B	2.78±3.19	2.00	5.69
Mean travel speed, km·h^{-1}	**2.90±0.42**	**2.04**	**3.74**
Site A	2.92±0.50	2.04	3.74
Site B	2.87±0.34	2.11	3.63
Travel speed loaded, km·h^{-1}	**2.49±0.42**	**1.69**	**3.49**
Site A	2.71±0.41	2.08	3.49
Site B	2.27±0.29	1.69	2.97
Travel speed unloaded, km·h^{-1}	**3.62±0.83**	**1.95**	**5.33**
Site A	3.24±0.79	1.95	5.33
Site B	4.01±0.68	2.20	4.95
Winching speed, m·s^{-1}	**0.09±0.04**	**0.03**	**0.19**
Site A	0.13±0.2	0.10	0.19
Site B	0.05±0.1	0.03	0.07
Road inclination, deg	**4.72±2.95**	**0.00**	**9.00**
Site A	2.13±1.70	0.00	5.00
Site B	7.30±1.02	5.00	9.00

* SD – standard deviation, PMH – productive machine hour, SMH – scheduled machine hour.

Productivity models and cost analysis

Delay-free skidder productivity was defined by the regression equations (7), (8), and (9), shown in Table 6. From the equations, to enhance delay-free productivity of the studied machine, skidding distance *L* and winching distance *l* should be reduced, whereas the load volume *V* should be increased. In the general model described by Eq. (7), the damage type should be from code 1D (*dt*=2) to improve the delay-free skidder productivity.

The skidder productivity including delays is expressed by equations (10), (11), and (12) also shown in Table 6. From equations (10), (11), and (12), to increase skidder productivity including delays skidding distance should be reduced, whereas the load volume per cycle *V* should be increased. In the general model (10), the lighter damages from type 1D make better skidder productivity including delays. The delay-free skidder productivity in Site B (damage corresponded to code 1A—uprooted whole tree with stump) is 65% from that in Site A (damages from type 1D). The mean productivity obtained at mean skidding distance of 264 m, mean winching distance of 14 m, mean load volume of 3.94 m^3 and mean 2.2 logs per cycle (turn) is 15.73 $m^3 \cdot PMH^{-1}$ and 13.80 $m^3 \cdot SMH^{-1}$ respectively. For LKT 81T cable skidders and LKT 81 ILT cable skidders with knuckle-boom operated mostly in beech, beech-fir and beech-oak stands Orlovský *et al.* (2020) registered at mean skidding distance of 300 m and 316 m respectively, mean load volume of 5.45 m^3 and 8.01 m^3 and gross production rate of 3.91 $m^3 \cdot SMH^{-1}$ and 4.21 $m^3 \cdot SMH^{-1}$, respectively. Stoilov and Krumov (2016) monitored a modification of the same machine (LKT81T), equipped without a knuckle-boom loader, reporting efficiency of 6.27 m^3 PMH^{-1} at a skidding distance of 1290 m, and a load volume of 5.65 m^3. The results obtained in terms of average net productivity with the skidder in salvage logging by Bodaghi *et al.* 2018 showed a value almost lower compared to 14.73 m^3 h^{-1} observed in this study. This notable difference was probably mainly due to the different stand characteristics. Comparing the results with those reported by Borz *et al.* (2015) for TAF 690 PE the net and gross production rates were around three time lower 4.41 $m^3 \cdot h^{-1}$ and 3.12 $m^3 \cdot h^{-1}$, respectively. Therefore, the productivity of the cable skidder in salvage cutting in beech stand with a removal intensity of 10% is close and higher than that of similar type skidders in ordinary logging activities.

Cost calculations were based on the assumption that companies worked all year round with the exception of adverse weather conditions (heavy rain, deep snow, thick fog), when cutting areas are not normally accessible by wheel skidder. The hourly fixed, operating (variable) costs of the studied skidder, and labour cost of a operator, are shown in Table 7. For downhill skidding semi-suspended stem sections of TAF 690 PE cable skidder the gross costs were calculated at 52.72 € per productive machine hour (PMH). In the structure of the gross costs, the fixed costs (25.75%) were slightly lower than the labor (29.60%) and variable costs (35.56%). Therefore, for the productive time of the machine, the mean extraction costs were estimated at 3.36 € per m^3. Thus, when the skidder was productive, the extraction costs were at 2.76 € m^{-3}, and 4.27 € m^{-3}, respectively for the stand, Site A, and Site B. The differences in the costs for site A, characterized by code 1D versus more severe code 1A (Site B), leading to 55% lower extraction costs. The increase of productive time of wheel skidder would lead to decrease in extraction costs. These costs are lower compared to the effective cost consumptions for the Timberjack 450C cable skidder and higher than those of SAME 140 Virtus operated in salvage hardwood logging in Iran and Italy, were calculated as 70.11 €·h^{-1} and 53.00 €·h^{-1}, respectively (Bodaghi *et al.* 2018).

Table 6. Summary of the productivity models.

Equations		F	R^2	R^2_{adj}	Std. Error	p-Value
P_{PMH} = 13.34+4.93·dt-0.051·L+2.58·V $m^3·h^{-1}$	(7)	87.20	0.91	0.90	2.06	$p < 0.05$
P_{PMH_A}=24.91-0.052·L+0.99·V, $m^3·h^{-1}$	(8)	40.90	0.89	0.87	2.52	$p < 0.05$
P_{PMH_B}=13.33-0.036·L+3.10 V-0.24·l, $m^3·h^{-1}$	(9)	26.56	0.85	0.82	1.39	$p < 0.05$
P_{SMH} = 11.24+3.97·dt-0.046·L+2.74·V, $m^3.h^{-1}$	(10)	64.07	0.88	0.87	2.10	$p < 0.05$
P_{SMH_A}=26.23-0.048·L+2.63·V, $m^3·h^{-1}$	(11)	37.01	0.89	0.86	2.37	$p < 0.05$
P_{SMH_B}=8.19-0.033·L+3.04·V-0.20·l, $m^3·h^{-1}$	(12)	19.83	0.81	0.76	1.52	$p < 0.05$

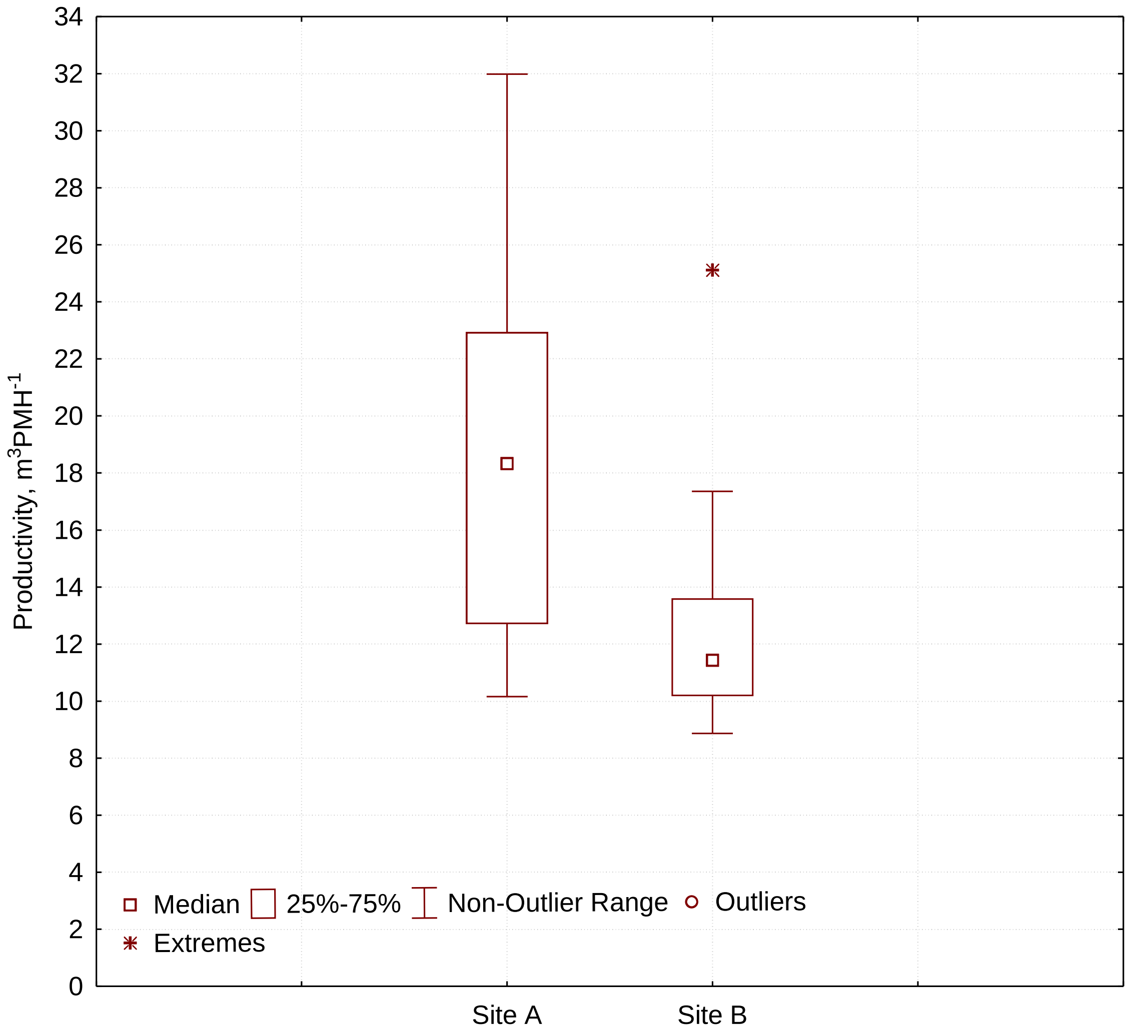

Figure 4. Summary statistics of the skidding productivity for the two sites

Table 7. Characteristics of costs of studied skidder

Costs in €	Costs per PMH	Costs per m^3	% of total	Costs per m^3	
				Site A Code 1D	Site B Code 1A
Fixed costs	13.60	0.86	25.75	0.71	1.10
Variable costs	18.68	1.19	35.56	0.98	1.52
Labor costs	15.64	0.99	29.60	0.82	1.27
Net costs(excluding profit)	47.92	3.05	90.91	2.51	3.89
Gross costs (including 10% profit)	52.72	3.36	100	2.76	4.27

Conclusions

In recent decades, forest disturbances have caused considerable damage to European forests and in particular in the Northern Hemisphere. In the near future, global climate warming is expected to increase the extent of biotic and abiotic disturbances and for these reasons, post-disturbance salvage logging will become more predominant to recover economic value from timber in disturbed forests. For this purpose, the objective of this study was to determine the productivity and costs of TAF 690 PE skidder in a European beech high forest damaged by wet snow disturbance. The importance of this study and the results are mainly related to enlarge existing knowledge on the productivity and costs of salvage logging operations. The results revealed that operational costs of salvage trees extraction are higher than traditional stand cutting but necessary to recovery the future economic value of the forest. In fact, salvage logging benefits can exceed the economic limit in these forests that should be managed to guarantee ecological and productive aspects.

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4.4 Forests and Logging Operations

Article 3
Modelling Productivity and Estimating Costs of Processor Tower Yarder in Shelterwood Cutting of Pine Stand

Salvatore F. Papandrea [1], Stanimir Stoilov [2], Georgi Angelov [2], Tanya Panicharova [2], Piotr S. Mederski [3] *, Andrea R. Proto [1]

[1]Mediterranean University of Reggio Calabria, Department of AGRARIA, Feo di Vito snc, 89122, Reggio Calabria, Italy; salvatore.papandrea@unirc.it (S.F.P.); andrea.proto@unirc.it (A.R.P.)

[2]University of Forestry, Department of Technologies and Mechanization of Forestry, Kliment Ohridski Blvd. 10, 1756, Sofia, Bulgaria; stoilovs@ltu.bg (S.S.); ggangelov@ltu.bg (G.A.); tania.panicharova@abv.bg (T.P.)

[3]Poznan University of Life Sciences (PULS), Faculty of Forestry and Wood Technology, Department of Forest Utilisation, ul. Wojska Polskiego 71A, 60-625 Poznan, Poland;

[*] Correspondence: piotr.mederski@up.poznan.pl; Tel.: +48-61-848-7761

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Article

Modeling Productivity and Estimating Costs of Processor Tower Yarder in Shelterwood Cutting of Pine Stand

Salvatore F. Papandrea [1], Stanimir Stoilov [2], Georgi Angelov [2], Tanya Panicharova [2], Piotr S. Mederski [3,*] and Andrea R. Proto [1]

[1] Department of AGRARIA, Mediterranean University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy
[2] Department of Technologies and Mechanization of Forestry, University of Forestry, Kliment Ohridski Blvd. 10, 1756 Sofia, Bulgaria
[3] Department of Forest Utilisation, Faculty of Forestry and Wood Technology, Poznan University of Life Sciences (PULS), ul. Wojska Polskiego 71A, 60-625 Poznan, Poland
* Correspondence: piotr.mederski@up.poznan.pl; Tel.: +48-61-848-7761

Abstract: Cable-based yarding technology has had a long tradition on steep slopes in Europe, and the new implementation of yarding functions in recent decades favored operational efficiency and lower extraction costs. The main goal of this study was to evaluate the performance of the Syncrofalke 3t truck-mounted Processor Tower Yarder (PTY) on steep terrain, in coniferous forests managed with the shelterwood system. In particular, the aim was to determine PTY productivity and costs, with attention to parameters that could increase PTY effectiveness. The study was carried out in the Sredna Gora Mountains, Central Bulgaria, in pure Scots pine stand, with trees of average DBH = 34 cm and height = 22 m. The study was carried out in six corridors with 120 work cycles of tree extraction up the hill, 28° (53%). The mean productivity of PTY was 15.20 m^3 per productive machine hour (PMH) and 12.29 m^3 per scheduled machine hour (SMH) and was mainly influenced by the productivity of the yarder unit. Under the given conditions, the performance of PTY significantly increased if more than one tree (at least two trees) were attached and extracted per yarder cycle, since the productivity of the processor was approximately twice that of the yarder. The gross costs of the studied PTY were calculated at 297.48 EUR PMH^{-1} and 16.17 EUR m^{-3}. The variable costs (75%) predominate in the net costs distribution, followed by the fixed costs (15%) and the labor costs (10%). The time, productivity and cost results obtained showed the high efficiency and level of integration of PTY operations in order to achieve economic efficiency of logging in montane pine forest managed in a shelterwood system.

Keywords: forest operations; cable extraction; wood harvesting; steep terrain

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1. Introduction

Bulgarian forests are characterized by the small dimensions of most cutting areas, and the predominance of deciduous timber. In the mountain forests of Bulgaria, about 60% are on steep slopes and hence, cable yarders are particularly suitable for timber extraction. In Bulgaria in the 20th century, large areas with coniferous plantations were created at very low altitudes. While coniferous plantations have usually served their primary purpose of helping to control erosion, numerous waves of mortality have been observed in recent decades due to the combined negative effects of drought, aging and lack of opportunities for regular thinnings [1,2]. Generally, 29% of the forests by area are coniferous, but they contribute 45% of growing stock [3]. The coniferous forests offer more options for highly mechanized harvesting technologies, e.g., harvesters and forwarders. The latter, however, have limited mobility and stability—up to slopes of 35%–40%, and the construction of a road network is necessary, requiring significant excavation and embankment works, and thus higher costs, of accessing forest stands.

Cable yarding systems are increasingly being used in all terrains as an alternative to conventional fully mechanized systems with harvesters and forwarders, because of their low impact on soils [4–6] and smaller dependency on slope gradient. Cable yarding can be also used for salvage logging on steep terrains [7] and their safety can be increased with the use of modern anchoring systems [8]. The productivity of cable yarders is strongly influenced by log volume, length of skyline, silvicultural treatment (removal intensity) and lateral yarding distance [9]. In addition, gradient slope, stand density and yarding direction (uphill/downhill) have an influence on the extracting timber volume per unit of time [10–15].

For highly productive harvesting operations on steep terrains based on yarder and mechanized primary tree processing, it is especially important to combine the two operations into one multi-operational machine—Processor Tower Yarders (PTY), representing two independent machines: a yarder and a processor, best if mounted on a single carrier [16]. PTY integrates the drums, a steel spar, power supply, a boom, and a processor head on one carrier [17]. The use of PTY technology is recommended in steep terrain given the improved productivity, which ranges from 90 to 120 m^3 per 8 h day [18]. Such technology enables tree processing, sorting, and piling after releasing the load consisting of whole trees [19–21]. Usually, PTY operate in forests affected by windstorms with high removal intensity due to their high productivity, allowing for quick damage coverage. These operating conditions of PTY were studied by Messingerová et al. [22], Bugoš et al. [20], Boyadzhiev and Glushkov [23]. Studies of PTY in thinnings are relatively rare [24]. The processor unit of the tower yarder and its cutting accuracy were typically investigated. Borz et al. [24] examined the performance of the Woody H60 processor of Mounty 4000 without measuring the yarding cycle performance. Marenče et al. [25] measured cutting accuracy with the same processor as part of the Syncrofalke 3t PTY system. The average hourly productivity of one crane processor, as part of PTY, with an average diameter of assortments of 27–28 cm, was 12 to 17 times greater than the productivity of one worker with a chainsaw [23]. The main goal of this study was to evaluate operations of PTY on steep terrain, in coniferous forests managed by the shelterwood system, with regard to economic aspects. Specifically, the objectives were: (*i*) to study the influence of the main operational factors on time consumption of PTY using a statistical modeling approach, and (*ii*) to improve our knowledge on the operational efficiency of PTY in the harvesting operations of coniferous stands managed by the shelterwood system. The study focused on the main operational factors; in this case, on factors during actual extraction of trees and processing of timber, without attention to any additional time and mounting activities preparing PTY for work on the spot. The efficiency improvement concerned the analysis of the time consumption, productivity, and costs, as these performances indicate the level of integration of PTY operations in order to achieve the economic efficiency of timber harvesting in montane coniferous forests.

2. Materials and Methods

2.1. The Study Site

The study was carried out in the Sredna Gora Mountains (42°39′51.5273″ N–22° 20′52.4569″ E) around the city of Koprivshtitsa, Sofia Province, Central Bulgaria (Table 1).

Six parallel-shaped corridors located every about 60 m with an average skyline length of 148 m were opened on terrain slopes at about 27° (51%), 28° (53%), 29° (55%), 27° (51%), 29° (55%), and 29° (55%) (Figure 1). Field observations were carried out on 20 work cycles (turns) at each corridor, with a total of 120 work cycles (turns). During the operations, the extraction direction was uphill, the single-span layout of the cable yarder unit was implemented each time and trees were felled manually with a chainsaw.

Table 1. Characteristics of the test site.

Parameter	Characteristics
Place Name	Sub-compartment 9009-l
Elevation	1100 m asl
Function	Natura 2000: BG 0001389, BG 0002054
Species composition	Scots pine (*Pinus sylvestris* L.)
Stand age	70 years
Stand type	Forest plantation
Total area	6.0 ha
Relative stocking	0.7
Sylvicultural system	Combined regular and shelterwood cut, removal intensity 25%
Average tree height	22 m
Average DBH of tree	34 cm
Average slope gradient	28° (53%)
Growing stock	1794 m^3 (299 m^3 ha^{-1})
Allowable cut	470 m^3 (78 m^3 ha^{-1})
Extraction direction	Uphill
Length of line in corridors	1: 80 m; 2: 160 m 3: 160 m; 4: 150 m 5: 150 m; 6: 185 m
Average lateral yarding distance	14.78 m

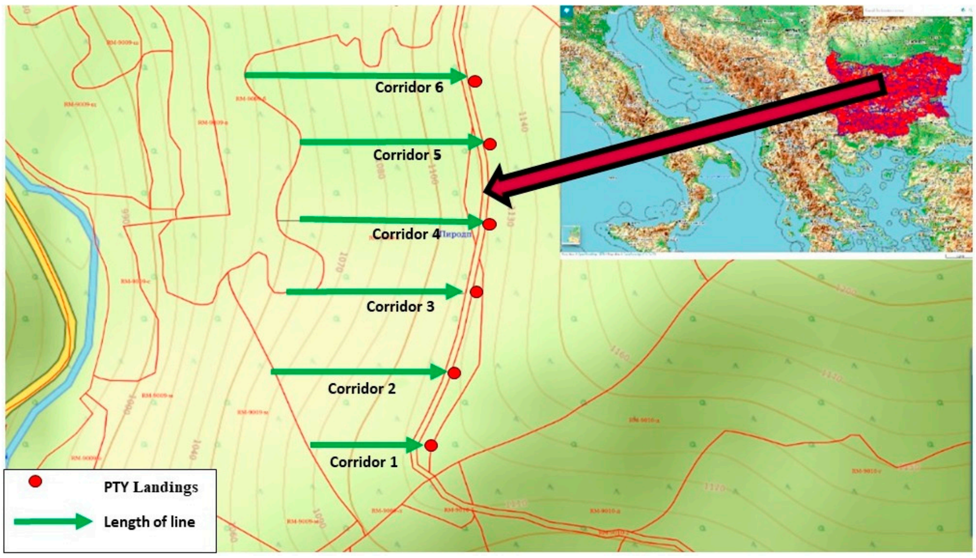

Figure 1. Site and yarding corridors.

2.2. Cable Yarder Unit

Within the study, a Syncrofalke 3t truck-mounted processor tower yarder (Mayr–Melnhof Forsttechnik GmbH, Frohnleiten, Austria, Table 2) was tested. The work team consisted of two men, of which one was the winch and processor operator at the landing, and the second was the choker setter in the stand. Each operator had at least 5 years of experience with cable yarding, and they were both 35–40 years old.

Table 2. Technical data of the studied Syncrofalke 3t processor tower yarder.

Parameter	Value
Tower yarder	
Skyline capacity	750 m, ø20 mm
Mainline	1800 m, ø11 mm
Haulback line	1800 m, ø8 mm
Guylines	4 × 70 m, ø18 mm
Foldable telescopic tower, height	11.5 m
Power station	Truck engine and hydrostatic transmission
Engine power of the truck engine	324 kW
Carriage	MM-Sherpa U3 active slack-pulling carriage
Choker system	Bardon choker
Hydraulic crane	Palfinger Epsilon S280L94—reach of 9.4 m and a lifting moment of 229 kNm at a working pressure of 250 bar.
Processor	
Processor head	Woody H60
Delimbing diameter	8–65 cm
Max. grapple opening	120 cm
Feed force	35 kN
Weight	1.450 kg
Operating pressure	300–350 bar
Chain speed	40 m/s
Length of the saw guide bar	820 mm
Max. cutting diameter	680 mm
Chain pitch	0.404″
Number of drive links	98
Carrier	6 × 4 Iveco, model 410 Trakker

The tested PTY is designed for all-terrain harvesting, mounted on a truck with pressure air brakes. The Syncrofalke 3t (Figure 2) has a powerful yarder unit, principally used for selective cutting and for regenerative harvesting operations using a carriage Sherpa U3 (Mayr–Melnhof Forsttechnik GmbH, Frohnleiten, Austria) for payloads up to 3t. The processing of felled trees was carried out on the site with the Woody H 60 processing head (Konrad Forsttechnik GmbH, Preitenegg, Austria), mounted on the Palfinger Epsilon (Epsilon Kran GmbH, Elsbethen-Glasenbach, Austria) model S280L94 hydraulic crane. The trees were yarded laterally to the carriage using the power of the yarder's mainline winch and active skyline clamps [26,27].

2.3. Productivity and Costs

A time and motion study were carried out to estimate the duration of work elements and productivity of the cable yarders in the given conditions. A yarding work cycle was assumed to be composed of repetitive elements [13,26–30]. In this study, six (1–6) work elements were separated and taken into account in order to estimate the yarder work cycle time and four for processor unit (7–10) [31]; they were similar to those described by Proto and Zimbalatti [26]:

(1) Carriage outhaul (CO): begins when the operator is ready to move the empty carriage from the landing out to the stump and ends when the choker setter touches the chokers;
(2) Lateral outhaul and hook (LOH): begins at the end of carriage outhaul and ends when the choker setter has completed hooking the chokers and signals to begin yarding;
(3) Lateral inhaul (LI): begins at the end of the hook up and ends when the turn is pulled up to the carriage and the carriage begins to move up the corridor;
(4) Carriage inhaul (CI): begins at the end of lateral inhaul and ends when the load has reached the deck, where it can be directly unhooked at the landing;
(5) Unhook (UN): begins at the end of carriage inhaul and ends when the chokers have returned to the carriage;
(6) Delay time of tower yarder unit (DELy): includes the rest, personal delays, organizational delays, service, and repair.
(7) Direction and gripping (DG): directing and gripping the tree with the processor head.
(8) Delimbing and bucking of the tree (DB): begins after aiming the processor and taking the tree off the landing.
(9) Sorting, piling (SP): after delimbing the tree, the sorting and piling of the woody assortments takes place, as well as the cleaning of any debris.
(10) Delay time of processor unit (DELp): includes rest, personal delays, organizational delays, service, and repair.

Figure 2. Syncrofalke 3t Processor Tower Yarder.

The time-motion study of both units of PTY was designed to evaluate the duration of work elements and the productivity of the yarder and the processor, and to identify those variables that are most likely to affect it. Each yarding cycle and each processor cycle were individually measured using a stopwatch and the productive time was separated from the delay time. The yarding distances and terrain slopes were measured with a professional laser range finder with a clinometer. The cycle load volume turn was determined by measuring the diameter at breast height and height of the tree and calculated by using biometric models of Nedyalkov et al. [32].

The machine costs were calculated using the COST model [33]. In order to calculate the production cost per 1 m^3 of timber, the cost analysis employed the following parameters: the number of operators, the hourly cost of an operator, the hourly cost of machines, the volume of extracted timber and the productive machine hours (PMHs), excluding all delay times. The machine costs per hour were reported as both PMHs and scheduled machine hours (SMHs). The purchase prices and operator wages required by the cost calculations were obtained from catalogues and accounting records [34]. The diesel fuel consumption was measured by evaluating the volume of fuel used to fill the fuel tank to the brim and recording the amount of fuel used during that day. A salvage value of 10% of the purchase price was assumed, and the Value Added Tax (VAT) was excluded. Cost calculations were based on the assumption that companies worked for 200 working days in the year and a depreciation period of 10 years. For extraction work, this amounts to 130–150 working days per year (20–21 working days per month), at an average of 6–7 scheduled working hours per day (assuming one to two hours spent on lunch, rest and other breaks). This yielded annual working times of 910–1050 SMH with a 70% use coefficient [26,34].

2.4. Data Analysis

A regression analysis was performed on the experimental data to obtain prediction models for estimating the work cycle time and productivity. The independent variables used in the modeling approach of the yarder unit and PTY included yarding distance L, lateral yarding distance l, load volume per cycle V, terrain slope angle i and the load's number of trees n, whereas the independent variable used in the modeling of the processor unit performance was load volume per cycle V. The descriptive statistics of the variables were computed, and a stepwise backward regression procedure was used to model the variability of yarding cycle time and productivity as a function of independent variables.

The confidence level used for regression analysis was 95% ($\alpha = 0.05$) and the assumed probability $p < 0.05$. Independent variables are significant at $p < 0.05$, i.e., strong presumption against neutral hypothesis. The experimental data were processed by Statistica 8 (StatSoft Inc., Tulsa, OK, USA) software.

3. Results and Discussion

There were experimental data from 120 yarding and processor cycles for each of the selected variables used in the cycle time (Table 3). Based on this, production equations were developed (Table 4). During each yarding cycle, one tree was extracted, which was further processed into logs on the landing site.

3.1. Duration of Work Cycle Elements

3.1.1. Tower Yarder Unit

The predominant part of the cycle time (Figure 3) was dedicated to the lateral outhaul and hook the tree (25% and 17%, respectively, excluding and including delays), followed by lateral inhaul (22% and 15%, respectively, excluding and including delays) and carriage inhaul by approximately the same proportion (22% and 15%, respectively, excluding and including delays). The other working elements have the following partitions in the cycle: carriage outhaul (16% and 12%, respectively, excluding and including delays), unhook (15% and 10%, respectively, excluding and including delays). Operational and mechanical delays accounted, respectively, for 26% and 5% of the total cycle time of the studied cable yarder unit.

Table 3. Mean experimental data.

Variables	Cycle Time, s			Distance, m		
	Mean Value ± St. dev.	**Min**	**Max**	**Mean Value ± St. dev.**	**Min**	**Max**
Yarding						
Carriage Outhaul (CO)	31.58 ± 11.09	14	62	67.44 ± 15.36	40	85
Lateral outhaul and hook (LOH)	47.21 ± 11.77	25	79	14.78 ± 3.77	7	22
Lateral Inhaul (LI)	41.64 ± 11.18	25	69	14.78 ± 3.77	7	22
Carriage Inhaul (CI)	41.13 ± 10.34	18	62	67.44 ± 15.36	40	85
Unhook (U)	28.22 ± 3.69	19	39			
Delays (DELy)	82.70 ± 120.18	0	660			
Total cycle time	272.48 ± 121.70	151	832			
Delay-free cycle time	189.78 ± 26.52	151	262			
Load volume per cycle (turn), m^3	1.23 ± 0.33	0.55	2.63			
Productivity, m^3 per PMH	23.84 ± 7.52	11.75	58.09			
Productivity, m^3 per SMH	18.41 ± 6.20	5.19	58.09			
Number of cycles per SMH	14.97 ± 4.57	4.33	23.84			
Tree Processing						
Directing and gripping the tree with the processor head (DG)	16.15 ± 2.88	11	26			
Delimbing and bucking of the tree (DB)	62.10 ± 8.47	46	84			
Sorting, piling the assortments and clearing the debris (SP)	24.27 ± 3.54	17	36			
Delays (DELp)	8.32 ± 74.95	0	305			
Total cycle time	110.83 ± 74.95	74	103			
Delay-free cycle time	102.52 ± 5.81	74	389			
Productivity, m^3 per PMH	42.71 ± 7.74	26.76	75.13			
Productivity, m^3 per SMH	40.89 ± 9.26	8.42	75.13			
Number of cycles per SMH	34.18 ± 4.14	24	50			
Processor Tower Yarder						
Total cycle time	383.83 ± 123.98	244	929			
Delay-free cycle time	292.29 ± 30.51	239	399			
Productivity, m^3 per PMH	15.20 ± 3.97	8.18	32.00			
Productivity, m^3 per SMH	12.29 ± 3.98	4.67	26.52			

St. dev.—standard deviation, PMH—productive machine hour, SMH—scheduled machine hour.

Operations related to the lateral yarding (the lateral pull to the main line, the chokers hooking, and the extraction of the load to carriage) occupied 27% of the work cycle time including delays, and 40% of the delay-free work cycle. In the given conditions, the tower yarder operated at relatively short yarding distance (mean 67.44 m out of nominal length), moderate lateral yarding distance (mean 14.78 m) and slope (mean 28.2°) and relatively low level of the carriage payload capacity usage. Lateral yarding had a great influence on the duration of the work cycle.

A regression analysis was performed on the time-study data using characteristics of independent variables (Table 3) in order to develop a prediction equation for estimating the yarding cycle time by excluding and including delays.

Table 4. Summary of the work cycle time models (T_{net}).

Equations		F	R^2	R^2_{adj}	SE	p-Value
$\mathbf{T_{net\_Y} = 4.34 \cdot i + 0.91 \cdot L + 3.88 \cdot l}$	**(1)**	**36.71**	**0.56**	**0.55**	**18.03**	**<0.05**
$T_{net\_Y\_1} = 0.99 \cdot L + 6.017 \cdot l$		24.05	0.82	0.78	12.09	<0.05
$T_{net\_Y\_2} = 66.10 + 0.86\ L + 3.64\ l$		15.76	0.58	0.53	15.76	<0.05
$T_{net\_Y\_3} = 53.43 + 0.99\ L + 3.97\ l$		24.34	0.74	0.71	13.37	<0.05
$T_{net\_Y\_4} = 158.09 + 0.90\ L + 3.80\ l - 65.85\ V$		18.99	0.78	0.74	14.45	<0.05
$T_{net\_Y\_5} = 150.13 + 0.76\ L + 3.36\ l - 41.51\ V$		16.51	0.76	0.71	12.31	<0.05
$T_{net\_Y\_6} = 92.86 + 1.07\ L + 2.67\ l$		23.30	0.72	0.69	11.93	<0.05
$\mathbf{T_{net,P} = 16.58 + 21.26\ V}$	**(2)**	**173.57**	**0.60**	**0.59**	**8.14**	**<0.05**
$T_{net\_P\_1} = 60.52 + 29.40\ V$		62.59	0.78	0.76	5.58	<0.05
$T_{net\_P\_2} = 64.04 + 25.45\ V$		130.13	0.88	0.87	5.44	<0.05
$T_{net\_P\_3} = 65.82 + 27.99\ V$		62.48	0.78	0.76	4.25	<0.05
$T_{net\_P\_4} = 48.38 + 44.55\ V$		37.11	0.67	0.66	4.22	<0.05
$T_{net\_P\_5} = 54.17 + 44.26\ V$		63.28	0.78	0.77	4.68	<0.05
$T_{net\_P\_6} = 66.66 + 37.22\ V$		23.82	0.56	0.53	5.64	<0.05
$\mathbf{T_{P} = 83.00 + 22.65\ V.}$	**(3)**	**6.44**	**0.05**	**0.04**	**32.32**	**<0.05**
$\mathbf{T_{net,PTY} = 8.28 \cdot i + 0.90 \cdot L + 3.94 \cdot l + 20.81\ V}$	**(4)**	**155.56**	**0.60**	**0.60**	**6.11**	**<0.05**
$T_{net\_PTY\_1} = 1.082 \cdot L + 6.58 \cdot l + 49.68\ V$		17.46	0.77	0.72	14.67	<0.05
$T_{net\_PTY\_2} = 132.22 + 0.89\ L + 3.48\ l + 24.01\ V$		13.83	0.72	0.67	15.76	<0.05
$T_{net\_PTY\_3} = 97.29 + 0.99\ L + 4.19\ l + 42.20\ V$		20.75	0.80	0.76	13.18	<0.05
$T_{net\_PTY\_4} = 174.88 + 0.97\ L + 3.88\ l$		20.48	0.71	0.67	15.39	<0.05
$T_{net\_PTY\_5} = 210.42 + 0.69\ L + 3.50\ l$		14.52	0.63	0.59	12.94	<0.05
$T_{net\_PTY\_6} = 187.43 + 1.20\ L + 3.46\ l$		18.28	0.67	0.63	15.75	<0.05

Y—tower yarder unit, P—processor unit, PTY—processor tower yarder.

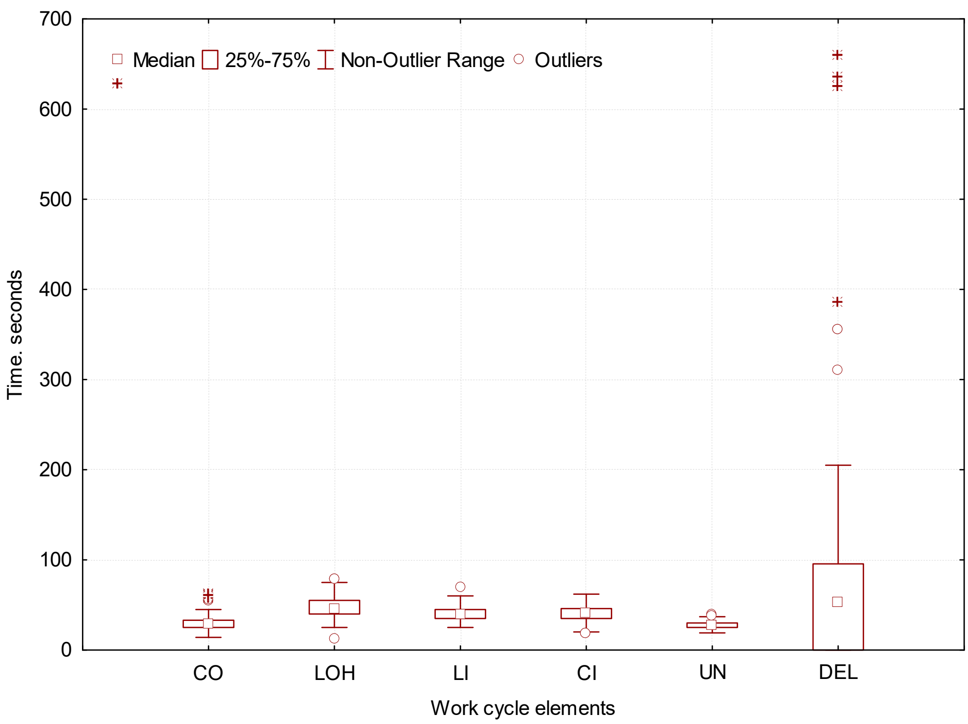

Figure 3. Elemental time consumption of tower yarder unit.

The delay-free yarder cycle time $T_{net,Y}$ regression model (1) obtained with significant variables (Table 4), in particular, for each corridor has been determined using a statistical equation to support the results obtained. In Equation (1), minimum values of $T_{net,Y}$ may be obtained in case of lower rates of yarding distance L, lateral yarding distance l and terrain slope angle i.

In corridors 1, 2, 3 and 6, the significant factors that determined the duration of the delay-free work cycle were the yarding distance and the lateral yarding distance, while in corridors 4 and 5, the load, i.e., the volume of the tree, also had an influence. This was probably due to the reduced variation in load volume in corridors 1, 2, 3 and 6.

3.1.2. Processor Unit

Analyzing the work cycle of the processor unit, it can be seen that the longest was the time for delimbing and cross-cutting (61% and 56%, respectively, excluding and including delays), followed by the time for sorting, piling and clearing (23% and 22%, respectively, excluding and including delays). The shortest time was for directing and gripping (16% and 15%, respectively, excluding and including delays). The delays comprised 15% of the total cycle time.

Generally, the mean duration of the total cycle time of the processor was 110.83 s and took place during the time of the yarder's next work cycle (mean 272.48 s). Under the given forest conditions, according to Equation (2) for delay-free processor cycle time $T_{net,P}$ and Equation (3) for the processor cycle time, including delays T_P, the minimum duration was achieved when load volume V was minimized (Table 4 and Figure 4).

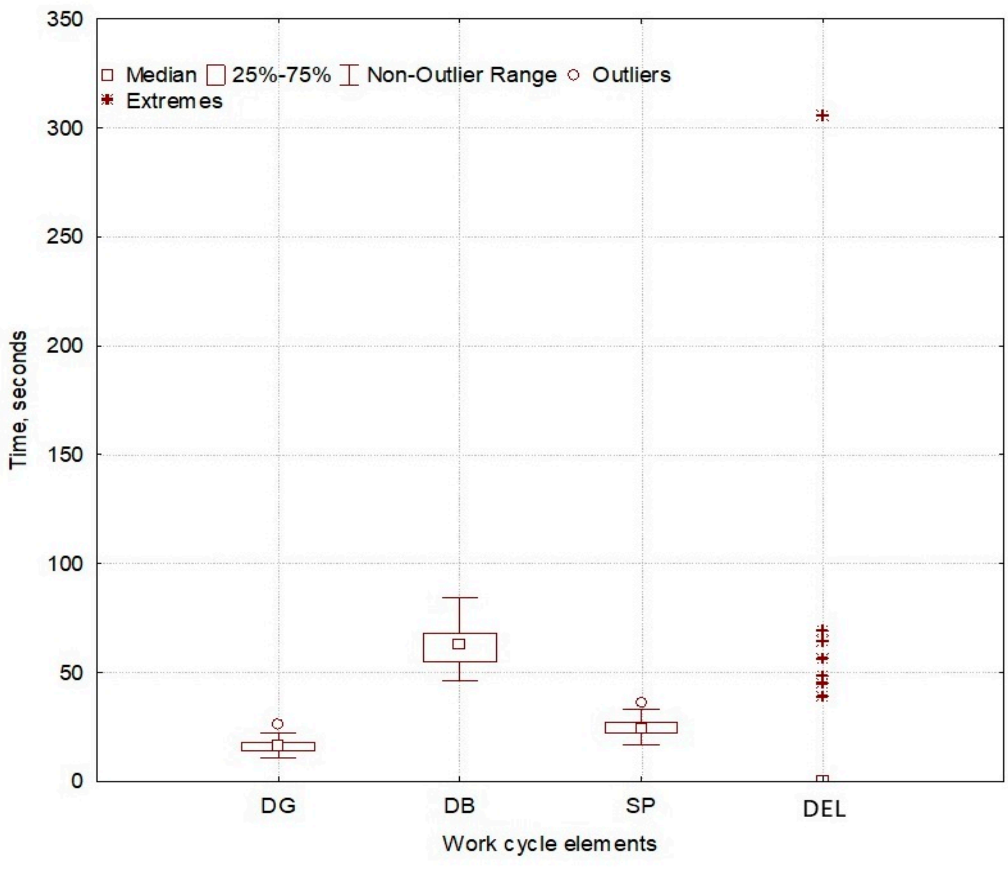

Figure 4. Elemental time consumption of processor unit.

Comparing the work cycle times of the yarder and processor, it can be concluded that under the given conditions, the processor usually had enough time to process two trees instead of one, which was what the carriage load consisted of.

3.1.3. Processor Tower Yarder

The analysis of the delay-free work cycle of PTY as a multi-operational machine showed the following distribution of work elements in yarding and processing a tree: the longest was delimbing and bucking (21%), followed by outhaul and hooking (16%), load outhaul and carriage inhaul (14% each), carriage outhaul (11%), unhooking (10%), sorting, piling and clearing (8%) and directing and gripping the tree (6%) (Figure 5). This was similar to the work cycle percentage distribution of the Mounty 4000 PTY, even though research was carried out in spruce stands affected by outbreak of bark beetle and fungi [20]. Similar work cycle proportions when Mounty 4000 was used were also found in oak stand [22]; however, tree trunks were processed after delimbing with chainsaw. Cross-cutting though, was recognized as difficult due to broadleaved tree species, and hard in this case [22].

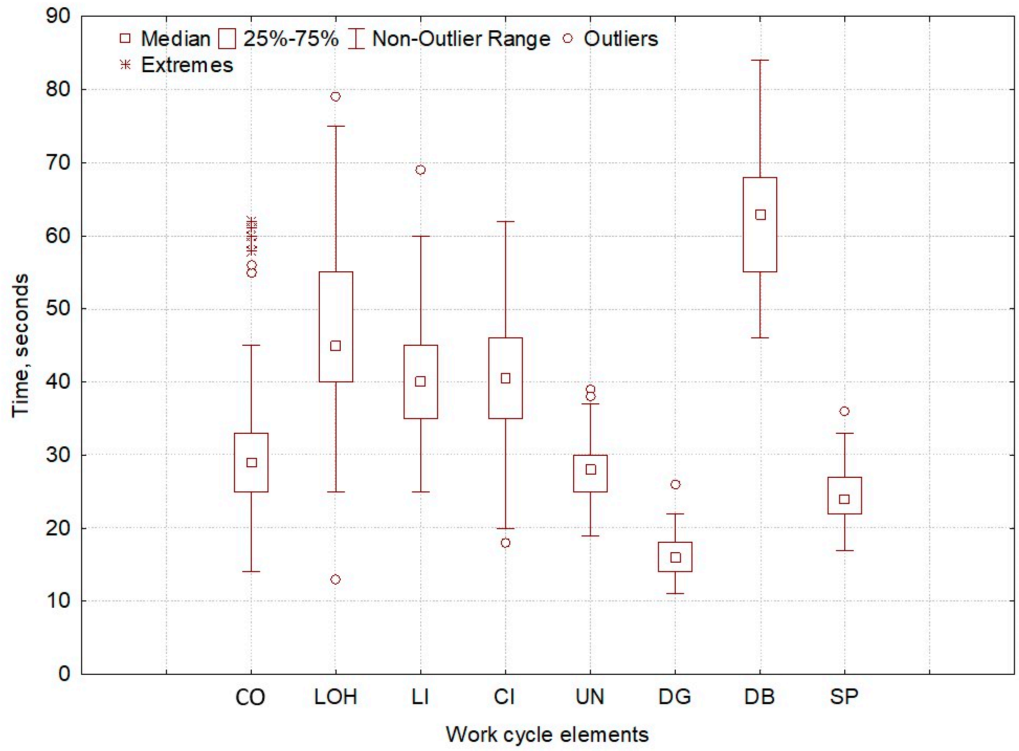

Figure 5. Elemental time consumption of processor tower yarder.

The mean duration of the delay-free work cycle of PTY in given operational conditions was 292.13 s. According to Equation (4) describing the delay-free work cycle time $T_{\mathrm{net,PTY}}$ (Table 4), a minimum duration can be expected at minimum values of all independent variables: yarding distance L, lateral yarding distance l, terrain slope angle i and load volume V.

3.2. *Productivity*

3.2.1. Tower Yarder Unit

To increase delay-free yarding productivity, defined by Equation (5), yarding distance L, lateral yarding distance l, and terrain slope i should be at low rates, whereas the load volume V per cycle will be at its maximum (Table 5).

From Equation (6), it can be seen that when increasing the volume of a load V to the allowed maximum, it could be expected that the yarding productivity per scheduled machine hour PSMH,Y will increase its maximum (Table 5).

Generally, the mean yarding productivity per hour at a mean slope yarding distance of 67.44 m and mean lateral yarding distance of 14.78 m, excluding and including delays, is estimated at 23.84 m^3 PMH^{-1} and 18.41 m^3 SMH^{-1} at the given operating conditions. The mean yarding productivity per hour compared to the rate of a tower cable yarder in a salvage operation in the same region for an extraction distance of 101 m and a lateral yarding distance of 18 m, resulting in a productivity rate of 20.1 m^3 PMH^{-1} and 12.8 m^3 SMH^{-1}, including delays, was very close [35]. This can be seen as good result in presented research with shalterwood cutting, as in salvage logging, all affected trees are harvested and extracted, and in the compared case, this occurred for 1/3 of them. Comparison to the results obtained in thinnings in spruce stand with Mounty 4100 by Borz et al. [24,36] show 5.88 m^3 PMH^{-1} at average lateral yarding distance of 22 m and yarding distance of 190.13 m, i.e., more than three times lower rates. This is natural, as in thinnings, smaller trees are usually harvested. In this case they were of 0.308 m^3 in average [35]. Additionally, the yarding distance was nearly three times longer when thinning was applied: 190.13 m compared with 67.44 m in the presented study. In order to improve the yarder productivity, the load volume (i.e., the number of trees) of the carriage is advisable to be increased, despite the increase in the lateral yarding time.

Table 5. Summary of the productivity (*P*) models.

Equations		*F*	R^2	R^2_{adj}	SE	*p*-Value
$\mathbf{P_{PMH,Y} = 29.89 - 0.65 \cdot i - 0.10 \cdot L - 0.44 \cdot l + 20.92 \cdot V, m^3 \cdot h^{-1}}$	**(5)**	**232.87**	**0.89**	**0.89**	**2.65**	**<0.05**
$P_{PMH\_Y\_1} = 16.45 - 0.12 \cdot L - 0.44 \cdot l + 18.54 \cdot V$		406.41	0.99	0.98	1.02	<0.05
$P_{PMH\_Y\_2} = 15.55 - 0.13\ L - 0.49\ l + 20.67\ V$		93.03	0.95	0.94	3.01	<0.05
$P_{PMH\_Y\_3} = 23.96 - 0.13\ L - 055\ l + 14.98\ V$		48.49	0.90	0.88	1.91	<0.05
$P_{PMH\_Y\_4} = -\ 0.090\ L - 0.39\ l + 26.23\ V$		40.04	0.88	0.86	1.80	<0.05
$P_{PMH\_Y\_5} = -\ 0.068\ L - 0.32\ l + 21.89\ V$		137.30	0.96	0.96	1.03	<0.05
$P_{PMH\_Y\_6} = 13.17 - 0.12\ L - 0.33\ l + 17.43\ V$		18.77	0.77	0.73	1.32	<0.05
$\mathbf{P_{SMH\_Y} = 14.25 \cdot V, m^3 \cdot h^{-1}}$	**(6)**	**19.20**	**0.40**	**0.38**	**6.38**	**<0.05**
$P_{SMH\_Y\_1} = 34.40 - 0.30 \cdot L$		29.41	0.62	0.60	3.72	<0.05
$P_{SMH\_Y\_2} = 14.18\ V$		12.91	0.42	0.39	9.62	<0.05
$P_{SMH\_Y\_3} = 46.15 - 0.22\ L - 055\ l - 0.69\ V$		5.15	0.38	0.30	5.82	<0.05
$P_{SMH\_Y\_4} = 38.95 - 0.75\ l$		5.61	0.40	0.33	5.05	<0.05
$P_{SMH\_Y\_5} = 20.72\ V$		11.63	0.39	0.36	5.10	<0.05
$P_{SMH\_Y\_6} = -0.15\ L + 25.54\ V$		3.23	0.36	0.25	3.91	<0.05
$\mathbf{P_{PMH\_P} = 16.58 + 21.26 \cdot V, m^3 \cdot h^{-1}}$	**(7)**	**581.26**	**0.83**	**0.83**	**3.19**	**<0.05**
$P_{PMH\_P\_1} = 15.98 + 23.33 \cdot V$		111.62	0.86	0.85	3.32	<0.05
$P_{PMH\_P\_2} = 18.43 + 21.82\ V$		318.86	0.95	0.94	2.98	<0.05
$P_{PMH\_P\_3} = 19.81 + 19.76\ V$		152.23	0.89	0.89	1.92	<0.05
$P_{PMH\_P\_4} = 23.11 + 16.06\ V$		29.04	0.62	0.60	1.72	<0.05
$P_{PMH\_P\_5} = 18.11 + 18.33\ V$		71.80	0.80	0.79	1.82	<0.05
$P_{PMH\_P\_6} = 18.60 + 16.95\ V$		36.00	0.65	0.64	2.09	<0.05
$\mathbf{P_{SMH\_P} = 15.03 + 21.04 \cdot V, m^3 \cdot h^{-1}}$	**(8)**	**155.56**	**0.57**	**0.57**	**6.11**	**<0.05**
$P_{SMH\_P\_1} = 27.54 \cdot V$		24.61	0.580.	0.55	8.31	<0.05
$P_{SMH\_P\_2} = 20.55 + 18.96\ V$		37.67	0.68	0.66	7.53	<0.05
$P_{SMH\_P\_3} = 17.54 + 19.57\ V$		15.85	0.47	0.44	5.90	<0.05
$P_{SMH\_P\_4} = 18.13\ V$		4.47	0.20	0.15	4.95	<0.05
$P_{SMH\_P\_5} = 18.34 + 17.56\ V$		15.56	0.46	0.43		<0.05
$P_{SMH\_P\_6} = 21.58\ V$		14.05	0.43	0.39	4.26	<0.05
$\mathbf{P_{PMH\_PTY} = 18.10 - 0.36 \cdot i - 0.05 \cdot L - 0.19 \cdot l + 10.88 \cdot V, m^3 \cdot h^{-1}}$	**(9)**	**319.61**	**0.92**	**0.91**	**1.16**	**<0.05**
$P_{PMH\_PTY\_1} = 11.00 - 0.062 \cdot L - 0.23\ l + 10.00 \cdot V$		208.41	0.98	0.97	0.76	<0.05
$P_{PMH\_PTY\_2} = 9.26 - 0.058\ L - 0.19\ l + 11.00\ V$		180.80	0.97	0.97	1.15	<0.05
$P_{PMH\_PTY\_3} = 12.63 - 0.08\ L - 0.23\ l + 8.81\ V$		69.89	0.93	0.92	0.86	<0.05
$P_{PMH\_PTY\_4} = -\ 0.011\ L - 0.17\ l + 12.98\ V$		46.64	0.95	0.88	0.80	<0.05
$P_{PMH\_PTY\_5} = 3.98 - 0.028\ L - 0.14\ l + 11.71\ V$		161.52	0.98	0.97	0.49	<0.05
$P_{PMH\_PTY\_6} = 8.23 - 0.037\ L + 0.95\ V$		28.54	0.76	0.73	0.68	<0.05
$\mathbf{P_{SMH\_PTY} = 7.60 \cdot V, m^3 \cdot h^{-1}}$	**(10)**	**25.02**	**0.47**	**0.45**	**2.96**	**<0.05**
$P_{SMH\_PTY\_1} = 12.38 - 0.11 \cdot L + 4.88 \cdot V$		208.41	0.98	0.97	0.76	<0.05
$P_{SMH\_PTY\_2} = 6.98\ V$		14.08	0.44	0.41	4.53	<0.05
$P_{SMH\_PTY\_3} = 24.22 - 0.37\ l$		3.80	0.31	0.23	2.93	<0.05
$P_{SMH\_PTY\_4} = -\ 0.29\ l + 9.36\ V$		46.64	0.90	0.88	0.80	<0.05
$P_{SMH\_PTY\_5} = 11.89\ V$		12.74	0.41	0.38	2.80	<0.05
$P_{SMH\_PTY\_6} = -\ 0.077\ L + 13.43\ V$		5.29	0.50	0.40	1.77	<0.05

PMH—productive machine hour, SMH—scheduled machine hour, Y—tower yarder unit, P—processor unit, PTY—processor tower yarder.

3.2.2. Processor Unit

Increasing the load volume of the yarder carriage (in this case, consisting of a single tree) led to an increase in processor's performance on both a productive machine hour and scheduled machine hour basis, as described by Equations (7) and (8), respectively (Table 5). Generally, the mean processor productivity per hour at a mean load volume of 1.23 m^3, excluding and including delays, was estimated at 42.71 m^3 PMH^{-1} and 40.89 m^3 SMH^{-1} at the given operating conditions. The productivity of the processor, like the duration of its cycle, was about twice that of the yarder. Comparison to the results of thinnings in a spruce stand obtained with Mounty 4100, provided by Borz et al. [36], showed 13.158 m^3 PMH^{-1}, i.e., three times lower production rates than of the processor unit presented in this study. Again, in Borz at al. [36] studies, thinning was provided in the stand with average DBH of 15 and 21 cm, which had a significant impact on lower productivity of processing.

3.2.3. Processor Tower Yarder

The delay-free productivity of PTY, showed by Equation (9), will increase as the terrain slope, yarding distance and lateral yarding distance decrease, and the load volume is maximized (Table 5). The factors that affect PTY delay-free productivity are analogous to those for delay-free yarding productivity. Interestingly, the PTY productivity with delays, given by Equation (10), is rather close to that of yarder productivity with delays, and depends only on the volume of the load—in this specific case, the volume of the tree. Therefore, the productivity of PTY was mainly determined by the productivity of the yarder unit, which determines the technological process and indicators of the combined machine.

Under the given conditions, the performance of PTY can be significantly increased if more trees (probably two trees) are attached and extracted per yarder cycle, since the productivity of the processor was approximately twice that of the yarder. In comparison, the productivity rates of studied PTY of 15.20 m^3 PMH^{-1} and 12.29 m^3 SMH^{-1} were higher than the productivity of two PTYs in salvage logging in windfall, which were found to be 6.57 m^3 ${PSH_{15}}^{-1}$ for Mounty 4000 and 7.29 m^3 ${PSH_{15}}^{-1}$ for Koller K501, with an average diameter of harvested assortments of 27.3 cm (under bark) [23].

3.3. Cost Analysis

The gross costs of Syncrofalke 3t for uphill whole tree yarding in Scots pine stand were calculated at 297.48 EUR PMH^{-1} (Table 6). Thus, when the studied tower yarder was productive, the extraction costs were 16.17 EUR m^{-3}. The increase in the productive time of a tower yarder would lead to a decrease in extraction costs.

Table 6. Costs characteristics of the studied processor tower yarder.

Costs	Costs per PMH, EUR	Costs, EUR m^{-3}
Fixed costs	36.40	1.98
Variable costs	186.75	10.15
Labor costs	24.96	1.36
Net costs (excluding profit)	248.1	13.48
Overheads and management costs	22.33	1.21
Gross costs (including 10% profit)	297.48	16.17

The costs of studied PTY were two times lower compared to the costs of 32.5 ± 5.9 EUR m^{-3} for Koller K507 and 36.2 ± 7.5 EUR m^{-3} for Valentini V400 (both including processing at roadside) reported by Schweier et al. [37] and carried out in Germany, where labor costs are higher (costs were analyzed with data collected in various stands of different characteristics) However, the obtained costs in the presented study were twice as high, which was expected, compared to the tower cable yarder without a processor operating in the same region [35]. Therefore, the PTY used in presented stand conditions, compared to other machines, is considered as production and cost efficient and minimally labor intensive.

In the distribution of the net costs of the studied Syncrofalke 3t PTY under these conditions, variable costs predominated (75%); they were three times higher than the sum of fixed costs (15%) and labor costs (10%). The increase in the share of variable costs of the studied PTY was due to the significantly increased prices of diesel fuel and motor, transmission and hydraulic oil, as well as other petroleum-related products. The other two groups of costs were not affected as much by the general increase in prices.

4. Conclusions

The productivity of PTY, 15.20 m^3 PMH^{-1} and 12.29 m^3 SMH^{-1} was mainly determined by the productivity of the yarder unit, which determined the technological process and indicators of the combined machine. The analysis of the delay-free work cycle of PTY showed that the most time-consuming processes were delimbing and bucking (21%), followed by outhaul and hooking (16%), load outhaul and carriage inhaul (14% each), carriage outhaul (11%), unhooking (10%), sorting, piling and clearing (8%) and directing and gripping the tree (6%). Under the given conditions, the performance of PTY significantly increased if more trees (at least two) were attached and extracted per yarder cycle, since the productivity of the processor was approximately twice that of the yarder.

The gross costs for uphill yarding of whole deciduous trees using the studied tower yarder were calculated at 297.48 EUR PMH^{-1} and 16.17 EUR m^{-3}. The variable costs (75%) predominated in the net costs distribution, followed by the fixed costs (15%) and the labor costs (10%).

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4.5 Forests and Logging Operations

Article 4
Forest operations using a combi – forwarder in deciduous forest

Stanimir Stoilov[1], Andrea Rosario Proto[*2], Delyan Oslekov[1], Georgi Angelov[1], Salvatore Francesco Papandrea[2]

[1]Department of Technologies and Mechanization of Forestry, University of Forestry, Kliment Ohridski Blvd. 10, 1756 Sofia, Bulgaria.

[2]Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy.

[*]Corresponding author: andrea.proto@unirc.it; ORCID 0000-0003-4630-898; Tel.: +39 (0) 965.1694275

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Forest operations using a combi – forwarder in deciduous forest

Stanimir Stoilov[1], Andrea Rosario Proto*[2], Delyan Oslekov[1], Georgi Angelov[1], Salvatore Francesco Papandrea[2]

[1]Department of Technologies and Mechanization of Forestry, University of Forestry, Kliment Ohridski Blvd. 10, 1756 Sofia, Bulgaria.
[2]Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy.

*Corresponding author: andrea.proto@unirc.it; ORCID 0000-0003-4630-898; Tel.: +39 (0) 965.1694275

Abstract

Forwarders are a mechanized alternative to agricultural and forestry tractors and animal logging and currently, these machines are among the most used ground-based machineries to extract the wood around the world. These machines are used to load logs from skid road and moves to the next pile, until the load space is fully loaded. Fortunately, in recent years the development of new technological progresses in forestry mechanization created an alternative operation on ground-based system with the use of a combi-forwarder for wood extraction. These innovative machines pull stems by the winch from the stump to the road, after they have been cross-cutted by chainsaws, it loads by the forwarder’s crane the logs and transports them to the landing, where they are unloaded with the crane in piles.
The aim of the present study was to analyse the operational time consumption, to estimate the productivity of the combi – forwarder with a built-in single-drum winch in beech stands evaluating the forwarding and winching distances, log’s volume transported per turn by the machine, as well as the extracting costs. The study was conducted in low-intensity shelterwood cuttings in beech forest, located in Western Balkan Mountains, Bulgaria. The mean productivity of the combi – forwarder was 7.09 m^3 PMH^{-1} and 6.11 m^3 SMH^{-1} close to that of the cable skidders and forwarders in similar conditions. The net costs for the studied combi – forwarder were calculated of 25.33 € per productive machine hour and 4.13 € per m^3. The variable costs (70%) have a leading role, followed by labour costs (22%) and fixed costs (8%). The use of a combi–forwarder provides facilitation of the chainsaw operators, as some of the operations are carried out at the roadside in better working conditions: flat terrain and support of crosscutting phase. The results from the study are useful to introduce and to integrate the combi – forwarders in shelterwood system and to achieve economic and environmental efficiency of timber harvesting in deciduous forests.

Keywords productivity, skidding, ground-based machine, forwarding, performance.

Introduction

Forwarders are a mechanized alternative to agricultural and forestry tractors and animal logging (Proto et al. 2018, Borz et al. 2019) and currently, these machines are among the most used ground-based machineries to extract the wood around the world (Lindroos et al. 2017; Borz et al 2021). These self-propelled vehicles were designed to the 60s when for use in the transport of trees or their parts into a bunk (ISO 6814 2009) and are used today in partly mechanized systems that integrate motor-manual felling and processing of trees. The actual concept of forwarders has not been changed significantly compared to the original one, but a significant progress in the forwarding machines development was achieved in key areas such as the ergonomics, environmental impact and automation (Spinelli et al. 2003; Pandur et al. 2009, Stankić et al. 2012; Apăfăian et al., 2017; Borz et al., 2021). Modern forwarders are an effective extraction option for timber harvesting operations that provide the opportunity for higher levels of mechanization and thanks to their ability to carry logs from the forest to the roadside or processing areas; they have an established lower environmental impact in comparison to tree-length skidding options (Spinelli et al., 2014; Proto et al., 2018c). The use of forwarder requires mainly the cut-to-length (CTL) system that offers several advantages compared to the other ground-based systems: less road construction, lower levels of soil disturbance, smaller landing size through reduced processing requirements, minimal damage to the logs during handling and extraction and fewer workers (Bettinger and Kellogg 1993; Cambi et al., 2017; Picchio et al., 2020). Forwarder productivity has been widely studied in Europe (Cadei et al. 2020); in fact, several studies have demonstrated that the productivity of this system depends on the forest stand, site and operational factors such as ground conditions, slope, operator's skill, branch size, operational layout, tree volume, tree form, log assortments processed, numbers of merchantable trees per unit area, hauling distance, undergrowth density and machine design (Stampfer 1999; Spinelli et al. 2002; Apăfăian et al., 2017). In recent decades, the fully mechanized cut-to-length timber harvesting system has become widely used in many industrialized European countries where the conditions and the stands are favourable such as in Sweden (ca. 98%), Ireland (ca. 95%) and Finland (ca. 91%), as compared to motor-manual harvesting (Karjalainen et al. 2001). In Austria, where forests are predominantly on mountainous terrains, the distribution of timber harvesting machines from stand to landing in 2009 is as follows: cable yarders – 20%, skidders – 49%, forwarders – 26%, and other means – 5% (Holzleitner et al. 2011). Ten years later, in 2019, this ratio has changed in favour of forwarders: cable yarders – 19%, skidders – 37%, forwarders – 43%, and other means – 5% (Prem and Bauer 2020). The important role and diffusion of this forest machine is supported by the large number of studies (Tiernan et al. 2004; Nurminen et al. 2006; Ghaffarian et al. 2007; Apăfăian et al., 2017; Proto et al., 2018a; Proto et al., 2018b; Cadei et al., 2020; Schweier and Ludowicy, 2020; Borz et al., 2021; Cataldo et al., 2022) that are still conducted to test the performance of these machines. Among the first, Sever (1988) determined the travel distance as the most important factor while Manner et al. (2013) identified the log concentration as influential parameter on the forwarding time consumption; in fact, the movement time during the loading significantly decreases with increasing concentration of the logs. Slugeň and Stoilov (2009) evaluated the slope of 25º as the upper limit for the use of forwarders and harvesters to obtain high productivity in regenerative cuttings and thinning operations while d) find that the productivity between forwarders with different payloads decreased with extraction distance, both in final felling and thinning. In Bulgaria, as in other European countries (Italy, etc.), although the forest areas are located on steep terrains with complex shapes, adapted agricultural tractors with logging equipment are predominance and forwarders are not very widespread or are not used frequently (Proto et al., 2018a; Stoilov 2021). In particular, in these countries, logs are extracted from the harvest area to the landing on the closest skid road or skid trail using a ground extraction system with a farm tractor and winch or animal force and only after, the forwarder loads the logs from one pile and moves to the next pile, until the load space is fully loaded. Often, this limit is mainly due to the type of cut (thinning, selective, or shelterwood cuts) which does not allow the forwarder to enter in the harvest area directly (felling site). Therefore, these two operations, winching and skidding, are conducted with different systems, machineries and workers. Fortunately, in recent years the development of new technological progresses in forestry mechanization created an alternative operation on ground-based system with the use of a combi-forwarder for wood extraction. These innovative machines pull stems by the winch from the stump to the road, after they have been cross-cutted by chainsaws, it loads by the forwarder's crane the logs and transports them to the landing, where they are unloaded with the crane in piles. The interest for this combi-forwarders can be explained mainly by the fact that it can operate as both skidder and forwarder, thus highly increasing the flexibility of the operator (Schweier and Ludowicy, 2020). In Central European countries, combi – forwarders, i.e. forwarders with a built-in single- or double-drum winch, are spreading but at the moment no papers published regarding their productivity potential and the factors that influence their performance. The aim of this research was to carry out early studies of the factors affecting the productivity of combi – forwarders in deciduous forests. The study objectives were to: (*i*) Analysis of the operational time consumption of the combi – forwarder with a built-in single-drum winch; (*ii*) Estimation of productivity in relation to common factors in harvesting operations; (*iii*) Determination of the operation costs for the forwarder with a built-in single-drum winch studied.

Materials and Methods

Study site and work organization

The study was conducted in Vitinya State Hunting Range, located in the Western Balkan Mountains, in Sofia Provence. The characteristics of the areas chosen for the study are shown in table 1. The topographical characteristics of the two study areas are very similar, with slopes that do not differ between the two sites. An articulated six-wheel-drive Timberjack-1010D forwarder, equipped with single-drum winch, as shown in Fig. 1 and Table 2, was used for the tests.

Table 1 Characteristics of test sites

	Site A	Site B
Location	Subcompartment 35-b N 42°48′5.1084″; E 23°46′41.9497″	Subcompartment 35-b N 42°48'11.82"; E 23°46'8.97"
Elevation	1150 m asl	1200 m asl
Function	Old-growth forest. EUNIS habitat type 3	Old-growth forest. EUNIS habitat type 3
Species composition	European beech (*Fagus sylvatica,* L) 100%	European beech (*Fagus sylvatica,* L) 100%
Stand age	150 years	150 years
Stand type	High natural forest	High natural forest
Total area	21.9 ha	25 ha
Logging operation	Shelterwood cutting, removal intensity 15%	Shelterwood cutting, removal intensity 15%
Average tree height	25 m	23 m
Average DBH of tree	40 cm	42 cm
Average slope gradient	31° (60%)	35° (70%)
Growing stock	5070 m^3 (317 m^3 ha^{-1})	5070 m^3 (317 m^3 ha^{-1})
Allowable cut	563 m^3 (26 m^3 ha^{-1})	563 m^3 (26 m^3 ha^{-1})
Extraction direction	Uphill	Uphill
Average slope gradient	6.3% (3.6°)	8% (4.5°)

Fig. 1. An overview of the tested Timberjack-1010D forwarder

The felling and processing of the trees took place with the same chainsaws in both site A and site B (Figure 2). The timber is inhauled from the cutting area by the forwarder's winch in the form of stems and stem sections, and the larger ones – in the form of assortments. On the road, after crosscutting, the obtained assortments were loaded by the forwarder's hydraulic crane and transported to the landing and the extraction direction was uphill.

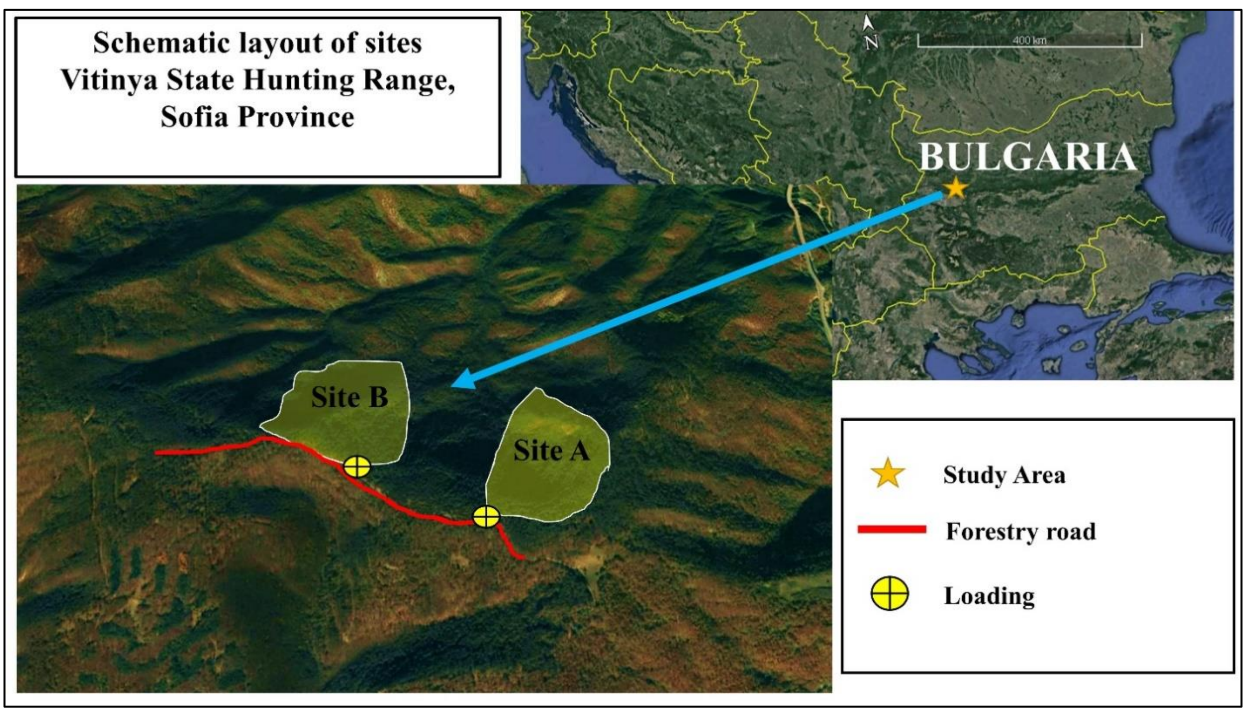

Fig. 2. Site map of the study and the schematic layout during the extraction operations.

Table 2. Technical data of Timberjack 1010D

Engine type:	John Deere 4045 HTJ76
Rated power	86 kW at 2000 min^{-1}
Maximum net torque	498 Nm at 1400 min^{-1}
Transmission	Hydrostatic-mechanical transmission
Travel speeds	High: 0–22 km/h; Low: 0–8 km/h
Max. tractive effort	140 kN
Dimensions:	
Length	9050 mm
Width	2700 mm
Transport height	3700 mm
Ground clearance	605 mm
Wheel base	4800 mm
Load capacity	11000 kg
Operating weight	12700-13700 kg
Wood bunk::	
Length	4550 mm
Width	2565 mm
Max. cross section	3,5 m^2
Max. load rating	10000 kg
Crane:	CF5
Gross lifting torque	102 kNm
Winch	One-drum
Cable length	65 m
Tractive force of winch cable	50 kN

Productivity study and costs

A detailed study of times and movements was carried out to estimate the duration of the elements of the work cycle and the productivity of the shipper taking into account the average value of the two sites under the given conditions. A work cycle was assumed to be composed of repetitive elements (Stokes et al. 1989; Olsen et al. 1998).

The work cycle of of the forwarder with winch was composed of following repetitive components:

- unloaded travel from landing to stand;
- maneuvering – the time for which the forwarder is as close as possible to the timber to be inhaul;
- outhaul and hook – the time for which a worker pulls the winch cable and hooks the load by chockers;
- inhaul – the time for which the stem sections are drawn to the forwarder with the winch cable;
- loading – the time for loading the obtained assortments on the forwarder with the hydraulic crane. When stems are pulled out, they are crosscutted during this work cycle element;
- loaded travel – the time for which the forwarder moves loaded from the stand to the landing;
- unloading – the time for which assortments are unloaded and piled in large piles on the landing by hydraulic crane;
- delays – the time for which the forwarder does not perform any work for organizational (waiting for the felling of a certain number of trees, crosscutting of the stems into assortments),

technical reasons (mechanical and repair delay time), weather or terrain conditions, and operator talking with managers and visitors.

During the study the forwarding distance, winching distance and slope gradient, as well as the number and volume of the assortments were measured. The time-motion study was designed to evaluate the duration of work elements and productivity of forwarder and to identify those variables that are most likely to affect it. Each work cycle was individually measured by a stopwatch. The productive time was separated from the delay time. Forwarding distance and the slope gradient of the road was measured by GPS device, whereas, winching distances were measured by a professional laser range-finder with clinometer. Load volume was determined by measuring the length and the mid-length diameter of all logs from each assortment.

The machine costs were calculated using the COST model (Ackerman et al. 2014). In order to calculate the production cost for 1 m^3 timber, the cost analysis employed the following parameters: the number of operators, the hourly cost of an operator, the hourly cost of machines, the volume of extracted timber, and productive machine hours (excluding all delay times). The machine cost per hour was reported both as productive machine hours excluding delays and scheduled machine hours. The purchase prices and operator wages required by the cost calculations were obtained from the accounting records (Proto et al. 2018c). Labor cost was set to 5.60 € SMH^{-1} inclusive of indirect salary costs. Diesel fuel consumption was measured by the commonly used method of refilling to full. A salvage value of 10% of the purchase price was assumed and the Value Added Tax (VAT) was excluded.

Cost calculations were based on the assumption that companies worked for 150 working days in the year and depreciation period of 10 years. For extraction work this amounts to 130–150 working days per year (20-21 working days per month) at an average of 6-7 scheduled working hours per day (assuming one to two hours spent on lunch, rest and other breaks). Thus yielded annual working hours to 910–1050 SMHs with a 70% use coefficient (Spinelli and Magagnotti 2011, Proto et al. 2018a).

Data analysis

Regression analysis was performed on the experimental data of the forwarder in order to develop prediction models for estimating the work cycle time and productivity. The variables used in the modelling approach included forwarding distance *L*, winching distance *l*, load volume per cycle *V*, slop gradient of the skidding road *i*, and the number of assortments in a load *n*. The descriptive statistics of the variables were computed and a stepwise backward regression procedure was used to model the variability of the cycle time and productivity as a function of independent variables. The confidence level used for regression analysis was 95% ($\alpha=0.05$) and the assumed probability $p<0.05$. Independent variables are significant at $p<0.05$. To process the experimental data the Statistica 8 (StatSoft Inc., Tulsa, OK, USA) software was used.

Results and discussion

Table 3 presents the mean experimental data of monitored combi-forwarder. In particular, the largest share of the working cycle elements occupies the operation “Inhaul of timber” (37% and 32% respectively, excluding and including delays), followed by the “Outhaul of line and hook” (33% and 29% respectively, excluding and including delays), travel loaded (11% and 9% respectively, excluding and including delays), “loading” and “travel unloaded” (both operations cover 7% and 6% respectively, excluding and including delays), “unloading” (3%), and the smallest has “maneuvering” (2%).

Table 3 Mean experimental data

Variables	Duration, s Mean value ± SD	Duration, s min	Duration, s max	Distance, m Mean value ± SD	Distance, m min	Distance, m max
Travel unloaded	378±112	139	600	802±232	270	1105
Maneuvering	120±92	20	345			
Outhaul of line and hook	1857±378	950	2680	13±5,95	0	22
Inhaul of timber	2098±500	1250	2845	13±5,95	0	22
Loading	428±226	234	1010			
Travel loaded	616±188	168	910	802±232	270	1105
Unloading	202±25	147	265			
Delays	801±231	301	1090			
Cycle time with delays	5973±1538	2384	8760			
Delay-free cycle time	5172±1381	2083	7670			
Number of logs per cycle	22±3,5	15	29			
Load volume, m^3	9.12±0.44	7.8	9.9			
Productivity, $m^3 \cdot PMH^{-1*}$	7.09±3.00	4.41	15.21			
Productivity, $m^3 \cdot SMH^{-1*}$	6.11±2.58	3.91	13.29			
Number of cycles per SMH*	0.67±0.29	0.41	1.51			
Mean velocity, km/h	5.83±0,45	5.03	7.07			
Mean velocity loaded, km/h	4.78±0.56	3.76	5.80			
Mean velocity unloaded, km/h	7.62±0.93	5.55	10.41			

* SD – standard deviation, PMH – productive machine hour, SMH – scheduled machine hour.

The breakdown by main groups of operations in delay-free cycle time shows the predominance of the winching of the load with the largest share of 70%, followed by the movement (18%), and loading and unloading at landing (10%).

The data from Table 3 indicate that productive time was 88% from scheduled time (Fig. 3). The delays (12%) are due to organizational reasons (delays are due to waiting for the felling of trees in the cutting area and crosscutting them into assortments at roadside) (7%), mechanical delays (1%), and those due to adverse weather conditions (rain, snow, thick fog) (2%).

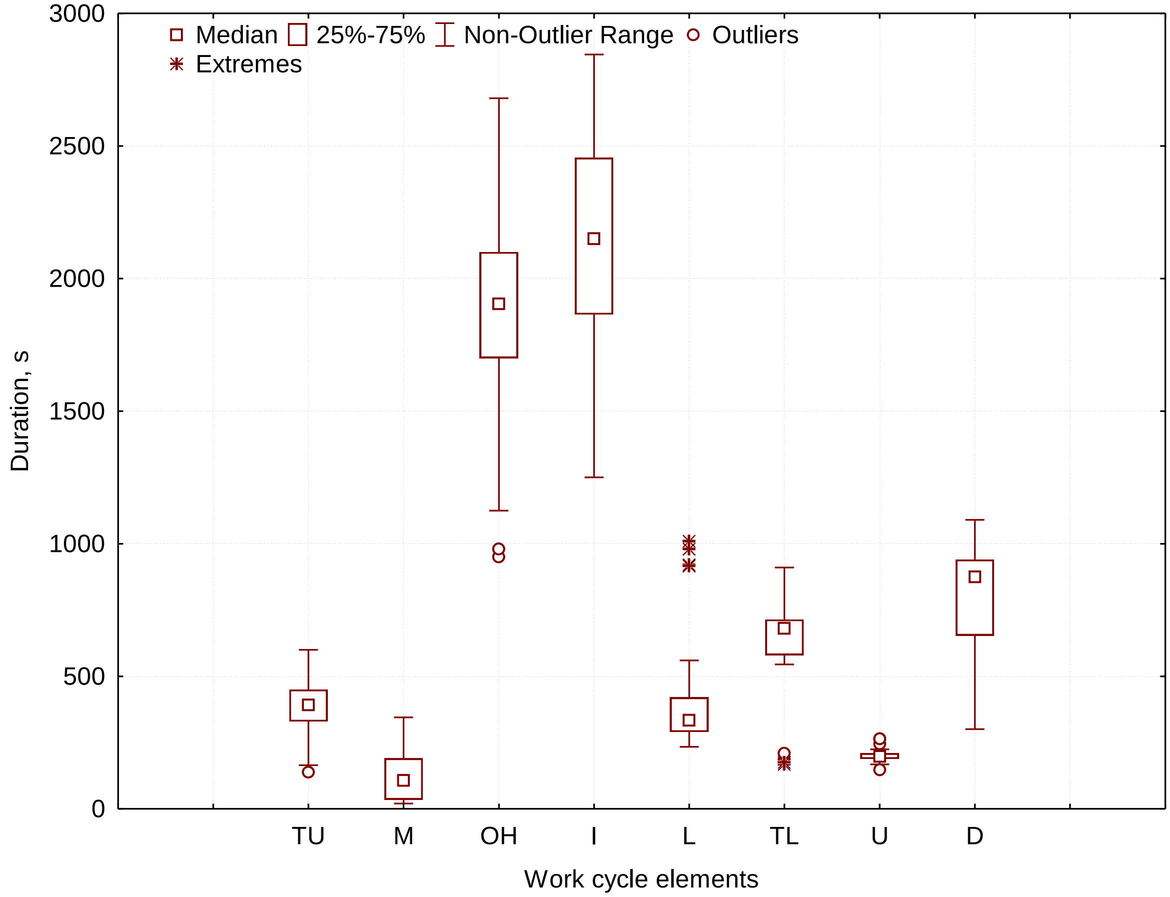

Fig. 3. Summary statistics of the work elemental time consumption (TU: Travel unloaded; M: Maneuvering; OH: Outhaul of line and hook; I: Inhaul of timber; L: Loading; TL: Travel loaded; U: Unloading; D: Delays)

Impressive is the fact that the operations of pulling the winch cable, hooking the chockers, inhaul the stem sections and loading the assortments obtained after crosscutting occupy respectively 77% and 68% of the duration of the work cycle without and with delays. This is due to the difficult terrain of the stand and the long and massive beech stems, which inhaul to the machine by the winch. If the unloading time is added, then the winching operations, loading and unloading operations reach 80% and 71% of the work cycle time, respectively without and with delays. The mean duration of the work cycle is 86.20 and 99.55 min (1 h 26 min and 1 h 40 min), respectively, excluding and including delays, which leads to 0.41 - 1.51 (average 0.60) turns per hour and the machine utilization ratio is on average 0.88.

The total movement time of the combi-forwarder has a share of only 20% and 17% of the duration of the working cycle (turn), respectively without and with delays. The forwarding distance varies widely between 270 and 1100 m, on average 803 m (Fig. 3). The regression analysis was done on the time-study data in order to develop prediction equations for estimating the combi-forwarder cycle time by excluding and including delays both shown in Table 4. The delay-free cycle time T_{net} regression equation obtained with significant variables given in equation (1) in Table 4.

Table 4 Summary of the work cycle time models

Equations		F	R^2	R^2_{adj}	Std. Error	p-Value
$T_{net} = 3.362 \cdot l$, min	(1)	46.61	0.77	0.76	11.28	$p < 0.05$
$T = 3.871 \cdot l$, min	(2)	61.61	0.82	0.80	11.25	$p < 0.05$

In Eq. (1) minimum duration of delay-free cycle time T_{net} can be achieved in case of short winching distances. The regression equation (2) for studied combi-forwarder cycle time including delays T is also presented in Table 4. Hence, combi-forwarder cycle time including delays also depends only on winching distance l and its minimum duration may be attaining by minimizing the skidding distance.

Travel speed and inhaul speed

The mean travel speed during the skidding phase has been 5.83 km h^{-1}. The mean speeds with and without load were 4.78 km h^{-1} and 7.62 km h^{-1} respectively. The difference is almost 3 km h^{-1}, due to movement loaded is downhill, and movement unloaded – uphill with acting grade resistance. Due to the load is entirely on the forwarder the speed is higher; in fact, Orlovsky et al. (2020) reported mean travel speed of four studied LKT 81T wheel cable skidders of 3.97 km h^{-1} (1.87-4.35 km h^{-1} unloaded and 2.56-4.05 km h^{-1} loaded). Spinelli and Magagnotti (2012) reported empty and loaded travel velocities of 96 kW agricultural tractor of 8.1 and 7.3 km h^{-1}, respectively, which were higher than those determined in this study. The mean inhaul speed of winching of stems was 0.01 $m \cdot s^{-1}$ (0.36 km h^{-1}).

Productivity analysis

Delay-free productivity was defined by the regression equation (3) shown in Table 5. From equation (3), to enhance delay-free productivity of the studied machine, winching distance l should be reduced.

Table 5 Summary of the productivity models.

Equations		F	R^2	R^2_{adj}	Std. Error	p-Value
$P_{PMH} = 15.44 - 0.46 \cdot l$, $m^3 \cdot h^{-1}$	(3)	58.59	0.81	0.80	1.35	$p < 0.05$
$P_{SMH} = 13.20 - 0.40 \cdot l$, $m^3 \cdot h^{-1}$	(4)	64.04	0.82	0.81	1.11	$p < 0.05$

The combi-forwarder productivity including delays is expressed by equation (4) also shown in Table 5. From equations (4), to increase productivity including delays again winching distance should be reduced, whereas the load volume per cycle V and forwarding distance L are found to be insignificant variables.

In equations (3) and (4), as well as in equations (1) and (2), a significant influencing factor is the winching distance because winching operations occupy a leading share in the work cycle. The mean productivity obtained at mean skidding distance of 802 m, mean winching distance of 13 m, mean load volume of 9.12 m^3 and mean 22 logs per cycle (turn) is 7.09 m^3 PMH^{-1} and 6.11 m^3 SMH^{-1} respectively. For LKT 81T and LKT 81 ILT cable skidders, latter with knuckle-boom, operated mostly in beech, beech-fir and beech-oak stands Orlovský et al. (2020), at mean skidding distance of 300 m and 316 m respectively, reported lower performance: mean load volume of 5.45 m^3 and 8.01 m^3, gross production rate of 3.91 m^3 and 4.21 m^3 SMH^{-1} respectively. Öztürk (2010a) found that hourly productivity of MB Trac 900 tractor in beech stands in Black sea region of Turkey were 14.4 m^3 h^{-1} for skidding distance of 55 m and 8.7 m^3 h^{-1} for skidding distance of 105 m, and 11.35 m^3 h^{-1} for skidding distance of 140 m and 7.70 m^3 h^{-1} for New Holland TD85D. Borz et al. (2015) reported for TAF 690 OP (shorter winching distance of 8.7 m, two time longer skidding distance of 1706.3 m, a lower load volume of 4.89 m^3 and 6.48 logs per turn) the net and gross production rates were around three time lower (4.41 m^3 h^{-1} and 3.12 m^3 h^{-1}, respectively). Due to the lack of studies on deciduous forests, the authors compared with the productivity of forwarders in coniferous forests. In comparison for the John Deere 1010 forwarder deployed in coniferous stands and mean forwarding distance 321 m, Dvořák et al. (2021) reported close in value mean hourly productivity ranged from 7.4 to 10.3 m^3 per machine hour; Borz et al. (2021) within evaluation of an HSM 208F 14-tone forwarder under conditions of steep-terrain and low-access dominated by Norway spruce stand found for an average forwarding distance of about 1.5 km, net productivity and efficiency rates were estimated at 14.4 m^3 h^{-1} and 0.07 h m^{-3}, respectively. Proto et al. (2018b) have found productivities of 14.4 and 15.7 m^3 h^{-1} for extraction distances of approximately 300 and 600 m, respectively, for two John Deere 1110D and 1010D models, operating on slopes of 26 and 29%, respectively. For steep terrain and similar skidding distance, Dinev et al. (2015) found productivities of 44 –53 m^3 per day (5–6 m^3 h^{-1} assuming a work shift of 8 hours). Ghaffarian et al. (2007) reported an average forwarding production ca. 17.9 m^3 PSH_0^{-1} at mean load per trip was 10.04 m^3 and average forwarding distance was 97 m.

Therefore, the studied combi-forwarder, unifying skidding and forwarding functions, demonstrates significant efficiency in respect of the productivity in shelterwood cutting in beech stand with a removal intensity of 15%.

Cost analysis

The hourly costs of the studied combi – forwarder, as well as the labor costs, are summarized in Table 6. As shown, the net costs for uphill extraction were estimated at 25.33 € PMH^{-1} (productive machine hour). In the structure of the gross costs, the fixed costs (8%) were considerably lower than the labor (22%) and variable costs (70%). Therefore, for the productive time of the machine, the net extraction costs were estimated at 4.13 € m^{-3}.

Table 6 Extraction costs

Classification of Costs	Costs per hour, € h^{-1}
Total fixed costs:	**1.97**
Depreciation	1.93
Insurance	0.03
Taxes	0.02
Total variable costs:	**17.75**
Fuel and lubricants	8.59
Tyres	4.74
Maintenance and Repair	2.91
Winch cables and choker cables	0.30
Labor Costs	**5.60**
Net costs	**25.33**
Net costs per m^3	**4.13**

For comparison, the results reported by Dvořák et al. (2021) for Czech forwarders in coniferous forests were personnel costs (35 to 66% of the total costs), followed by materials (14.9–27.1%), amortization (12.5–15.7%), and services (3.3–22.1%). The corresponding machine productivity was within 3.5 and 12.3 m^3 SMH^{-1}. Also in Czech Republic in clear-felling operations in coniferous forests Jiroušek et al. (2007)

found the total machine costs of 63.82 € PMH^{-1} for forwarders of a class similar to that of the studied forwarder.

In the study in beech stands in Black sea region of Turkey mentioned above, the cost of skidding of MB Trac 900 tractor were 3.5 and 9.6 $\$\cdot m^{-3}$ at skidding distance ranges between 55 and 105 m and average load volume for every cycle was found 1.490 and 2.130 m^3, respectively (Öztürk 2010a). The cost of New Hollad TD85D in the same region for longer skidding distance ranges between 140 and 320 m were 4.5 $\$ m^{-3}$ and 8.6 $\$ m^{-3}$ respectively (Öztürk 2010b). The costs of C Holder 870 F tractor during thinning of beech stands were ranges from 69.16 kn m^{-3} (approx. 9.19 $€\cdot m^{-3}$) for skidding distance of 25 m to 106.66 kn m^{-3} (approx. 14.17 € m^{-3}) for skidding distance of 250 m (Zečić et al. 2005).

Proto et al. (2018b) found that the extraction costs of a John Deere 1110D and John Deere 1010D were 3.40 $€\cdot m^{-3}$ in a Calabrian pine stand and 4.50 € m^{-3} in a Silver fir stand. The calculated unit cost of forwarder extraction in a selective harvest in Calabria, Italy (with John Deere 1110E), in a clear-cut on the West Coast of New Zealand (with John Deere 1910E) and in a larger clear-cut operation in Canterbury, New Zealand (with two John Deere 1910E) forwarders ranged from 2.55 to 4.70 $€\cdot m^{-3}$ (Proto et al. 2018a).

In Czech Republic Dvořák et al. (2021) monitored forwarders LVS 5, John Deere 1010, and John Deere 1110E in coniferous forest stands with a mean stem volume between 0.10 and 0.84 m^3 and forwarding distance between 261 and 560 m, the costs obtained were between 20.95 and 84.39 € PMH^{-1}. Consequently, the mentioned data show that the studied combi-forwarder, compared to other ground-based machines, is advantageous in terms of unit costs of extraction operations in low-intensity shelterwood cuttings in beech stands.

Conclusions

In recent years, severe labor shortages have led foresters to use new extraction machines to compensate for this problem. Combi-forwarders combine equipment typical of skidders with that of forwarders and represent a competitive machine for improving the mechanization of winching stem sections and assortments around the forest road, loading the received assortments, transporting them to the landing for sorting and piling phases. The data provided show a clear opportunity for promote this machine during forest operations. The combi–forwarder provides high productivity and cost efficiency compared to many extraction machines, which makes it very suitable for logging operations in deciduous forests in mountainous conditions. These results will be of practical help in terms of improving logging planning, and consequently for performing and achieving cost competitiveness of the wood supply chain (Proto et al., 2018b).

Author Contributions

Conceptualization: [Stanimir Stoilov, Salvatore F. Papandrea, Andrea R. Proto]; Methodology: [Stanimir Stoilov, Salvatore F. Papandrea]; Formal analysis and investigation: [Salvatore F. Papandrea, Delyan Oslekov, Georgi Angelov, Stanimir Stoilov]; Writing - original draft preparation: [Salvatore F. Papandrea, Andrea R. Proto, Stanimir Stoilov]; Writing - review and editing: [Salvatore F. Papandrea, Georgi Angelov, Stanimir Stoilov]; Funding acquisition: [Stanimir Stoilov]. All authors read and approved the final manuscript.

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4.6 Forests and Logging Operations

Article 5

Effect of the Different Concentration of Assortments on Forwarder Productivity and Costs in Coniferous Forests

Salvatore F. Papandrea[1] · Stanimir Stoilov[2] · Pavel Nichev[2] · Georgi Angelov[2] · Maria Francesca Cataldo[1*] · Andrea R. Proto[1]

[1]Department of Technologies and Mechanization of Forestry, University of Forestry, Kliment Ohridski Blvd. 10, 1756 Sofia, Bulgaria.

[2]Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy.

[*]Corresponding author: Correspondence: maria.cataldo@unirc.it; Tel.: +39-(0)965-169-4202

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Salvatore F. Papandrea · Stanimir Stoilov · Pavel Nichev · Georgi Angelov · Maria Francesca Cataldo · Andrea R. Proto

Abstract

Forwarders often load assortments of large piles that are harvested by modified farm tractors, skidders, animals, other forwarders, etc., but currently, there are no studies on the time consumption, productivity and cost of the different concentrations of assortments in small piles in the stand versus concentrated in greater piles roadside, on loading process and on overall forwarder performance. A study was conducted in two locations: in site A the assortments were spread in small piles in the stand, whereas in site B they were concentrated in greater piles roadside. The average forwarder productivity in site A obtained from a mean forwarding distance of 1780 m, a mean load volume of 9.83 m^3, and an average number of grips of assortments with the crane grapple during loading (22.97), and during unloading (8.97) per cycle (turn), is 10.43 $m^3 \cdot PMH^{-1}$ and 9.93 $m^3 \cdot SMH^{-1}$, respectively. These productivity rates are higher than that registered by the forwarder operated in site B – 9.38 $m^3 \cdot PMH^{-1}$ and 8.81 $m^3 \cdot SMH^{-1}$, respectively, but under more than two times longer mean forwarding distance (3760 m), larger mean load volume of 15.04 m^3, and a number of grips of assortments with the crane grapple during loading, and during unloading of 23.57 and 14.10 respectively per cycle (turn). The ratio between the number of grips of assortments with the crane grapple during loading and unloading operations in site A is on average 2.56, but in site B is significantly smaller – mean of 1.67, due to the larger number of assortments in the grapple when loading from large piles. This ratio characterizes the concentration of assortments in the stand. Concentration in larger piles results in a larger volume of grappled assortments by crane, and hence, lower time for loading of the forwarder and higher productivity. The obtained results express that the dispersion of small piles of assortments results in a smaller volume grappled, a greater number of crane cycles and a larger loading distance, which generally, increases loading time. The larger volume of assortments in the crane's grapple and the shorter loading distance when loading from larger piles roadside lead to less loading time.

Keywords: forest operation; cycle time; economic evaluation; work elements; loading.

1. Introduction

Bulgarian forest territories are characterized by steep terrains and small extensions of most cutting areas. The traditional harvesting system in Bulgaria is based on motor-manual tree felling, and processing and extraction mostly by skidder, yarder, and animal force, which corresponds to an early stage of mechanization. Traditional extraction methods are based mainly on modified agricultural tractors with related logging equipment, as well as wheeled cable skidders. Modified farm tractors are the most widely used equipment for timber extraction not only in Bulgaria but in other Balkan countries, Italy, etc. (Borz et al. 2013, 2015; Spinelli et al. 2013; Moskalik et al. 2017; Bodaghi et al. 2018; Proto et al. 2018a, 2018b; Cataldo et al. 2020). The predominance of modified tractors in Bulgarian forestry does not correspond to the fact that most of the forest areas are located on steep terrains with complex shapes, despite this feature requiring the use of purpose-built skidders and cable yarders.

In Bulgaria, the number of forwarders (48 machines in 2019) is 4 times greater than that of harvesters, and it can be expected that forwarders will gradually replace military off-road trucks and have the greatest potential to increase their number and share (Stoilov 2021). A forwarder is a rubber-tired, articulated vehicle used for transporting short-wood or cut-to-length logs. The forwarder is equipped with a grapple loader for loading and unloading (Kellogg et al. 1992). Although being rather similar in appearance, forwarders have gone through substantial development during the more than half a century they have been used in forestry (Nordfjell et al. 2019).

Variation in slope reflects the difficulty, and thus costs, of accessing forest stands and road density has a positive effect and has the largest impact of all factors (Sanchez-García et al. 2016). The magnitude of this effect reflects the fact that the forest road network in Bulgaria is a limiting factor for forestry and, in particular, for the logging industry. The density of the forest road network of 7.9 $m \cdot ha^{-1}$ (MoAF 2014, Yonov and Velichkov 2004) is insufficient, similar to Romania, where typical extraction distances ranged widely from 0.5 to more than 1 km; in some cases, the typical hauling distances were indicated to reach up to 2-3 km (Borz et al. 2019). For forwarder extraction, Ghaffariyan et al. (2009) propose in Austrian forest conditions optimum road spacing of 463 m, optimum road distribution of 21.6 $m \cdot ha^{-1}$, and

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e-mail: crojfe@sumfak.hr

optimum extraction distance of 285 m, whereas 641 m, 15.6 m·ha^{-1}, and 321 m respectively were proposed by LeBel et al. (2003) for forestry conditions of Canada.

The lack of workers in the Bulgarian logging industry leads to the renewal of the logging machinery, which while more expensive, will ensure efficiency, higher productivity and lower unit costs (Stoilov 2021). The cut-to-length systems (CTL) typically require less labour, less access road construction, and fewer landing areas than other ground-based systems such as whole tree harvesting (Bettinger and Kellogg 1993), and leads to more efficient wood recovery (McDonald and Seixas 1997). According to many studies (Tiernan et al. 2004; Ghaffarian et al. 2007; Spinelli and Magagnotti 2010), the efficiency of forwarder extraction is affected by numerous factors, the most important factor of them is travel distance (Sever 1988).

Manner et al. 2013 found that forwarded log concentration is influential on the forwarding time consumption. Productivity is also affected by the average assortment volume (i.e., number of pieces in the load) and quantity of timber on a felling site, which is more pronounced in thinning operations (Tufts and Brinker 1993; Tufts 1997). The largest time consumption of the forwarder work cycle is related to timber loading and unloading (Minette et al. 2004). A terrain slope higher than 30% considerably decreases the productivity of forwarders because vehicle mobility becomes limited (Zimbalatti and Proto 2010). The terrain slope of 25º is the upper limit for the efficient use of harvesters and forwarders due to their productivity decrease by 25-35% (Slugeň and Stoilov 2009). The so-called winch-assist system has significantly increased the ability to operate on steep slopes by up to 60% and avoid soil damage (Kuhmaier and Stampfer 2010, Visser and Stampfer 2015, Cavalli and Amishev 2017). However, there is still insufficient information to define all of the major positive or negative aspects of ground-based harvesting cable assist systems (Mologni et al. 2016).

The use of semi-tracks in conditions of limited soil bearing strength increases fuel consumption but provides increased vehicle mobility (Wästerlund et al. 2011). Forwarder efficiency also depends on its payload, as forwarders of higher capacity normally achieve lower costs and higher productivity per product unit (Jiroušek et al. 2007). Nurminen et al. (2006) reported that in central Finland, harvesting density, extraction distances, forwarder load capacity, timber assortment and bunching of assortments had significant effects on the productivity of the extraction systems.

Currently, there are no studies on the time consumption, productivity, and cost of the different concentrations of assortments – in small piles in the stand versus concentrated in greater piles roadside, on loading phase and on overall forwarder performance. This is necessary because forwarders often load assortments from large piles that are extracted by modified farm tractors, animals, etc.

The aim of this study was to evaluate forwarder operations in coniferous forests in Bulgaria. The specific objectives were: (*i*) to calculate production rates (m^3 h^{-1}) and respective costs (€ m^{-3}) of forwarding, (*ii*) to develop models of cycle time and productivity for forwarding, and (*iii*) to determine the most influential factors for each work phase, in particular, to assess the influence of concentration of assortments in piles of different sizes on loading and overall forwarder efficiency.

2. Materials and Methods

2.1. Study site and work organization

The study was conducted at two separate experimental sites: site A located in the Zemen Mountains, in the western part of Bulgaria; site B in the eastern Rhodope Mountains in southern Bulgaria. Fig. 1 shows the localization on the map of the study sites.

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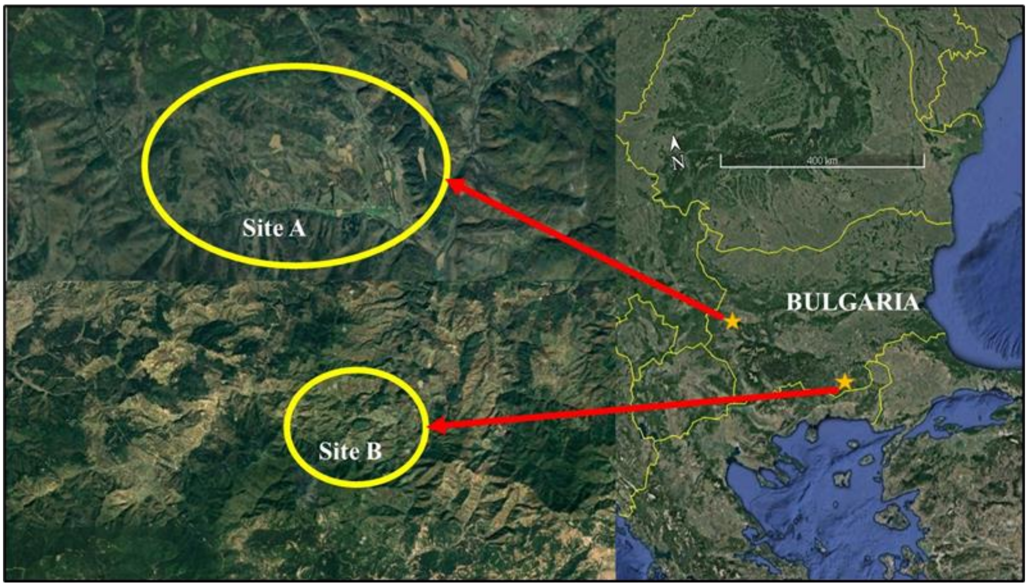

Fig. 1 Map and schematic layout of sites.

Table 1 shows the main information on the study sites and operations performed, while Figs. 2 and 3 show the subdivision into compartments of the two sites with the relative slope profiles of the land.

Table 1. Characteristics of the study sites.

Site	A				B
Machine (Forwarder)	Ponsse Gazelle				John Deere 1420
Province	Pernik				Kardzhali
State forest range	Zemen				Krumovgrad
Sub-compartment	38-e 42°35'06.23137" N, 22°38'55.45277" E	52-f 42°34'34.93277" N, 22°42'49.70729" E	52-sht 42°34'42.87212" N, 22°42'52.06309" E	56-m 42°34'50.07734" N, 22°42'57.66008" E	592-v 41°19'54.56" N, 25°36'39.25" E
Elevation (m)	1050	750	760	800	550
Species	SP 100%	SP 90%, IO 10%	SP 70%, IO 20%, TO 10%	SP 100%	SP 80%, AP 20%
Stand type	High forest plantation				
Operation type	Regular thinning and sanitary felling				Regular thinning and shelterwood cutting
Total area (ha)	1.1	1.2	1	16.1	22.2
Site volume ($m^3 \cdot ha^{-1}$)	236	192	190	222	336
Removal volume ($m^3 \cdot ha^{-1}$)	95	80	76	100	84
Average tree volume (m^3)	0.6	0.6	0.6	0.6	0.65
Average DBH (cm)	20	SP 20	SP 20	20	SP 24 cm; AP 30 cm
Average height (m)	16	SP 16	SP 16	16	SP 17 m, AP 16 m
Average slope (%)	23	51	29	31	34
Roughness	Medium				
Note: SP (Scots pine – *Pinus sylvestris* L.), AP (Austrian pine – *Pinus nigra* Arn.), IO (Italian oak – *Quercus frainetto* Ten.), TO (Turkish oak – *Quercus cerris* L.)					

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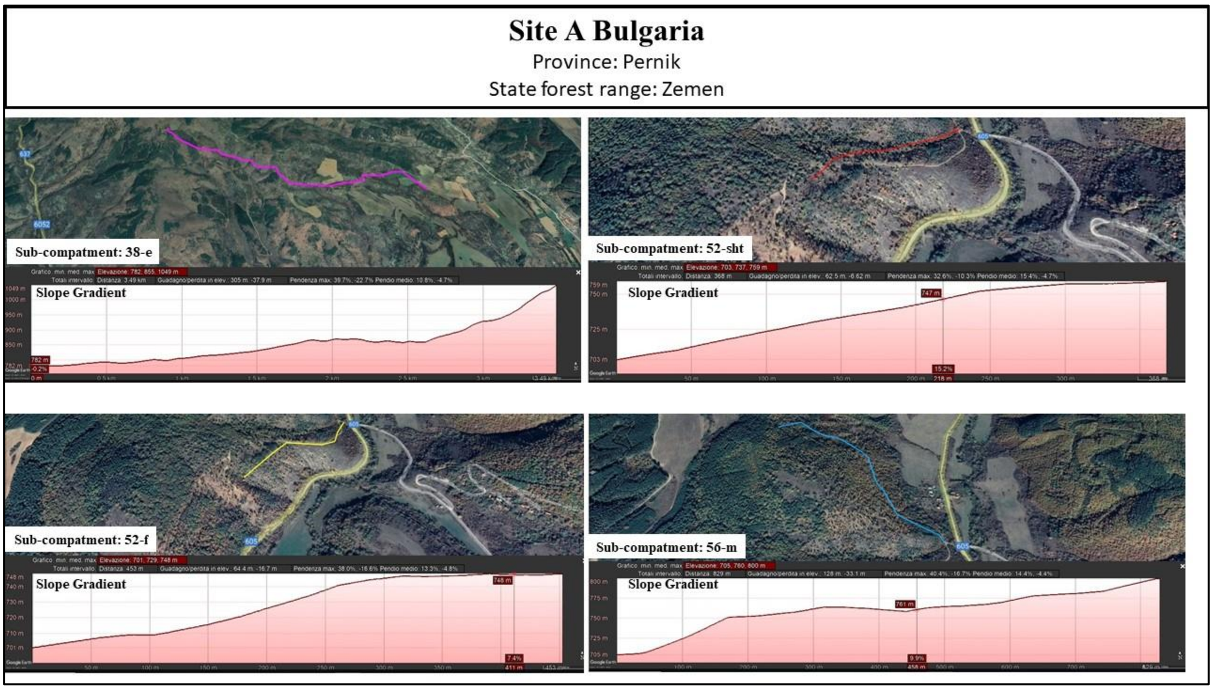

Fig. 2 Testing of study compartments and land profiles gradients for site A.

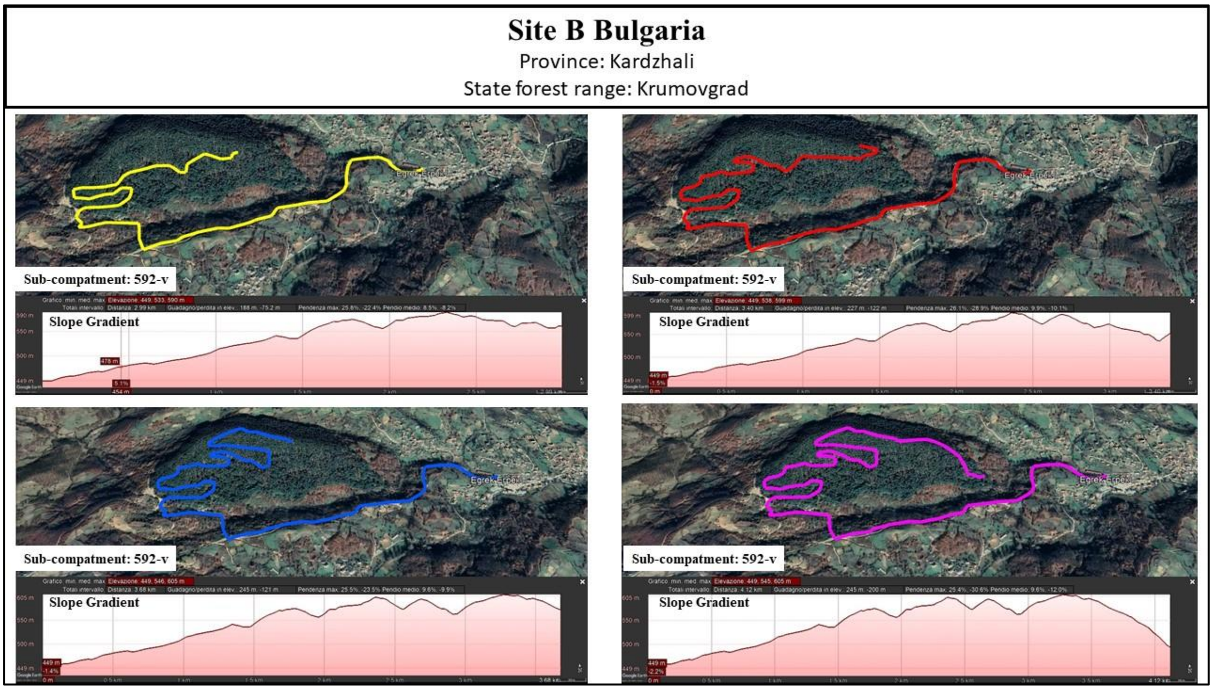

Fig. 3 Testing of study compartments and land profiles gradients for site B.

Trees were felled and cross-cut into assortments manually by a chainsaw or by a harvester. The extraction direction was downhill, where the Scots pine and Austrian pine assortments in sites A and B were transported by forwarders. The observations of the forwarder's activities were carried out on 30 work cycles (turns) for each machine: the Ponsse Gazelle forwarder (Ponsse Plc, Vieremä, Finland), shown in Fig. 4-A, operating in Site A, which includes sub-compartments 38-e, 52-f, 52-sht, and 56-m, and the John Deere 1420 forwarder (Deere & Company, Moline, USA) operating in site B in sub-compartment 592-v (Fig.4-B). The characteristics of the machines are presented in Table 2.

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Fig. 4 Tested forwarders (a) Ponsse Gazelle, (b) John Deere 1420.

Table 2. Technical data of the studied forwarders.

Features	Measurement unit	Value	
		Ponsse Gazelle	John Deere 1420
Engine power	kW	150	129.1
Max. torque	Nm	850	779.6
Cylinders	-	4	6
Number of wheels	-	8	8
Number of drive wheels	-	8	8
Max. travel speed	$km \cdot h^{-1}$	20	22
Total weight empty	kg	15400	17500
Max. load capacity	kg	10000	14000.2
Tyre size	-	600/50-22,5	700-26,5
Crane	-	K70+	CF 785
Gross lifting capacity	kNm	106	125
Max. reach lengths	m	10	7.8

2.2. Productivity study and costs

The purpose of the detailed time and motion study was to estimate the duration of work elements and productivity of the forwarders in the given conditions. A work cycle was assumed composed of repetitive elements (Nurminen et al. 2006, Proto et al. 2018b, Borz et al. 2021, Cataldo et al. 2022) as follows:

- ⇒ travel unloaded (TU) begins when work starts or when the unloaded forwarder drives from the landing to the felling area after unloading logs at landing;
- ⇒ loading (L) starts when the forwarder is at the side of the logs to be loaded, displacement stops, and the crane arm begins to move or the seat begins to turn in order to begin loading. This operation includes the time spent after the forwarder finishes loading the logs from one pile and moves to the next pile until the forwarder is fully loaded;
- ⇒ travel loaded (TL) begins when the bunk of the forwarder is full and the machine moves with the load to the landing;
- ⇒ unloading (U) starts when the forwarder uses the crane to unload the logs from its bunk at landing. This activity also includes the small movements required to sort the materials into piles;
- ⇒ delays (D) include personnel rest, personal delays, organizational delays, service, and repair.

The productive time was separated from the delay time. Forwarding distance and slope gradient of the road were found by the GPS receiver using Digital Terrain Model. Load volume was determined by measuring the length and the mid-length diameter of all logs (applying Huber's formula) in each load.

Machine costs were calculated using the COST model (Ackerman et al. 2014). In order to calculate the production cost for 1 m3 timber, the cost analysis employed the following parameters: the hourly cost for an operator, the hourly cost of the machine, the volume of extracted timber and productive machine hours (excluding all delay times). The machine cost per hour was reported both as productive machine hours (PMHs) excluding delays and scheduled machine hours (SMHs) including delays. The purchase price and operator wages required by the cost calculations were obtained from the accounting records

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(Proto and Zimbalatti 2016). Diesel fuel consumption was calculated using diesel fuel consumption norms. A salvage value of 10 % of the purchase price was assumed and the Value Added Tax (VAT) was excluded.

Cost calculations were based on the assumption that companies worked for 150 working days in a year and the depreciation period is 10 years. For extraction work, this amounts to 130–150 working days per year (20–21 working days per month) at an average of 6–7 scheduled working hours per day (assuming one to two hours spent on lunch, rest and other breaks). Thus, yielded annual working hours are 910–1050 SMHs with a 70% use coefficient (Spinelli and Magagnotti 2011, Spinelli et al. 2014, Proto et al. 2018a).

2.3. Data Analysis

Regression analysis was performed on the experimental data of both studied forwarders in order to develop prediction equations for estimating time consumption and productivity. The variables used in the modelling approach included forwarding distance *L*, load volume per cycle *V*, slope gradient of the skidding road *i*, the number of grips of assortments with the crane during loading *nl*, the number of grips of assortments with the crane during unloading *nun*, and the number of trees in a load *nas*. The statistical analysis consisted of the identification and exclusion of outliers, correlation analysis for independent variables with a correlation coefficient set at $R \geq 0.75$ as an acceptable threshold to exclude the independent variables from regression analysis for reasons such as the inflation of determination coefficients. The descriptive statistics of the variables were computed, and a stepwise backward regression procedure was used to model the variability of the cycle time and productivity as a function of independent variables. The confidence level used for regression analysis was 95 % ($\alpha = 0.05$) and the assumed probability $p < 0.05$. Independent variables are significant at $p < 0.05$, i.e., a strong presumption against the neutral hypothesis. To process the experimental data Statistica 8 (StatSoft Inc., Tulsa, OK, USA) software was used.

3. Results and Discussion

In Table 3 and Figs. 5 and 6 are shown the main descriptive statistics related to the time spent and extraction distances during field observations of the forwarding operations. The observations covered a total of 85.23 h, of which 33.54 h were recorded at site A, and 51.69 h at site B. During the studies, the forwarders extracted a total of 746.10 m^3 of timber, of which 295.00 m^3 was from site A and 451.10 m^3 from site B.

3.1. Work cycle time

In site A, the working cycle elements with largest duration were the operation of loading (34% and 32% respectively, excluding and including delays), followed by travel loaded (32% and 31% respectively, excluding and including delays), travel unloaded (26% and 25% respectively, excluding and including delays), and, at the end, the shortest one was unloading phase (8%). In site B, the arrangement of the work cycle elements in descending order of duration was different compared to site A, namely travel unloaded (40% and 37% respectively, excluding and including delays), travel loaded (37% and 35% respectively, excluding and including delays), loading (15% and 14% respectively, excluding and including delays), and the shortest one was unloading (8%). The breakdown by main groups of operations in delay-free cycle time in sites A and B shows the predominance of the movement (travel) of the forwarders with the larger share of 58% and 77% respectively, whereas loading and unloading occupy 42% and 23% respectively.

The data in Table 3 indicate that productive time in site A was 96% of the scheduled time (Fig. 5), and the delays in site B accounted for 6%. The delays in site A (4%) are due to organizational reasons (1%), mechanical delays (2%), and due to adverse weather conditions leading to the low accessibility of the stands (1%). The delays at site B are due to organizational reasons (4.5%), technical reasons (1%) and unfavorable weather conditions and poor access to the stand (0.5%).

Within the work cycle in site B travel unloaded occupies a 3% larger share than the travel loaded. This is perhaps due to the travel uphill, the difficult terrain in some places and the poor condition of some road sections.

Table 3. Descriptive statistics of the time consumption and operational distances.

Variables	Site A						Site B					
	Duration, min			Distance, m			Duration, min			Distance, m		
	Mean value ±SD	min	max	Mean value ±SD	min	max	Mean value ±SD	min	max	Mean value ±SD	min	max
Travel Unloaded (TU)	17.63 ±12.21	6	35	1783.33±1173.66	400	3500	38.67 ±12.21	29	51	3760.28 ± 283.71	3000	4120

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Loading (L)	22.70 ±4.28	12.00	30.00	19.63±4.65	11	28	14.16 ±0.54	12.00	15.00	11.37 ± 2.79	5	15
Travel Loaded (TL)	21.48 ±14.39	5	46	1783.33±1173.66	400	3500	36.29 ± 4.33	27	43.40	3760.28 ± 283.71	3000	4120
Unloading (U)	5.27 ±1.38	3.00	9				8.17 ±0.34	8.00	9.00			
Delays (D)	2.38 ±5.11	0	18				6.10 ±3.71	5.00	15.00			
Total cycle time	69.92 ±27.96	40	115				103.39 ±10.46	91.80	121.50			
Delay-free cycle time	67.08 ±28.03	40	112				97.29 ±10.78	76.80	116.50			
Number of grips of assortments with the crane grapple during loading per cycle	22.97 ±3.53	19	33				23.57 ±1.07	23	25			
Volume of assortments in the crane grapple during loading	0.44 ±0.06	0.29	0.52				0.64 ±0.03	0.60	0.72			
Number of grips of assortments with the crane grapple during unloading per cycle	8.97 ±0.81	8	12				14.10 ±1.12	12	17			
Volume of assortments in the crane grapple during unloading	1.10 ± 0.11	0.80	1.25				1.07 ± 0.08	1.07	1.25			
Cycle payload volume, m^3	9.83 ± 0.86	8	11.04				15.04 ± 0.06	15.00	15.20			
Productivity, m^3 per PMH*	10.43 ±4.17	4.53	16.50				9.38 ±1.05	7.73	11.72			
Productivity, m^3 per SMH*	9.93 ±3.99	4.36	16.50				8.81 ±0.89	7.41	10.80			
Number of cycles per SMH*	0.99 ±0.35	0.95	1.50				0.59 ±0.06	0.49	0.72			
Mean speed, $km \cdot h^{-1}$	5.48 ±1.36	3.75	9.36				6.08 ±045	5.24	6.72			
Speed loaded, $km \cdot h^{-1}$	5.07 ±1.59	3.33	10.22				6.25 ±0.32	5.70	6.84			
Speed unloaded, $km \cdot h^{-1}$	6.27 ±1.68	4.29	10.50				5.92 ±0.56	4.85	6.61			

Note: * SD – standard deviation, PMH – productive machine hour, SMH – scheduled machine hour

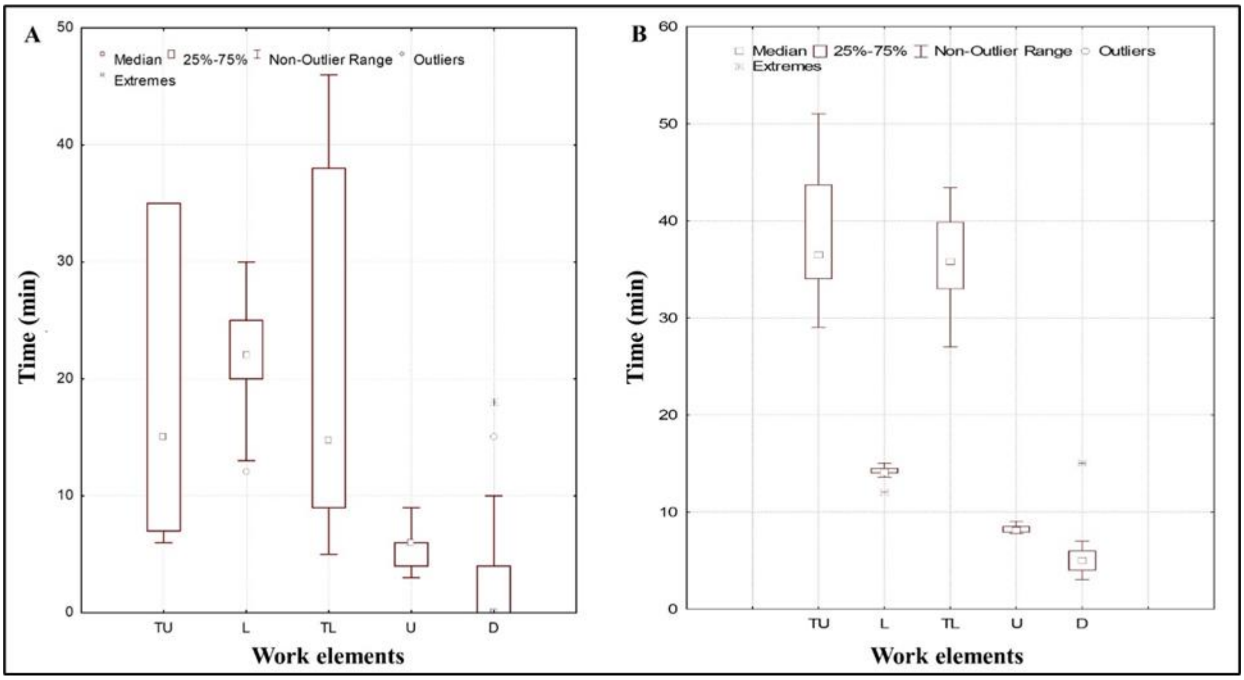

Fig. 5 Elemental time consumption of forwarders in both sites. (A) Site A, (B) Site B. (TU: Travel unloaded; M: Maneuvering; OH: Outhaul of line and hook; I: Inhaul of timber; L: Loading; TL: Travel loaded; U: Unloading; D: Delays)

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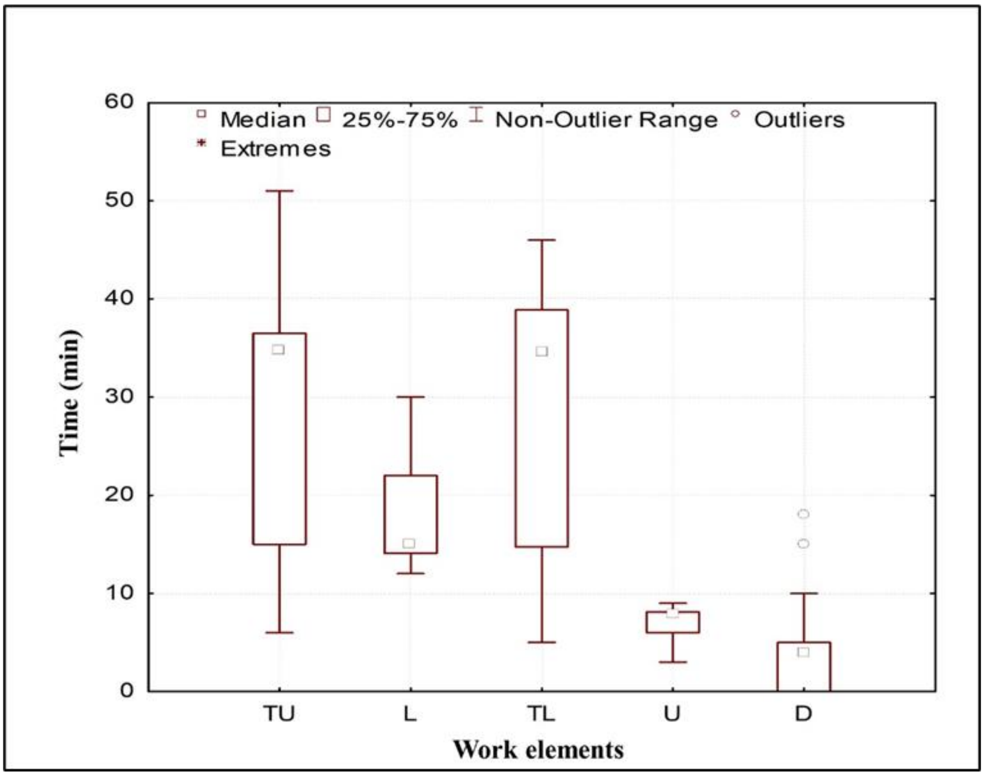

Fig. 6 General elemental time consumption of forwarders. (TU: Travel unloaded; M: Maneuvering; OH: Outhaul of line and hook; I: Inhaul of timber; L: Loading; TL: Travel loaded; U: Unloading; D: Delays)

Impressive is the fact that the share of loading in Site B (15% in the delay-free cycle time) is 44% of that of Site A (34% in the delay-free cycle time), as it was characterized by piles 1 m high, located at the roadside. In terms of the ratio of the assortments found during loading and unloading in the forward grapples at the two sites, the data indicate that their volume during loading averaged 39.5% at site A and 59.6% at site B of those at unloading. Obviously, the conditions when unloading assortments from the forwarder bunk using the crane are similar for both machines, therefore the difference in the volumes of timber in the grapples during loading and unloading is due to the different concentrations of assortments in site A, and in site B. It was seldom necessary for the forwarder in site B to leave the road and move along the terrain in the cutting area. In terms of duration in site A, the loading operations, due to frequent movement of the forwarder between the small piles, is almost twice as long as the unloading.

The mean duration of the delay-free work cycles in sites A and B were 67.08 min and 97.29 min respectively, whereas the mean durations of the work cycles including delays were 69.92 min and 103.39 min respectively. Thus, in the given conditions per 8 h-shift in site A the forwarder made 6-7 (mean 6.9) work cycles (turns), and in site B – 4-5 (mean 4.69) work cycles (turns).

The regression analysis was done on the time-study data in both sites in order to develop prediction equations for estimating the forwarder cycle time by excluding and including delays both shown in Table 4.

Table 4. Summary of the work cycle time models.

Equations		F	R^2	R^2_{adj}	Std. Error	p-Value
$T_{net,A}$ =27.58 +0.22·L, min	(1)	172.24	0.86	0.86	10.67	$p < 0.05$
T_A= 60.61+0.023·L, min	(2)	142.08	0.91	0.91	8.53	$p < 0.05$
$t_{l,A}$=35.02 – 30.86 $V/n_{l,A}$, min	(3)	46.46	0.44	0.44	3.95	$p < 0.05$
$t_{ul,A}$=5.19 – 0.50·V – 4.29 $V/n_{l,A}$, min	(4)	52.32	0.65	0.64	1.07	$p < 0.05$
$T_{net,B}$ = 0.93·n_{ul}+0.041·L + 3.05·i, min	(5)	140.63	0.93	0.91	2.15	$p < 0.05$
T_B =0.037·L+3.46·i, min	(6)	31.41	0.87	0.84	4.19	$p < 0.05$
T_{net} =34.72 +0.023·L +2.10·i– 50.11·V/n_l, min	(7)	159.38	0.90	0.89	8.64	$p < 0.05$
T= 36.99 +0.024·L +1.68·i – 43.88·V/n_l, min	(8)	129.89	0.94	0.93	7.16	$p < 0.05$

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t_l= 26.62 + 0.27·l – 23.11·V/n_l, min	(9)	28.76	0.50	0.48	3.77	p < 0.05
t_{ul}= 0.50·n_{ul}, min	(10)	94.84	0.62	0.61	1.10	p < 0.05

In equation (1) the minimum duration of delay-free cycle time $T_{net,A}$ (site A) may be attained in the case of short forwarding distances L and small number of grips during loading n_l, i.e., a large volume of assortments in the grapple of the crane. The regression equation (2) presents a cycle time including delays T_A in which forwarding distance has a similar influence as in equation (1). The loading time in site A (Eq. 3) decreases with an increase in the ratio between the payload volume of the forwarder and the number of grips of assortments with the crane grapple during loading per cycle, respectively the volume of assortments gripped in the grapple. The unloading time (Eq. 4) depends on the payload volume of the forwarder and the number of grips of assortments with the crane grapple during unloading per cycle; it will be minimal when increasing the ratio between these two factors. In equation (5), a minimum delay-free cycle time $T_{net,B}$ (site B) will result in the case of short forwarding distances L, but also decreased the number of grips of assortments with the crane grapple during unloading per cycle n_{ul} and road gradient i. In site B, the cycle time including delays T_B given by equation (6) depends on forwarding distances L and road gradient i, and it will decrease as the values of these factors decrease.

Generally, the cycle times, excluding or including forwarder delays, according to equations (7) and (8) respectively, decrease in cases when the forwarding distance L is at a low level, and the ratio between the payload volume of the forwarder and the number of grips of assortments with the crane grapple during loading or unloading per cycle, respectively, are at a high level.

Reducing loading distance l, and increasing the ratio between the payload volume V of the forwarder and the number of grips of assortments with the crane grapple during loading per cycle n_l will shorten the loading time (Eq. 9). However, the unloading time (Eq. 10) can be shortened by reducing only the number of grips of assortments with the crane grapple during unloading per cycle n_{ul}, i.e., increasing the volume of the assortments in the grapple during unloading.

3.2. Productivity analysis

The mean forwarder productivity in site A obtained from a mean forwarding distance of 1780 m, a mean load volume of 9.83 m^3, and a mean number of grips of assortments with the crane grapple during loading n_l of 22.97 per cycle (turn) and during unloading n_{un} of 8.97 per cycle (turn) is 10.43 m^3·PMH^{-1} and 9.93 m^3·SMH^{-1}, respectively (Table 3). These productivity rates are higher than that registered by the forwarder operated in site B (9.38 m^3·PMH^{-1} and 8.81 m^3·SMH^{-1}, respectively), but under more than two times longer mean forwarding distance of 3760 m, larger mean load volume of 15.04 m^3, and a number of grips of assortments with the crane grapple during loading n_l, and during unloading n_{un} of 23.57 and 14.10 respectively per cycle (turn) (Table 3).

Although many studies (Sever 1988, Raymond 1989, Valenta and Neruda 2004) have shown that the most important factor influencing forwarding productivity was draw distance and load volume, in this study the doubled distance at site B had little influence on productivity. This was likely caused by concentration in larger stacks which results in a higher volume at site B and therefore in high productivity despite the long distance. Such a phenomenon has also been observed in other studies. Strandgard et al. (2017), Holzfeind et al. (2018) and Hildt et al. (2020), showed that extracting logs with higher mean volume consumed less time than logs with smaller volumes as larger logs require fewer gripper movements to complete the load. The results from Sweden reported by Erikson and Lindroos (2014) shown the mean productivity of the forwarding work in final felling was 21.4 m^3·PMH^{-1} and in the thinning operations was 12.9 m^3·PMH^{-1} but at extraction distance 2-5 times shorter than these found in this study. The average forwarding production in Southern Austria was estimated to be about 17.9 m^3 per productive system hour, while the mean load per trip was 10.04 m^3, but the average forwarding distance was only 97 m (Ghaffariyan et al. 2007).

The ratio between the number of grips of assortments with the crane grapple during loading and unloading in site A is in a mean of 2.56, but in site B is significantly smaller – on average 1.67, due to the larger number of assortments in the grapple when loading from large piles. This ratio characterizes the concentration of assortments in the stand. Concentration in larger piles results in a larger volume of assortments grappled by crane, and hence, lower time for loading of the forwarder and higher productivity. As also identified by Tufts (1997) and Tufts and Brinker (1993) productivity was also affected by the average assortment volume (i.e., number of logs in the load) and quantity and concentration of timber on a felling site.

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Delay-free forwarder productivity of site A was defined by the regression equations (11) and (12) shown in Table 5. From equation (11), the increase in delay-free productivity of the forwarder in site A is a consequence of increasing the payload volume V and decreasing the forwarding distance L. The effect of these two factors on productivity with delays is similar (Eq. 12).

According to equation (13), to increase the delay-free productivity of the forwarder in site B, the payload volume V should be increased, whereas the number of grips of assortments with the crane grapple during unloading n_{un}, forwarding distance L, and road slope gradient i should be decreased. The productivity including delays in site B should be raised by increasing the forwarding distance L and decreasing the road slope gradient i (Eq. 14). Generally, the productivity of forwarders in both sites, excluding delays (Eq. 15) and including it (Eq. 16), can be increased in cases when the forwarding distance L is at a low level, but the ratio between the payload volume of the forwarder and the number of grips of assortments with the crane grapple during loading be maximum.

Dispersion of small piles of assortments results in a smaller volume grapple and a greater number of crane cycles and loading distance and generally increases loading time. The larger volume of assortments in the crane's grapple and the shorter loading distance when loading from larger piles roadside result in less loading time. Moreover, as observed in recent studies (Nurminen et al. 2006, Stankic et al. 2012, Manner et al. 2013; Hildt et al. 2020), the number of logs along the strip roads in thinning, required a higher number of travels between log piles to complete the load in each work cycle.

Table 5. Summary of the productivity models.

Equations		F	R^2	R^2_{adj}	Std. Error	p-Value
$P_{PMH,A} = 1.24 \cdot V - 0.0026 \cdot L$, $m^3 \cdot h^{-1}$	(11)	121.58	0.93	0.93	1.13	$p < 0.05$
$P_{SMH,A} = 1.14 \cdot V - 0.003 \cdot L$, $m^3.h^{-1}$	(12)	193.86	0.93	0.93	1.06	$p < 0.05$
$P_{PMH,B} = 1.79 \cdot V - 0.087 \cdot n_{ul} - 0.0039 \cdot L - 0.20 \cdot i$, $m^3 \cdot h^{-1}$	(13)	233.47	0.97	0.97	0.18	$p < 0.05$
$P_{SMH,B} = 0.003 \cdot L - 0.25 \cdot i$, $m^3.h^{-1}$	(14)	32.22	0.87	0.84	0.35	$p < 0.05$
$P_{PMH} = 3.46 - 0.0026 \cdot L + 17.85 \cdot V/n_l$, $m^3 \cdot h^{-1}$	(15)	120.70	0.81	0.80	1.36	$p < 0.05$
$P_{SMH} = 6.99 - 0.0026 \cdot L + 17.60 \cdot V/n_l$, $m^3 \cdot h^{-1}$	(16)	184.21	0.87	0.86	1.09	$p < 0.05$

3.3. Travel speed

The mean travel forwarder's speeds were 5.48 km·h^{-1} (site A) and 6.08 km·h^{-1} (site B) (Table 3). The mean speeds with and without load were in site A 5.07 km·h^{-1} and 6.25 km·$h^{-1}$and in site B 6.25 km·h^{-1} and 5.92 km·h^{-1}, respectively. These speeds were within those reported by Proto et al. (2018b) where the average speed for travel empty was 6.68 km h^{-1} at the site in Calabria (Italy), and 3.77 km h^{-1} and 6.90 km h^{-1} in two sites in New Zealand, respectively. For travel loaded the average speed mentioned by the same paper was 3.75 km·h^{-1} at the site in Calabria, and 3.68 km·h^{-1} and 6.17 km·h^{-1} for New Zealand test areas, respectively.

In this study the speeds of the forwarder with load and without load were very similar, and Hildt et al. (2020) confirmed the same trend in similar conditions with an average speed equal to 4.3 km h^{-1}. The lack of correlation between the speed and the load volume for the loaded travel showed that the weight of the load was not a limiting factor under the conditions of this study. Similar speed of empty and loaded travel could be due to a good soil bearing capacity, and a soft relief with low slope and with no rocks that would make difficult the movement of any forwarder size (Stankić et al. 2012). Theoretically, the movement time of a forwarder could be reduced by increasing the travel speed loaded and unloaded, but in sites A and B the terrain and road conditions practically do not allow a significant increase in travel speed.

3.4. Cost analysis

Cost calculations were based on the assumption that companies worked all year round with the exception of adverse weather conditions (heavy rain, deep snow, thick fog) when cutting areas are not normally accessible by a wheeled skidder.

The hourly fixed operating (variable) costs of the studied forwarders and the labor cost of the operator are shown in Table 6 and Fig. 7. The gross costs for forwarders were calculated at 65.14 € per productive machine hour (PMH) in site A, and 72.96 €·PMH^{-1} at site B. Thus, when the forwarders were productive, the costs were at 6.35 €·m^{-3} and 7.90 €·m^{-3}, in site A and site B respectively. The increase in the productive time of both forwarders would lead to a decrease in gross costs.

Table 6. Characteristics of costs of the studied forwarders.

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Costs	Site A		Site B	
	Costs per PMH, €	Costs, €·m^{-3}	Costs per PMH, €	Costs, €·m^{-3}
Fixed costs	12.81	1.23	15.78	1.68
Variable costs	24.64	2.46	28.14	3.11
Labor costs	17.92	1.72	17.92	1.91
Net costs (excluding profit)	55.37	5.41	61.84	6.70
Overheads and management costs	3.85	0.37	4.49	0.48
Profit	5.85	0.58	6.63	0.72
Gross costs (including profit)	65.14	6.35	72.96	7.90

In the distribution of the net costs of forwarders operated in site A and site B (Fig. 7), variable costs predominated, followed by labor costs and fixed costs. Overall, the net cost distribution across the two sites was very close.

Proto et al. (2017) calculated the extraction costs at 3.40 €·m^{-3} and 4.50 €·m^{-3} at a mean extraction distance of 306 m and 597 m in two stands in southern Italy, which was lower than the costs we found at more than 5-time longer extraction distances.

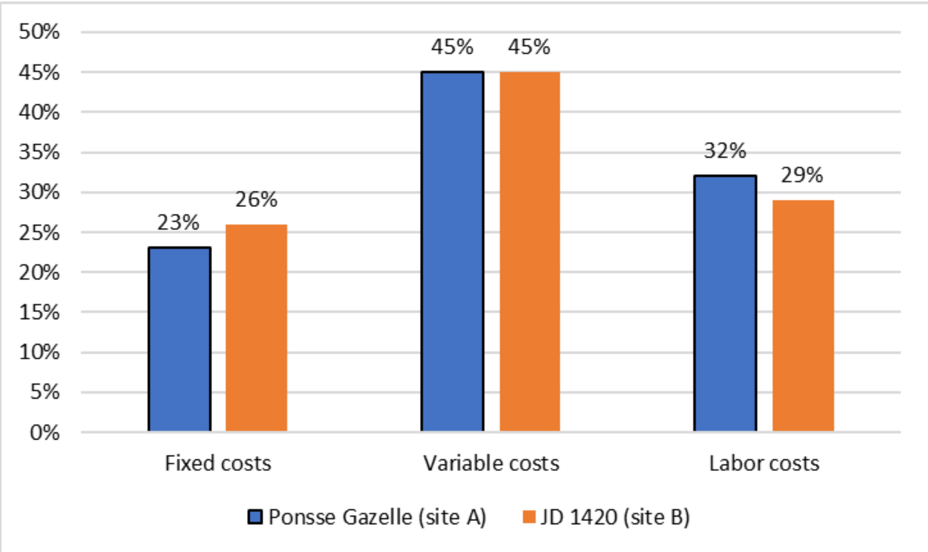

Fig. 7 Percentage distribution of forwarder's net costs.

4. Conclusions

The cut-to-length (CTL) harvesting chain has been studied periodically over the last few decades. In Bulgaria forwarders often load assortments of large piles that are extracted by modified farm tractors and animals. In addition, Bulgarian forest territories are characterized by steep terrains and small dimensions of most cutting areas. Currently, there are no studies on the time consumption, productivity and cost of the different concentrations of assortments – in small piles in the stand versus concentrated in greater piles roadside, on the loading process and on overall forwarder performance. The obtained results can contribute to the database of the productivity of forwarders in mechanized harvesting operations in Bulgaria and in particular also in the management of the Bulgarian forest industry. In fact, the scattering of small stacks of assortments results in a smaller grip volume and increased number of crane cycles and load distance and generally increases load time. The handling of logs in larger piles along the road and the greater volume of assortments in the crane grapple associated with shorter loading distances translate into shorter loading times and higher productivity. The results obtained from this first study in the Bulgarian territories could help predict and plan better productivity of the system under similar conditions and characteristics.

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Authors' contribution

SFP, SS, PV, GA and ARP: Designed the study, contributed to revise the manuscript. SFP, SS, PV, GA: performed research and carried out the experiments. SFP, SS, MFC and ARP: Wrote and revised the manuscript.

Conflicts of Interest

The author declare no conflict of interest.

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Authors' addresses:

Salvatore F. Papandrea
e-mail: salvatore.papandrea@unirc.it
Maria Francesca Cataldo, PhD.*
e-mail: maria.cataldo@unirc.it
Assoc. Prof. Andrea R. Proto, PhD.
e-mail: andrea.proto@unirc.it
Mediterranean University of Reggio Calabria
Department of AGRARIA
Feo di Vito snc, 89122 Reggio Calabria, Italy
89122, Reggio Calabria
ITALY

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e-mail: crojfe@sumfak.hr

Assoc. Prof. Stanimir Stoilov, PhD.
e-mail: stoilovs@ltu.bg
Pavel Nichev
e-mail:
Assist. Prof. Georgi Angelov, PhD.
e-mail: ggangelov@ltu.bg
University of Forestry
Department of Technologies and Mechanization of Forestry
Kliment Ohridski Blvd. 10
1756, Sofia
BULGARIA

* Corresponding author

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4.7 Ergonomic Condition in Forest Operations

Article 6

Postural Assessment of Three Wood Measurement Options by the OWAS Method: Digital Solutions Seem to Be Better

Stelian Alexandru Borz [1], Salvatore F. Papandrea [2,*], Marina Viorela Marcu [1], Jacopo Bacenetti [3] and Andrea R. Proto [2]

[1]Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Şirul Beethoven 1, 500123 Brasov, Romania; stelian.borz@unitbv.ro (S.A.B.); viorela.marcu@unitbv.ro (M.V.M.)

[2]Department of AGRARIA, Mediterranean University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy; andrea.proto@unirc.it

[3]Department of Environmental and Policy Science, Università degli Studi di Milano, Via Celoria 2, 20133 Milan, Italy; jacopo.bacenetti@unimi.it

[*]Correspondence: salvatore.papandrea@unirc.it; ORCID: 0000-0002-2974-7760 Tel.: +39 (0)965-169-4202

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Article

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Stelian Alexandru Borz [1], Salvatore F. Papandrea [2,*], Marina Viorela Marcu [1], Jacopo Bacenetti [3] and Andrea R. Proto [2]

1 Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Şirul Beethoven 1, 500123 Brasov, Romania
2 Department of AGRARIA, Mediterranean University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy
3 Department of Environmental and Policy Science, Università degli Studi di Milano, Via Celoria 2, 20133 Milan, Italy
* Correspondence: salvatore.papandrea@unirc.it; Tel.: +39-096-5169-4275

Abstract: Ergonomic assessment and validation are important in designing sustainable forest operations. Measurement and grading play a central role in the wood supply chain and updated solutions have started to emerge for such activities. Procuring biometric data by mobile scanning platforms has been shown to have a high potential in replacing traditional wood measurement methods, but no assessments were carried out to see if these solutions are sustainable from an ergonomics point of view. Based on more than 63 k still images, this study evaluates the working postures of three measurement options, namely, traditional measurement, scanning by a smartphone, and scanning by a commercial laser scanner. The OWAS method was used as an assessment framework to compute the postural risk indexes. A correspondence analysis was implemented to explore the association between the studied work tasks and severity of exposure, and the postural similarity of tasks was evaluated by the Canberra metric. The use of digital measurement solutions seems to be better from a postural point of view since their risk indexes were well below 200. In contrast, traditional wood measurement tasks produced postural risk indexes that were close to 250. By considering the body components, digital measurement solutions seemed to indicate a distinct postural profile. Moreover, the digital solutions stood well apart in the range of the first two action categories, indicating no urgent need for postural improvement, which was not the case for manual measurements. The main conclusion of the study is that state-of-the-art digital solutions are better from a postural point of view. For full validation, population-level studies should be carried out.

Keywords: wood supply chain; ergonomics; digitalization; wood measurement; sorting; scanning; postural analysis; risk

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1. Introduction

Wood measurement and grading are essential activities in the wood supply chain, mainly because they provide quantitative and qualitative information for commercial transactions [1,2]. In addition, they support other relevant processes such as the conformity checking and traceability of wood products [3,4], being practiced in several points along the supply chain, which include the forest, roadside, and the sawmill's gate. Traditionally, wood measurement and grading have been conducted by manual means which require the use of forestry calipers and tapes, while the development and implementation of new wood measurement means depend on the level of available technology, standards used at the country or regional scales, and local forestry practices [5–7].

Still, in many regions of the world the wood is manually measured, an approach which may suppose a considerable effort in handling the required equipment, as well as poorer ergonomic conditions in terms of postures taken by the workers. Although there is no available data to characterize the postures taken in manual measurement of the wood, several studies have found that operations characterized by a low mechanization degree are challenging from this point of view [8–12]. In addition, wood measurement should benefit from updates in technology, whose implementation is now seen as an important component of ergonomic sustainability in forest operations [13,14]. However, the introduction of new technology itself in operations seems to be challenging [14] and needs ergonomic assessment and validation with the aim of checking whether it will provide at least a similar if not a better work environment.

A promising alternative to manual measurement is the use of platforms which operate by proximal remote sensing in collecting the data required to characterize the biometry of logs. On the one hand, this is because the use of such platforms was found to provide accurate data [4,15], while enabling other functions which are important in the wood supply chain [3,4]. On the other hand, their use was found to be comparable in terms of resources spent with that of manual measurement, while being able to provide an important economy of scale in terms of resources used [3]. Altogether, these features could contribute not only to their reliability and responsivity but also to their cost effectiveness.

There are many methods that could be used in the postural assessment, of which the observation-based assessments were described to be versatile in providing the basis needed for establishing priorities for intervention [16]. One of them is the Ovako Working posture Assessment System (OWAS) method, which holds the ability to measure deviation from normal (natural) body postures, being relatively simple to use, and having the capability of evaluating the whole body [17,18]. The method can be characterized as being flexible since the data collected by its use supports intra- and inter-task comparisons, either by implementing statistical tests [8,10] or by using similarity metrics [19]. In turn, such comparisons are helpful in understanding the changes brought by a new way of carrying out work, as compared with the way in which it is currently conducted. In addition, the method supports the calculation of a postural risk index (PRI), which is based on the frequency of observations in four action categories [20], providing the means for deciding the most appropriate actions to be taken for postural improvement. Similar to other postural assessment methods, OWAS was designed to characterize the risk of exposure to musculoskeletal disorders [16], serving as an important tool for distinguishing between the potential hazards brought by various types of tasks or ways of doing work.

The literature on forest operations is relatively abundant in ergonomic assessments by considering various types of exposure, and an important share of them are implemented as postural evaluations [21]. However, to the best of our knowledge, wood measurement was not evaluated by dedicated studies, even though such operations may expose the workers to risks, given the way in which they are implemented. For instance, when the logs are located on the ground, manual measurements could suppose a frequent bending of the back because they require a direct contact between the instruments used in measurement and the logs. In contrast, scanning by mobile, proximal-sensing platforms excludes the necessity of a direct contact; however, the use of some platforms may require uncomfortable postures to cover the logs by scanning when directing the sensing devices towards the place at which they meet the ground. Last, but not least, the exposure to potentially harmful working postures may depend to a certain extent on the behavior of the workers.

To document the efficacy of proximal-sensing platforms in wood measurement, a project [22] has been implemented since 2021. A core component of the project is the evaluation of postural conditions in such activities. Although this study documents the postural condition in wood measurement of both manual and proximal sensing methods, the main goal is to check if the latter meet the postural sustainability criteria in terms of risks. The objectives of the study are to (i) characterize the postures of the main body parts, (ii) characterize the association between the relevant measurement tasks and their postural condition, and (iii) check the postural similarity between the manual and proximal-sensing wood measurement methods.

2. Materials and Methods

2.1. Study Location and Measurement Instrumentation

The field phase of the study accounted for a total of 5 days, and it was implemented between 7 to 10, and 13 July 2021, in a wood storage facility located in Firiza (47°42′58.28″ N—23°37′05″ E, 325 m a.s.l.), which is managed by the Regional Forest Directorate of Maramureş, a branch of the National Forest Administration—RNP Romsilva. The facility is used to store the broadleaved and coniferous wood harvested from the surrounding forests until selling it to the final customers. During the field phase of the study, each log was measured three times, once manually, a second time by using a professional laser scanner, and finally by scanning by a smartphone (Figure 1). Prior to implementing the measurement activities, groups were formed from broadleaved logs placed at distances of 1 to 1.5 m from each other. The logs were selected so as to reflect the variability in length, which was between approximately 4 and 12 m.

(**a**) (**b**) (**c**) (**d**)

Figure 1. Examples from the operations taken into study: (**a**) log marking; (**b**) manual measurement; (**c**) scanning by a smartphone; and (**d**) scanning by a professional platform.

Manual measurement was designed to take the diameters of the logs at a 0.5 m interval, as well as to measure their lengths and mid-diameters. It was carried out in two steps, firstly by marking the logs by spraying, which required the use of a forestry tape, and then by measuring their diameters with a caliper. Diameter and length data were noted on a

A second measurement was taken by a mobile laser scanner (Zeb Revo, GeoSLAM, https://geoslam.com/; accessed on 10 September 2022) which supports the simultaneous localization and mapping (SLAM) technology. The instrument is typically carried in a backpack, and the scanning sensor is integrated in an external device which is handled by the operator during scanning. Using this instrument, the measurements were taken by a movement that started and ended at the same location, which aimed at surrounding the groups of logs by scanning. The third measurement was taken by a smartphone (Huawei P40 Pro, Huawei, Shenzhen, China) running a copy of the Forest Design (https://forestdesign.ro/index.php/ro/; accessed on 10 September 2022) Scanner application (FD Scanner) which was designed for wood scanning applications. More detailed descriptions of the platforms, as well as of the software used can be found in [3].

2.2. Data Collection

The data needed for this study were collected externally, in the form of high-resolution video files by a GoPro Hero 5 (GoPro Inc., San Mateo, CA, USA, https://gopro.com/en/us/, accessed on 10 September 2022) video camera which was successively placed at locations from where all the measurement activities were framed in its field of view. To extend its battery life, the device was connected to an external power source and it was set to collect video files of ca. 18 min each, in a continuous mode. A number of 37 video files were collected accounting for a total duration of approximately 9.5 h, and they were initially stored on a memory card, then downloaded and ordered into a computer at the end of each observation day. Three researchers of the Hypercube 4.0 project carried all the measurement tasks and were considered the subjects (S1–S3) of the study.

2.3. Data Processing

The collected video files were used to extract still images at a rate of one second using the software Free Video to JPG Converter (DVD Video Soft Ver. 5.0.101.201, Roseau, Dominica), then each image was analyzed one to three times depending on the subject identified in the field of view, resulting in a number of 66,638 still images taken into analysis. These images were analyzed at a detailed task level according to the OWAS method. This was done by tracking and recording the tasks by codes as shown in Table 1, then the codes were given to the main body parts according to the method [17,18,23]. The images that failed to provide the necessary data for evaluating the posture of all the body parts were excluded from analysis, and the force exertion was coded in all cases by 1 (Table 2, F1), given the specificity of tasks taken into study.

After the exclusion of the non-useful images, the dataset used to achieve the objectives of the study contained a number of 63,744 images. Following their analysis, it was identified that scanning by the mobile laser scanner (MS) was done only by S1, while marking the logs by paint (LM) was done by S1 and S2. Manual measurement of the diameters (MM), moving (MV), delays (DE), and preparing the tasks (PR) were identified for all subjects, while scanning by the smartphone (PS) and writing the data (WR) were identified only for subjects S2 and S3.

The coded data were stored in a Microsoft Excel ® (Microsoft, Redmond, WA, USA, 2013 version) sheet by considering the dates of field observation, name of the subjects, image number (assimilated to the second of extraction from the movie files), task codes (Table 1), codes attributed to body parts (Table 2), as well as codes of the action categories as described by the used method. The codes given to action categories were computed automatically by running a procedure developed in Visual Basic for Applications ® (Microsoft, Redmond, WA, USA). More detailed descriptions of the OWAS method, as well as information on its implementation, may be found in [17,18,20,23,24].

To support the statistical analysis, the data were sorted on the main tasks, then two contingency tables were developed to characterize the frequency of data at the task level by considering the codes given for the postures of the body parts, as well as the codes computed for the action categories. Data sorted on tasks served for estimating the relative frequencies of the body parts postures, relative frequencies on action categories, and for the computation of postural risk indexes as described in [20]. Contingency tables served as inputs for the correspondence analysis, and for checking inter-task similarity.

Table 1. Description of the main observed tasks following the OWAS analysis.

Task	Abbreviation	Description
Scanning by the mobile laser scanner	MS	Moving with the scanner carried on the backpack around the logs by starting and ending the movement at the same location while directing the scanning sensor by hand towards the logs.
Marking the logs by paint	LM	Placing a forestry tape on the log, marking the log by spraying a line on the upper part at each 0.5 m, spraying a dot at the middle of the log, and spraying the remaining length at one end, when it was less than 0.5 m. The task includes the movements of the operator along the log.
Measuring the diameters manually	MM	Using a caliper to take the diameters at the marked locations by placing it with the arms downwards in a vertical plane over each mark. The task includes movements of the operator along the log.
Moving	MV	Any other movement made by an operator to access a new log or log groups as well as those movements which were needed to complete the measurement tasks.
Delays	DE	Any other event not related directly with the measurement tasks such as resting, eating, talking, and personal necessities.
Scanning by smartphone	PS	Moving with the smartphone held in hand around the log while directing the scanning sensor towards the log. The task includes the activities of setting up the application and saving the data after each scan.
Preparing the tasks	PR	Any other event related to the implementation of measurement activities such as preparing the scanning devices.
Writing data on a field book	WD	Writing down the data on log diameters and lengths.

Table 2. The OWAS framework used to attribute postural codes to the main body parts.

Body Segment Code [1]	Description
B1	Back straight
B2	Back bent forward or backward
B3	Back twisted or bent sideways
B4	Back bent and twisted or back bent forward and sideways
A1	Both arms below shoulder level
A2	One arm is at or above the shoulder level
A3	Both arms are at or above the shoulder level
L1	Sitting
L2	Standing with both legs straight
L3	Standing with the weight on one straight leg
L4	Standing or squatting with both knees bent
L5	Standing or squatting with one knee bent
L6	Kneeling on one or both knees
L7	Walking or moving
F1	Weight or force needed is less than 10 kg
F2	Weight or force needed exceeds 10 but is less than 20 kg
F3	Weight or force needed exceeds 20 kg

[1] Note: B stands for the posture of back, A stands for the posture of arms, L stands for the posture of legs, and F stands for force exertion. In the database, the coding procedure excluded the letters from the codes.

2.4. Data Analysis and Software Used

Data analysis was implemented in four steps. A first step was that of estimating the relative frequency distributions on body part postural codes, which was based on their absolute frequencies and the number of valid observations used for each task. The relative frequency distributions were developed to characterize the differences in terms of body part postures between the observed tasks. A similar approach was taken to compute the relative frequencies on action categories which were then used to compute the postural risk indexes (PRIs) of the observed tasks, standing for the second analytical step.

Dependencies in postural, action category data, and observed tasks were mapped in a dimensionality reduction approach by implementing a correspondence analysis (CA), which was the third analytical step of this study. Correspondence analysis is similar in function to principal component analysis (PCA) but fits better to categorical data. Mapping the variability in a lower number of dimensions by CA is helpful in understanding the trends in data and in observing the associations of the data profiles, which is typically evaluated by a χ^2 test for independence. The worked example given in [25] as well as the explanations given in [26,27] were used to run the correspondence analysis in Microsoft Excel ® under the Real Statistics add-in in the software [28]. Frequency data on postures of the body parts (14, column profiles) mapped against the observed tasks (8, row profiles) formed a contingency table with a dimensionality of 14×8, while the frequency of data on action categories (4, column profiles) coupled with that of the observed tasks (8, row profiles) formed a contingency table with a dimensionality of 4×8. The aim of CA was to understand which body part postures and which action categories associate more frequently with the observed tasks, hence to characterize the tasks in terms of body postures and action categories, assuming that there would be a difference between them, by lowering the number of dimensions and still preserving a high proportion in variability explained. In CA, choosing the number of dimensions is usually based on the inertia and explained variance.

The last analytical step of the study was that of pairwise checking the similarity of tasks, which was implemented by considering the absolute frequencies of action categories on the observed tasks. For this step, the Canberra metric was used as a measure of dissimilarity ($1 - CM$ stands for the similarity metric). The procedural steps, advantages, and limitations of using similarity metrics in comparing the body postures in the framework of the OWAS method are given elsewhere [19], from where the main methods used for similarity checking were adapted. Definition and mathematical formulation of the Canberra metric may be found, for instance, in [29,30].

3. Results

3.1. Statistics of the Postural Data

Table 3 shows the relative frequencies in terms of postures of the body parts by considering the 8 observed tasks. For example, MV and DE tasks were characterized by the highest shares of the back kept straight. PS, MM, LM, and MS, had the worst condition in terms of back posture, with a dominance of B4 code, meaning that the back was bent and twisted, or bent forward and sideways. In terms of arm postures, the worst condition was that of tasks MM and PR (both arms above the shoulder level), while the L7 code (walking or moving) characterized mainly the MS (96.5%) which involved moving around the logs, MV, where the difference of up to 100% was due to small stops which were not accounted separately, and PS, which was a task supposing an important share of walking.

By the design of the manual measurement tasks, LM and MM accounted for shares of leg movement of approximately 58% and 44%, respectively, characterizing different paces of carrying them on. Obviously, MM was done at a lower moving pace than LM, which explains the shares in data on code L7. Although some of the data on postural shares indicate rather concerning results for the use of mobile platforms, it is a fact that action categories, which characterize the urgency of interventions, may take completely different proportions based on key associations between the postures of the body parts.

3.2. Action Categories and Postural Risk Indexes

Having in mind the shares of body part postures on tasks, Figure 2 shows the relative shares of action categories at the task level, as well as the estimated postural risk indexes. As shown, LM and MM stand apart by the frequency of action categories, having a dominance in the second action category, as well as an important presence in the fourth action category.

Table 3. Share of body postures on tasks.

Task	No. of Pictures	Share of Pictures on Postures of the Body Segments [1]													
		B1	B2	B3	B4	A1	A2	A3	L1	L2	L3	L4	L5	L6	L7
MS	5284	10.94	7.17	39.93	41.96	86.71	8.31	4.98	0.02	0.70	1.76	0.62	0.40	0.00	96.50
LM	2229	7.67	60.48	1.48	30.37	63.71	31.00	5.29	0.00	8.43	8.93	16.24	8.03	0.00	58.37
MM	4237	5.05	49.02	2.50	43.43	62.21	20.37	17.42	0.57	8.38	8.12	17.35	21.15	0.00	44.44
MV	7199	64.97	24.70	6.49	3.85	98.37	1.18	0.44	0.22	2.47	2.47	0.46	0.17	0.00	94.21
DE	18,685	36.75	53.24	6.44	3.56	96.99	2.73	0.28	72.87	6.56	15.54	1.84	1.31	0.00	1.89
PS	16,484	3.08	21.49	26.40	49.04	92.66	3.95	3.39	0.08	5.56	8.04	5.68	0.45	0.04	80.14
PR	4407	15.18	77.17	2.79	4.86	80.89	7.31	11.80	12.07	16.45	22.85	43.23	1.43	0.16	3.81
WD	5219	19.18	74.04	2.59	4.20	99.98	0.00	0.02	65.24	3.31	21.92	3.66	3.89	0.00	1.97

[1] Note: B1—back straight; B2—back bent forward or backward; B3—back twisted or bent sideways; B4—back bent and twisted or back bent forward and sideways; A1—both arms below shoulder level; A2—one arm is at or above the shoulder level; A3—both arms are at or above the shoulder level; L1—sitting; L2—standing with both legs straight; L3—standing with the weight on one straight leg; L4—standing or squatting with both knees bent; L5—standing or squatting with one knee bent; L6—kneeling on one or both knees; and L7—walking or moving.

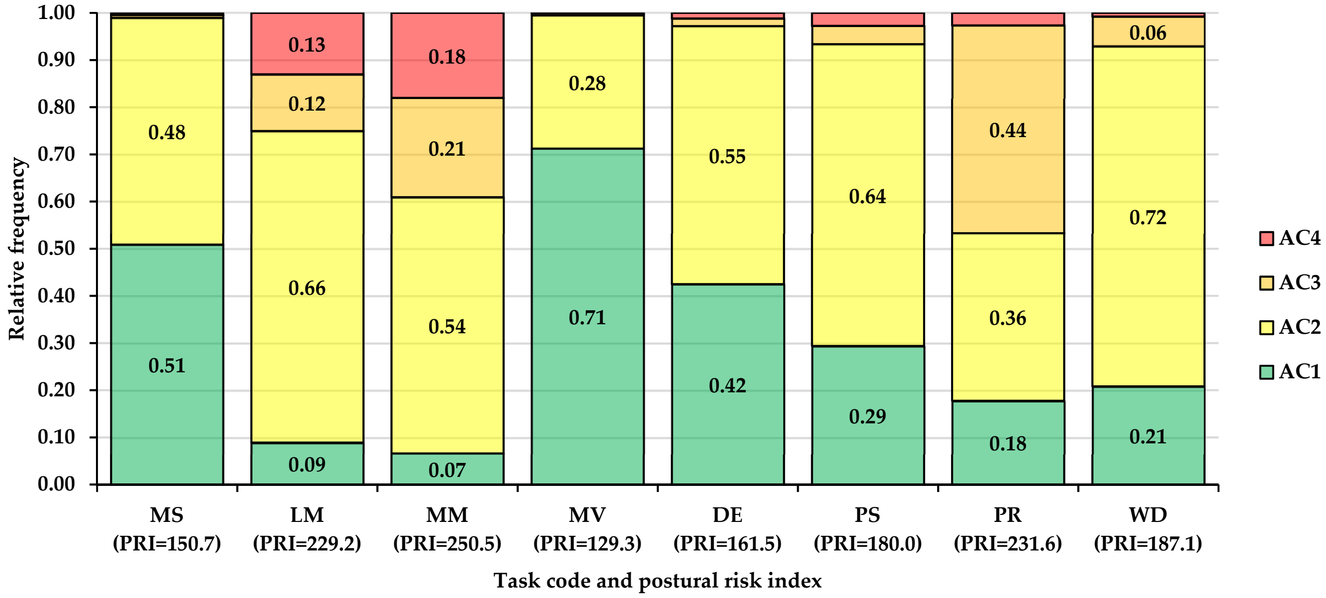


Figure 2. Share of action categories on tasks and postural risk indexes. Legend: MS—scanning by the mobile laser scanner; LM—marking the logs by paint; MM—measuring manually the diameters; MV—moving; DE—delays; PS—scanning by the smartphone; PR—preparing the tasks; WD—writing data on a field book; AC1—first action category, no corrective actions needed; AC2—second action category, corrective actions needed in the near future; AC3—third action category, corrective actions needed as soon as possible; and AC4—fourth action category, corrective actions needed immediately. Sources: [17,18,23].

Movement was the task which yielded the best postural condition, where the share of the first action category dominated (71%). From this point of view, second in line was MS (51%), followed by DE (42%) and PS (29%). Presence of an important share of the third action category in PR (44%) was due to movements which involved some degree of back bending associated with standing or squatting with the knees bent. MS returned a better postural condition as compared with PS, which was expected since the latter required a higher degree of back bending associated with the knees bent to reach during scanning of the bottom parts of the logs.

The postural risk indexes calculated for the main tasks indicate the trends described above, placing the manual measurement in the worst condition (PRI = 250.5), followed by log marking (PRI = 229.2), phone scanning (PRI = 180.0), and scanning by the mobile laser scanner (PRI = 150.7). By action categories, these would mean that log measurement would require corrective actions as soon as possible, phone scanning would require corrective measures in the near future, while scanning by the mobile laser scanner was at the border of the first and second action category.

3.3. Association between Body Segments' Postures, Action Categories, and Tasks

The main results of the correspondence analysis are shown in Figure 3, including the developed biplots, variation in eigen values, and in the explained variance as a function of the number of dimensions. As a rule of thumb, the number of dimensions explaining at least 50% of variance can be accepted to characterize the data dependencies in a lower dimensional space [26]. The association between the postures of the body parts and the observed tasks is described in Figure 3a. As shown, by accepting a bidimensional representation, the proportion of the explained variance was close to 80% (Figure 3b, bottom panel); therefore, the representation from Figure 3a preserves most of the variance in the sample. Interpretation of dependencies among the data may be carried out by projecting perpendiculars from the data points on a line crossing the center of origin from a given observed task, in which the location of a data point (i.e., posture) to the same part relative to the origin indicates its frequency in a task relative to the sample's average, whereas the distance from the plot's origin to a given intersection characterizes the size of the posture's frequency [28]. As an example, MM was characterized by higher frequencies of the A3 (both arms at or above the shoulder level) and A2 (one arm at or above the shoulder level) than on the average at the sample level. Conversely, A1 (both arms below shoulder level) was less frequent in MM than on the average in the sample. Similar interpretations apply to the postures of the back. In MM, B4 (back bent or twisted or bent forward and sideways) and B3 (back twisted or bent sideways) were more frequent than B2 (back bent forward or backward) and B1 (back straight) in comparison with the sample's average. Excepting L1 (sitting), all the postures of the legs were more frequent in MM than on average.

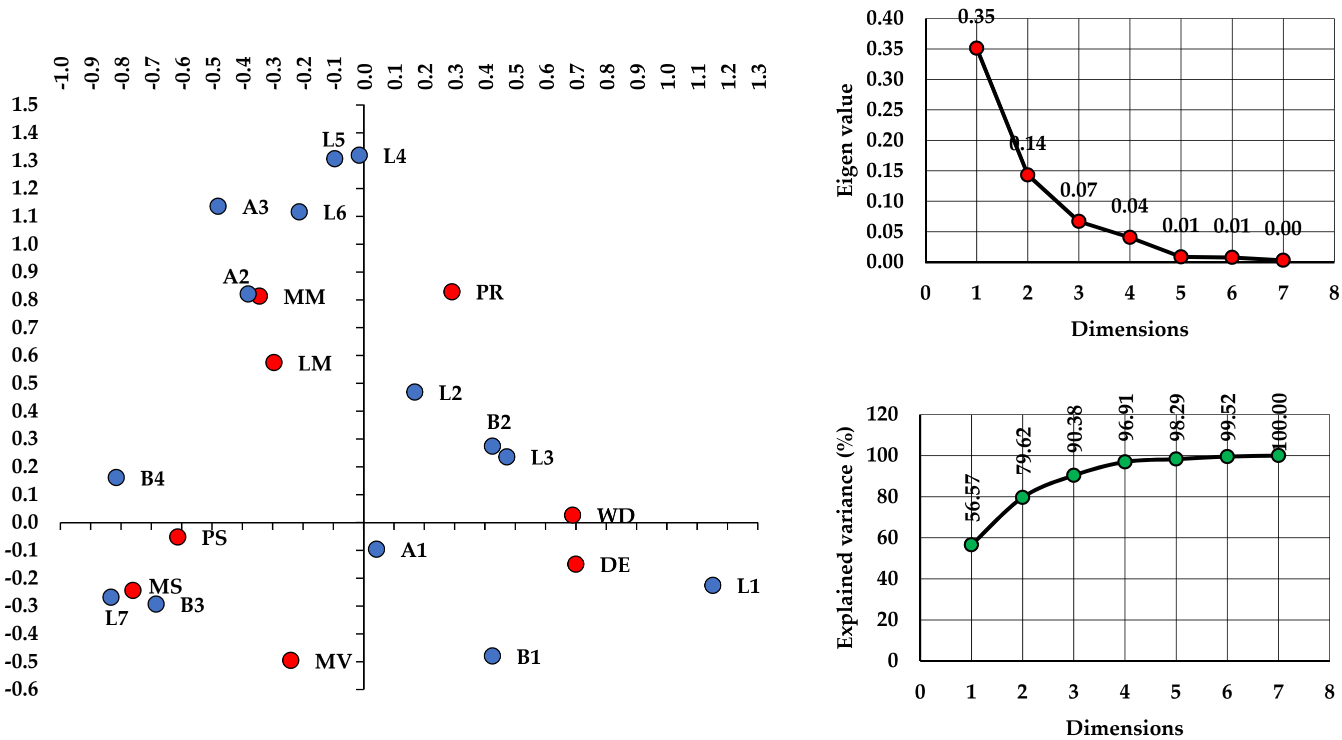
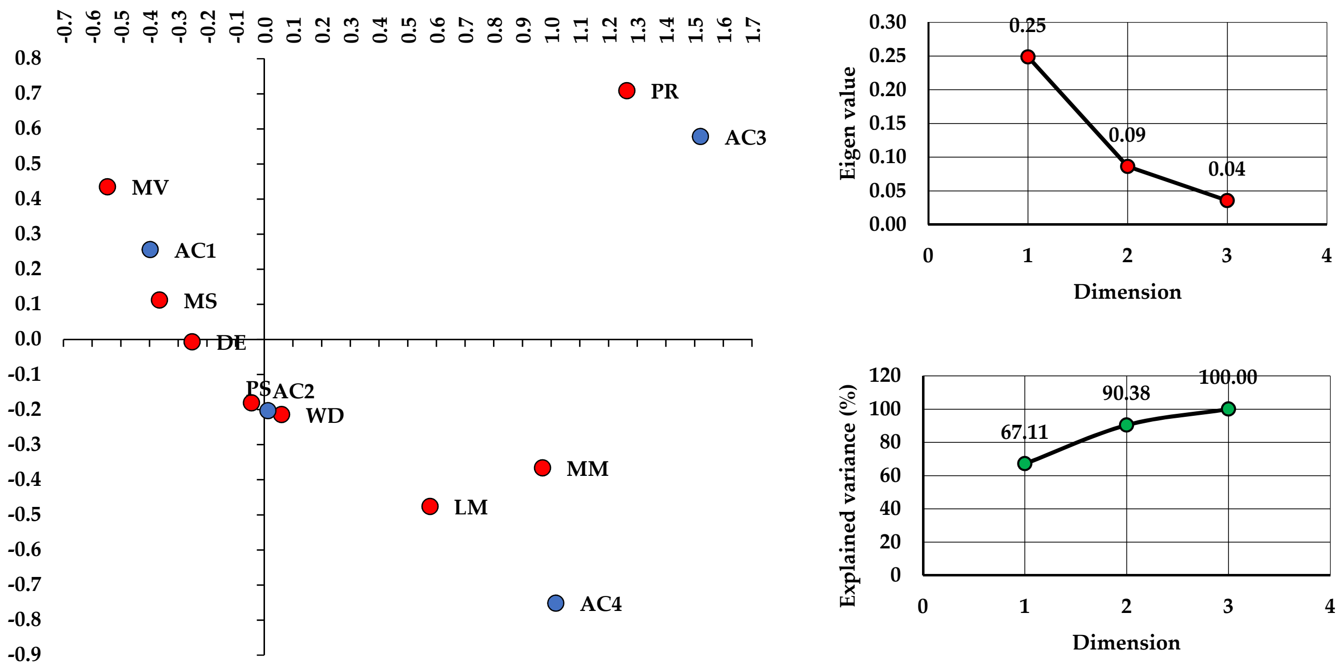


Figure 3. *Cont.*



(**c**) (**d**)

Figure 3. Results of the correspondence analysis showing the trends in data dependencies: (**a**) biplot of body postures and tasks; (**b**) eigen values and the proportion of explained variance as a function of the number of dimensions characterizing the data from (**a**); (**c**) biplot of action categories and tasks; (**d**) eigen values and the proportion of explained variance as a function of the number of dimensions characterizing the data from (**c**). Legend: B1—back straight; B2—back bent forward or backward; B3—back twisted or bent sideways; B4—back bent and twisted or back bent forward and sideways; A1—both arms below shoulder level; A2—one arm is at or above the shoulder level; A3—both arms are at or above the shoulder level; L1—sitting; L2—standing with both legs straight; L3—standing with the weight on one straight leg; L4—standing or squatting with both knees bent; L5—standing or squatting with one knee bent; L6—kneeling on one or both knees; L7—walking or moving; MS—scanning by the mobile laser scanner; LM—marking the logs by paint; MM—measuring manually the diameters; MV—moving; DE—delays; PS—scanning by the smartphone; PR—preparing the tasks; WD—writing data on a field book; AC1—first action category, no corrective actions needed; AC2—second action category, corrective actions needed in the near future; AC3—third action category, corrective actions needed as soon as possible; and AC4—fourth action category, corrective actions needed immediately. Sources: [17,18,23].

In the MS task, the most frequent postures of the arms were A1 (both arms below the shoulder level), and the least frequent were A2 (one arm at or above the shoulder level) and A3 (both arms at or above the shoulder level), in that order. For the same task (MS), the order of the frequency in back postures was B3 (back twisted or bent sideways), B4 (back bent or twisted or bent forward and sideways), B1 (back straight), and B2 (back bent forward or backward), and the order of the frequency in leg postures was L7 (walking or moving), L6 (kneeling on one or both knees), L2 (standing with both legs straight), L5 (standing or squatting with one knee bent), L3 (standing with the weight on one straight leg), and L1 (sitting). On the other hand, the PS task was characterized by frequencies higher than on the average of the sample for the arm postures A3 (both arms at or above the shoulder level) and A2 (one arm at or above the shoulder level), back postures B4 (back bent or twisted or bent forward and sideways) and B3 (back twisted or bent sideways), and leg postures L7 (walking or moving) and L6 (kneeling on one or both knees).

Considering the biplot of tasks and action categories (Figure 3c) and the explained variance (Figure 3d), the solution of representing the data in two dimensions accounted for a similar amount of explained variance (90%, Figure 3d, bottom panel). MM (Figure ilar amount of explained variance (90%, Figure 3d, bottom panel). MM (Figure 3c) was characterized by a higher frequency of AC4 (corrective measures immediately), AC3 (corrective measures as soon as possible), and AC2 (corrective measures in the near future), while MS stood at the opposite side, being characterized by higher frequencies in AC1 (no corrective measures). PS seemed to be closer to the average profile of the sample (closeness to the origin) and it was characterized by a higher frequency in AC2 (corrective measures in the near future) and AC1 (no corrective measures).

3.4. Similarity of Tasks

Similarity of the observed tasks was calculated by considering their frequency in action categories based on the Canberra metric; the results are shown in Figure 4. As shown, MS was more similar (1 − CM = 0.716) to MV, which was expected since the scanning task involved movement around the groups of logs. MM was more similar (1 − CM = 0.656) to LM, which was also expected given the common specificity of the two tasks. Moreover, PS was more similar (0.761) to DE, which was not expected, but was reasonable given that the postural behavior of the observed subjects during delays was at their free will.

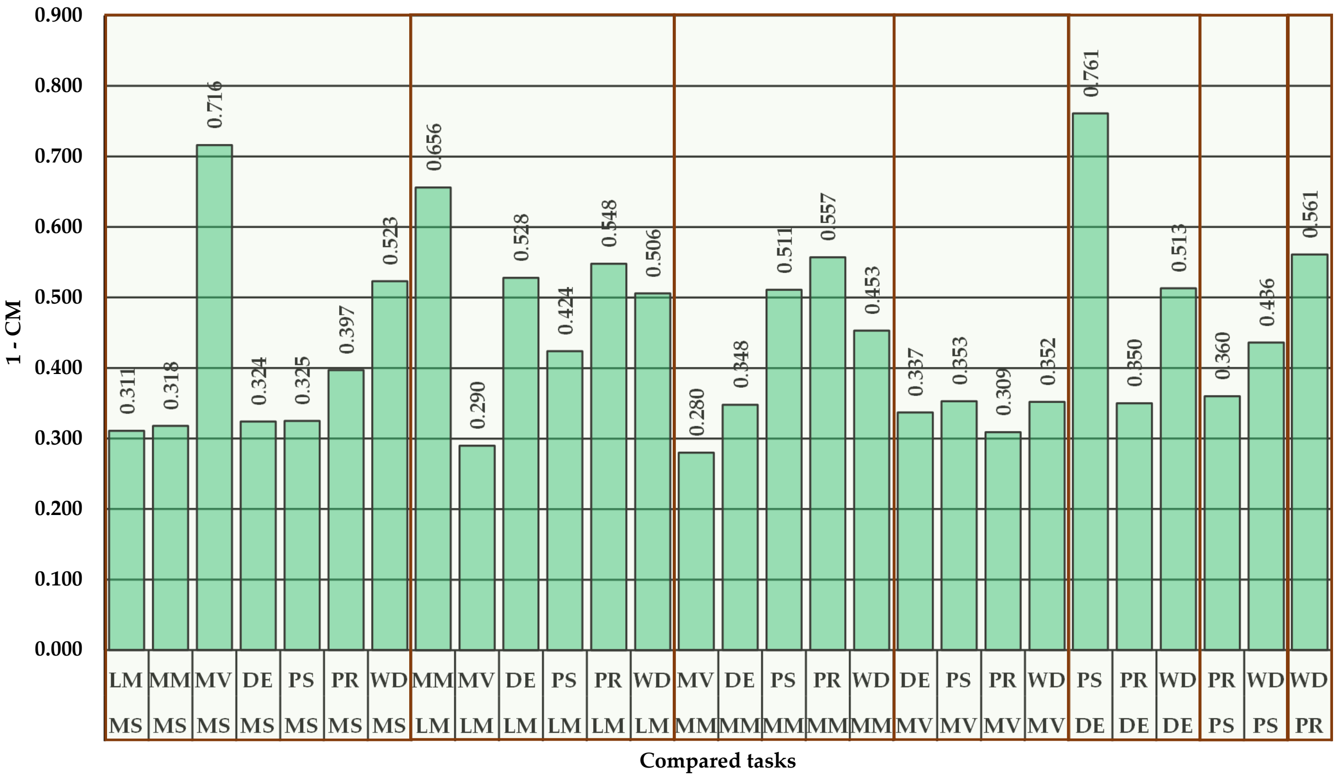


Figure 4. Similarity of tasks by the frequency of action categories.

Last, but not least, MS was rather dissimilar to MM (1 − CM = 0.318) and PS (1 − CM = 0.325), while PS was more similar to MM (1 − CM = 0.511) but not to the same extent as the similarity between MM and LM. Form this point of view, at least scanning by a mobile scanner stood well apart from manual measurement tasks in terms of similarity. Moreover, it is worth to note that writing data on the field book following manual measurement of diameters was more similar to the preparation task (1 − CM = 0.561), as well as, in general, the tasks not supported by mobile platforms tended to be more similar among each other.

4. Discussion

Implementing effective ways of doing work in forest operations is important for both industry's competitiveness and for the creation of safer work environments in terms of exposure to harmful factors. In wood measurement applications, the use of state-of-the-art data collectors does not bring important burdens from an ergonomic–postural point of view, as proved by the results of this study. In fact, by the use of OWAS method, conventional measurements yielded a worse postural condition as compared with the tasks of scanning by a mobile laser scanner and a smartphone, respectively. This outcome was associated to the specific postural combinations of the body parts in the analyzed tasks, which ultimately reflect the urgency of measures to be taken. As such, log marking and manual measurement could require measures to be taken as soon as possible; however, these tasks yielded results which were associated to the design of the study aiming to compare the efficacity by several key performance indicators, including the time consumption and accuracy of mobile platforms [3,22]. In a real-world scenario, it would be less likely for the measurements by a caliper to repeat at the same frequency, since the measurements are typically based on sampling diameters at the middle or at the ends of the logs [31]. Therefore, the postural condition of manual measurements, as found in this study, are only indicative and stand for a close to maximal exposure in terms of postural risks. Still, compared with scanning, manual measurements will require a more frequent bending of the back which could be associated with uncomfortable postures of the legs and of the arms, resulting in important shares of the fourth action category.

A differentiation of the tasks specific to mobile scanning was found as compared with the manual measurement tasks by the use of correspondence analysis and of the Canberra metric. For instance, scanning by the mobile laser scanning was more similar to regular movement and more frequent in the first action category, requiring no corrective measures. In fact, manual measurement had less in common with both scanning by a mobile laser scanning and by a smartphone, which indicates that the latter tasks are distinctly configured in terms of biomechanical exposure as compared with conventional measurement. Largely, these differences came from the frequency of movement events which was higher in mobile-based wood measurement tasks.

Postural risk indexes are aggregated metrics which were commonly used to characterize a given type of job or work task, as well as to compare among jobs and tasks [8–12,20,24,32], reflecting the weighted share that action categories hold in a sample taken into study. Scanning by a mobile laser scanner and by a smartphone, respectively, yielded postural risk indexes that indicate general postural conditions located in between no corrective measures and corrective measures needed in the near future, respectively; therefore, the postural condition of these tasks does not indicate high risks of exposure to musculoskeletal disorders. For instance, other traditional forestry and wood processing jobs were characterized by similar to higher postural risk indexes [8–10,12,20,24,32]; ultimately, the postural risk indexes are related to the specificity of jobs which, in turn, are characterized by the inter-relation between the worker, work object (its mass characteristics and locations taken in the work environment), and the technology used in the work. Therefore, the manual jobs that require handling of work objects or of tools which make a direct contact with the work objects, may be more prone to higher risks as opposed to those using mechanization or automation. This was the case of this study because the platforms used did not require a direct contact for measurement.

Postural diversity and posture changes have been identified to be important challenges in characterizing the biomechanical exposure [33] and in getting postural profiles to characterize the diversity in biomechanical exposure of different jobs [19]. Ideally, the OWAS method should use very fine, systematically obtained samples, to arrive at results which are close to reality [34], although random sampling may perform similarly when a sufficient sample size is considered [35], an approach that has been taken by similar studies [8,10]. Although this study attempted to build the sample at a rate of one second, due to some occlusions, some data were lost; therefore, the real sequence of events may have been interrupted in some cases. However, the study builds on a high number of observations which, in our opinion, adjusts the outcomes to the real sequence of events. In addition, it characterizes the dependencies in postural exposure at task level and maps the similarity of tasks based on the identified levels of exposure.

Characterizing the biomechanical exposure based on population-level data is essential to getting a broader picture which also reflects the variability in anthropometry, work habits, and personal techniques of carrying out a job. Unfortunately, the scanning tasks taken into study are in their infantile stage in the industry; therefore, getting population-level data would be possible once they replace or complement the conventional measurement operations. Still, prototyping is among the first steps taken to develop or study new technologies, products, or work methods, which can provide important information before full scale deployment, which was the case of this study. As there is some body of knowledge which indicates less association between the exposure and development of musculoskeletal disorders, i.e., [36], the results of postural analysis may be interpreted as mapping the biomechanical exposure in terms of risks. Still, there is a big chance for a given individual to develop musculoskeletal disorders as a consequence of improper postures [23], a reason for which the postural risk assessment may provide important information for prevention.

There are several other approaches to the problem of postural condition in forest or related industries [11,37,38] workers. Acknowledging that there might be several studies on the topic, the main aim of postural analysis in forestry work was to check the postural condition in different jobs and tasks or to compare between alternatives. These main goals are supported by the studies referenced so far in this paper [8–10,12,20,24,32], as well as by other studies on the topic [39–42]. Few forestry-related studies have been published on the concepts, methods, and sampling approaches in postural assessment [18–20,35,43], although there are examples adapting state-of-the-art technology to existing postural assessment methods [44]. This study could complement the procedural approach by using new statistical techniques able to detect association or dependencies in categorical data, which is typical to some postural assessment methods.

Limitations of this study are important to understand the applicability of its results. First of all, due to the infancy of the studied tasks, it was not possible to use a greater pool of subjects. Largely, this comes from the fact that a given subject should have some experience in scanning tasks so as to replicate the movements and body postures required to complete the job. As an example, the phone-based scanning requires eye interaction with the display to check the scanning quality in real time. If the application would indicate that some log parts were unsuitably covered by scanning, the subject would have to adjust their movements to correct such an issue. Therefore, using subjects with no experience just to mimic the scanning operations, without concerns on data coverage and quality, would have deformed the postural profile of the job, probably indicating a better condition. A second limitation may be that of the postural method used for evaluation. Largely, this method is used for the evaluation of static work [16], being less sensitive to magnitudes in movement (i.e., it uses categories). This is a limitation brought by its observational character which, for instance, makes no difference between a back bent at 20° or 40°; obviously, the burden posed by the two postures will differ. Somehow, this limitation may be compensated by the variation in posture magnitudes as observed in this study, in which back bending covered a wide range of angles at least in manual measurement of diameters, log marking, and scanning by phone. This was possible due to a relatively systematic sampling approach taken in this study at a rate of one second. On the other hand, the approach taken in this study was that of evaluating static instances extracted systematically from the real sequence of tasks. From this point of view, the results also characterize the dynamics of postures in the studied tasks.

5. Conclusions

Updated technology is required in many forestry applications, including wood measurement. Although such technology is already available, its use in wood measurement activities is still in an infantile stage, being implemented mostly as occasional tests to prove its effectiveness. For these reasons, ergonomic assessments are required to validate its sustainability in use, assuming a full or complementary scale deployment. When used in wood measurement applications, mobile scanning platforms do not bring significant risks in terms of biomechanical exposure. In fact, such measurement tasks seem to be characterized by a different postural profile, which balances the share of difficult postures by adding a higher degree of movement; in turn, it eases these tasks from a postural exposure point of view. Further studies could validate the results reported herein by considering a population-level approach with which to include the potential variability brought by other factors.

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4.8 Ergonomic Condition in Forest Operations

Article 7

What is the current ergonomic condition of chainsaws in non-professional use? A case study to determine vibrations and noises in small-scale agroforestry farms

Salvatore F. Papandrea[1], Maria F. Cataldo[1]*, Giuseppe Zimbalatti[1], Stefano Grigolato[2], Andrea R. Proto[1]

[1]Mediterranean University of Reggio Calabria, Department of AGRARIA, Feo di Vito snc, 89122, Reggio Calabria, Italy; salvatore.papandrea@unirc.it (S.F.P.); gzimbalatti@unirc.it (G.Z.); andrea.proto@unirc.it (A.R.P.) ORCID 0000-0003-4630-8986

[2]University of Padua, Department of Land, Environment, Agriculture and Forestry, Viale dell'Università 16, 35040, Legnaro, Padua, Italy; stefano.grigolato@unipd.it (S.G.)

*Correspondence: maria.cataldo@unirc.it (M.F.C.); Tel.: +39-(0)965-169-4275

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Article

What Is the Current Ergonomic Condition of Chainsaws in Non-Professional Use? A Case Study to Determine Vibrations and Noises in Small-Scale Agroforestry Farms

Salvatore F. Papandrea [1], Maria F. Cataldo [1,*], Giuseppe Zimbalatti [1], Stefano Grigolato [2] and Andrea R. Proto [1]

[1] Department of AGRARIA, Mediterranean University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy
[2] Department of Land, Environment, Agriculture and Forestry, University of Padua, Viale dell'Università 16, Legnaro, 35040 Padua, Italy
* Correspondence: maria.cataldo@unirc.it; Tel.: +39-(0)965-169-4275

Abstract: Agroforestry or agricultural forestry is an important resource for the exploitation of wood resources commonly based on a low level of mechanization and integrating agriculture crops land-management. Agroforestry areas consist often of buffer strip forest along the farms' boundaries or on small forest stands within the same farms. Felling is commonly based on the use of chainsaws which are used occasionally, and are often aged models and with little maintenance done on them. In this context, the present study analyzes the vibration and noise generated by chainsaws in the specific contest of the agroforestry farms. The aim is to verify the hand-arm vibrations and noise level, which self-employed agroforest operators are exposed with the occasional use of aged and rarely maintained chainsaws. The main results show that vibration exposures are significantly affected by the model and condition of use of the chainsaw and at lower level, but still significant, by the wood and the position of the handle. Regarding noise levels, the chainsaw model and condition of use also has significant effects. In summary, this study highlights that the importance of the condition of use of the chainsaw has an important effect on the vibrations and noise exposition and that these, although limited due to the limited daily use by operators, must be carefully taken into consideration, and provide for containment actions through adequate information and training.

Keywords: noise; vibration; small-scale; mechanization; forest operations; softwood; hardwood

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1. Introduction

In rural areas, small-scale agroforestry is widely recognized for increasing and diversifying farm productivity while releasing pressure on existing forests. As a consequence, agroforestry or agriculture forestry represents an important local wood resource exploitation in rural areas in which wood harvesting is commonly based on semi-mechanized harvesting system. This can be described generally as a labor-intensive, low-input land-use approach, employing man-power or draft animals harvesting system, rather than machine-intensive harvesting system based on full-mechanized approach [1,2]. In agroforestry practices, the advantage consists of growing even of high economic value with low energy and management inputs compared to industrial forest plantations.

Different tree species may be present in form of scattered trees, along contours, on farm boundaries, or established as rotational woodlots or blocks [3–5]. Such trees are managed in combination with crops in agroforestry systems and serve a number of ecological and economic functions that are partly similar to those of trees in forests, although different in extent [6,7].

Focusing on the harvesting operation, most of the agroforestry stands are normally managed by the same self-employed owners and commonly the motor manual felling is the unique process used. Even if occasionally, the use of the chainsaw in agroforestry system can take place intensively and consequently for periods ranging from a couple of days to a couple of weeks per year. This depends on the intensity and the extension of the wood exploitation and on the planning of the farm activities. As a consequence, farmers can be exposed to vibration and noise risks, even if occasionally by pushing the chainsaw to the maximum engine power. Its application presents a threat to workers' safety and health.

This condition is even more accentuated in the circumstance of using aged chainsaws and with a lack of maintenance and thus the larger exposure to vibration and noise. As the activity of wood harvesting is irregular and not constant over the years, accident prevention studies aimed at small-scale agroforestry work have been limited [8]. However, as it is reported recently by FAO [9], agroforestry-related work is among the most hazardous of all non-military activities. In this context, vibrations and noise risks are underestimated by farmers, as they do not pose an immediate risk to human health. It is well known that the consequences of exposure to noise and vibrations can be very serious [10], but the symptoms of the disease can appear several years after the exposure. Occupational noise [11] is defined as sound pressure perceived by the human ear as an undesirable sound with different frequencies, intensities, and phases [12]. According to EU Directive 2003/10/EC [13], the noise maximum exposure threshold is equal to 87 dB(A) considered as the time-weighted average value of noise exposure levels for a nominal eight-hour working day. Exposure to noise is an important and preventable cause of hearing loss [14], and can be caused by short exposures to extremely high sound levels or by repeated exposures to moderate levels [15]. High-intensity sound can negatively affect hearing capability with a temporary or permanent loss of sensitivity and acuity [16–18].

When working with chainsaws, loads on hands and arms caused by vibrations can exceed the daily exposures action value [19–21]. The vibrations, considered to be short, rapid, and irregular shaking movements, and expressed by EU Directive 2002/44/EC [19] as frequency weighted acceleration, have a daily exposure action value set of 2.5 m s^{-2} and a daily exposure limit value of 5 m s^{-2}.

According to previous research [21,22], the vibration level of the chainsaw is affected by a large number of parameters (worker, chain tension, bar length, fuel quantity in the tank, method of holding the saw). The firm grip of the chainsaw handle, affecting the transfer of hand-arm vibrations, depends on the worker's experience, work operations and wood hardness [23]. The consequences related to exposure of workers to vibrations have been extensively studied in the literature, noting numbness of the hands and arms or tingling in the fingers and deterioration of the tactile perception of the fingers [24,25] during and after exposure, especially during the night-time [26]. Carpal tunnel syndrome [27], tendonitis, and bicipital epicondylitis [28] are observed, and several associations between physical workload factors and some common upper limb disorders are noted [29].

In general, numerous research has been done with regard to the measurement of the vibration and the noise generated by chainsaw during felling and cross-cutting operations, according to the chainsaw technologies [15,30–32] as well in terms of wood characteristics [33]. Anyway, no studies so far have examined the potential levels of acoustic and vibrations pressures on agroforestry farms in which a desultory use of chainsaws is more evident. As a consequence, the present work collected a set of nine chainsaws currently used by a sample of self-employed forest owners.

The aim of this paper is to determine if there are significant differences in terms of operator exposure to noise and hand-arm vibrations due to use of chainsaws. In order to obtain a representative analysis of the present condition of exposure to the risk of noise and vibrations, the work was based on the collection of a random sample of chainsaws in agroforestry farms in the same condition of use declared by the chainsaw operators.

2. Materials and Methods

The study was conducted in the Sila area in the Calabria region (Southern Italy). This area is characterized by a large number of small-size agroforestry farms. To obtain a representative analysis, random old chainsaws were tested. The selection of the chainsaws was based on the identification of farms identified on the base of small-size dimension, forest management by the self-employed, and occasional use of the chainsaws.

Nine farms were selected, and each owner was informed with the aim of the study, and for this reason, each farm lends the chainsaw for the test. Therefore, nine different chainsaw models (Figure 1) were selected, and their characteristics are reported in Table 1. To reduce the uncertain variability, the study was developed under controlled conditions i.e., during the tests, the chainsaws were operated by the same operator, aged 48, with 20 years of work experience, and the field test was free from external artificial noises. The daily exposure values were normalized to three different scenarios: four, six, and eight hours, on the basis of information given from the owners.

Table 1. Chainsaw characteristics and the values declared by constructor.

Code	Power (kW)	Weight kg	Bar Size cm	Noise Sound Power—Pressure dB(A)	Vibration Front—Rear m s^{-2}	Years in Use	Annual Days of Use
A	4.4	6.7	50	105–117	3.8–4.0	5	35
B	2.6	4.7	40	102–110	3.4–4.3	8	45
C	3.9	6.2	45	103–115	4.6–5.2	12	40
D	3.5	5.6	46	101–112	4.0–5.9	15	45
E	3.2	6.2	50	102–112	4.4–6.1	20	50
F	2.3	6.1	40	102–112	6.4–7.2	25	40
G	3.4	6	40	103–112	3.8–5.1	14	50
H	3.6	6.4	45	108–119	4.0–5.1	8	40
I	2.1	4.3	40	104–112	5.2–5.5	11	45

Two different wood types, softwood (SW) and hardwood (HW), which are represented in this study by Corsican pine (*Pinus laricio* Poiret) and European beech (*Fagus sylvatica* L.), were considered to evaluate the influence of wood density on the vibrations and noises during the cross-cutting operations.

The cross-cutting tests were conducted on wood logs with an originally length of 2 m and a diameter ranging from 23 to 25 cm at the middle of their length. They were placed on a sawbuck 45 cm above ground, so that the operator was able to cut slices of approximately 5 cm width. Wood density was determined in laboratory (in according with ISO 13061-1) [34] using wood samples from each disc generated during the cross-cutting test. Oven-dry density results in 520 kg/m^3 and 715 kg/m^3, respectively, for Corsican pine and European beech.

Each chainsaw was tested using a saw directly sharpened by the owners, in order to not alter the common condition of use by them and to adopt the same cutting tooth profile. In fact, the purpose of this study has been to determine noise and vibration exposure in the typical using of a chainsaw in a small-scale agroforestry farm.

The situation without wood cross-cutting was therefore also considered. In this situation, the use of the chainsaws at full RPM (Rotation Per Minutes) rate (chainsaw engine running at the maximum), and at minimum RPM rate (chainsaw engine running without acceleration) were considered.

The cross-cutting was thus repeated 3 times for front and rear handles (A and B in Figure 2 and H in Formula 1) for each chainsaw (Figure 3). During the sampling of vibration applying minimum and maximum engine power, the test lasted 60 s for each mode. A total of 108 different combinations were registered and 324 measures were determined following this scheme:

$$N \times W \times H \times EP \times T \quad (1)$$

where:

N = 9 different chainsaws; W = 2 different wood species; H = 2 different handles; EP = 3 different RPM rates; T = 3 repetitions for each combination.

Figure 1. The nine chainsaws analyzed in this work.

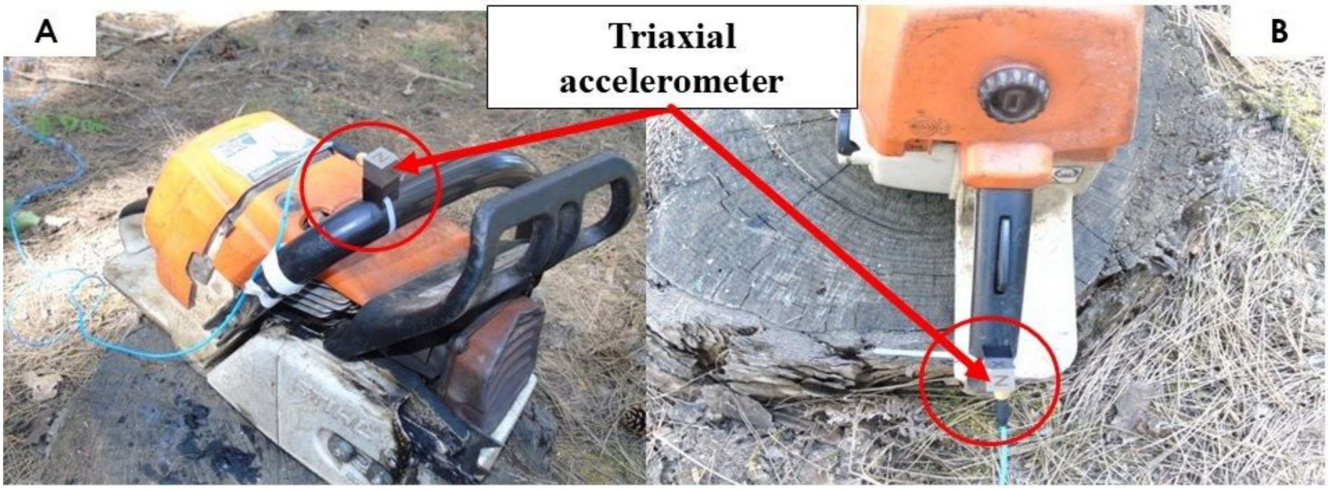

Figure 2. The triaxial accelerometers position on the chainsaw on the front (**A**) and rear (**B**) handles.

Figure 3. The noise and vibration measurements during cross-cutting operation.

Vibration and Noise Measurements

In accordance with ISO standard 5348 [35], vibrations were correctly measured using a cubic triaxial piezoelectric accelerometer ICP® (Integrate Current Preamplifier) by PCB Piezotronics (356A02 model, 10 mV/g sensitivity, 10.5 g mass) fixed on the chainsaw (Figure 2), and using an accelerometer mounting adapter following the orientation of the measurement axes as described in the ISO standards 5349:1-2 [36,37]. The accelerometer was mounted in a position that could not interfere with the operator during the cross-cutting. A cable of 5 m, which was connected the triaxial accelerometer, transferred the vibration measurements obtained in three perpendicular directions (ISO 5349-1) [37] on four channels vibration meter-analyzer Delta Ohm HD2030. Data were stored on a SD memory cards for post-processing analysis. The HD2030 analyzer complied with all measurements required by the European regulations regarding the protection of workers from exposure to mechanical vibrations. In particular, the frequency range of spectral analysis varies from 3.15 Hz up to 3.15 kHz, and for the analysis of octave band spectrum, the range applicable is 4 Hz to 2 kHz. The collected vibration data were analyzed with the Noise Studio software licensed with application module "Workers' Protection". Calibration was performed every time that changed the chainsaw tested using a calibrator portable Delta Ohm HD2060, which produces a frequency of 15.915 Hz and an acceleration signal of 1 m s^{-2}.

As reported in similar studies [16,23,33,38], the accelerations were simultaneously measured along the three perpendicular axes (a_x, a_y, a_z) following the recommendations of the EN ISO 20643/A1 standard [39], and the signals from the accelerometers were frequency weighted using the weighting curve Wh (ISO 5349-1 standard) [36]. Thus, the weighted acceleration levels in all three axes (a_{hwx}, a_{hwy} and a_{hwz}) were obtained, and the vibration total value (a_{hv}) was determined according to the following relation:

$$a_{hv} = \sqrt{a^2{}_{hwx} + a^2{}_{hwy} + a^2{}_{hwz}} \quad (2)$$

Progressively, the daily vibration exposure was derived from the magnitude of the vibration (vibration total value) and the daily exposure duration. Considering the use of these sampled chainsaws is occasional and non-continuous, three different reference periods were studied: four, six, and eight hours. The daily vibration exposure has been expressed in terms of the h energy-equivalent frequency-weighted vibration total value:

$$A(h) = ahv\ \sqrt{\frac{T}{T_0}} \quad (3)$$

where T is the total daily duration of exposure to the vibration a_{hv} and T_0 is the reference duration of h hours. The considered h in this study had values of 4, 6, or 8 h.

Simultaneously, the sound pressure level was monitored according to the international standards (ISO 9612) [40] and European Directive [13]. The tests have been carried out with the use of a precision integrator phonometer, Delta Ohm HD 9020 class 1, connected with a 10 mt extension cable to a microphone MK221, which was fixed to the helmet and placed 10 cm from the worker's right ear. The sound level meter was able to perform the measurements required to evaluate workers' noise exposure [40,41]. This instrument is set every year at the laboratory S.I.T. (Italian Calibration Service—Accredia), and after each chainsaw series of measurements, the setting was controlled by calibrator Delta Ohm HD 9101. The acoustic levels and noise generated during the tests have been stored using a SD memory card (2 GB) allocated in the sound meter and transferred through a serial cable to a laptop to be processed successively, using the same software used for vibration data. Following the guidelines of ISO 9612 [40], the equivalent continuous sound pressure level (L_{eq}) with full sound frequency spectrum in 1/3 octave bands and the maximum value of the instantaneous sound pressure (L_{peak}) were calculated; the acoustic levels obtained were expressed in decibels (dB), adjusted to curve A (LA_{eq}) and curve C (LC_{peak}). Similarly to vibrations exposure, the sound pressure level was been expressed in terms of the h energy-equivalent frequency-weighted noise total value (L_{EX},h) with equation

$$L_{EX,h} = LA_{eq,Te} + 10 \log (T_e/T_0)(dB(A)) \quad (4)$$

$$LA_{eq,Te} = 10\ \log \{\frac{1}{T_e}\int_0^{T_e}\left[\frac{P_A(t)}{P_0}\right]^2 dt\} \quad (5)$$

where:

T_e = period of a worker's personal exposure to noise;
T_0 = 4, 6, or 8 h;
P_A = instantaneous acoustic pressure (weighting scale A), in Pa;
P_0 = 20 μPa.

3. Statistical Analysis

To identify and explain the sources of variation in (*i*) vibration total value (a_{hv}) (Formula 2) and in the equivalent (*ii*), continuous sound pressure level (L_{eq}) was adjusted to curve A (LA_{eq}) based on chainsaw model, chainsaw engine RPM rates, wood species, and wood moisture content. A multifactor analysis of variance (multifactor-ANOVA) would be applied to better understand the effect of the covariates, factors, and the relationships between them.

ANOVA table decomposes the variability of the vibration total value (a_{hv}) or the equivalent continuous sound pressure level (L_{eq}) adjusted to curve A (LA_{eq}) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor was measured having removed the effects of all other factors. The *p*-values test the statistical significance of each of the factors by considering *p*-values less than 0.05 at the 95.0% confidence level.

The method used thus to discriminate among the means will be the Fisher's least significant difference (LSD). With this method, there is a 5.0% risk of calling each pair of means significantly different when the actual difference equals 0.

The statistical analyses were supported by STATGRAPHICS Centurion 19® and R.

4. Results

Table 2 shows the vibration total value (a_{hv}) on front and rear position according to two cases (*i*) the minimum and maximum RPM rates and (*ii*) the different type of wood (Corsican pine—softwood and European beech—hardwood) during the cross-cutting operation.

Table 2. Means of the vibration total value (a_{hv}) and mean of peak level (a_{pl}).

a_{hv}, m s^{-2}									
	Minimum RPM		Maximum RPM			Cross-Cutting			
						Front		Rear	
Code	Front	Rear	Front	Rear	Code	SW	HW	SW	HW
A ^{cde}	4.08	4.31	4.60	4.90	A ^{b}	5.04	6.15	6.74	7.61
B ^{bcd}	3.57	4.56	4.78	5.29	B ^{b}	4.46	4.69	6.54	6.79
C ^{a}	2.75	3.24	4.62	5.13	C ^{a}	3.41	3.51	5.37	4.93
D ^{e}	3.31	4.03	5.06	5.54	D ^{d}	5.61	5.79	10.69	11.64
E ^{abc}	3.18	4.24	3.77	4.35	E ^{ab}	3.73	4.02	7.89	7.12
F ^{abc}	3.17	4.50	4.71	4.88	F ^{c}	7.89	7.95	8.09	8.16
G ^{bcde}	2.48	5.78	4.13	5.64	G ^{ab}	4.37	6.41	7.09	7.27
H ^{ab}	3.82	3.56	4.03	4.80	H ^{b}	4.92	5.55	7.23	7.60
I ^{ab}	3.28	4.50	4.44	4.95	I ^{c}	8.02	8.72	8.34	8.88
a_{pl}, m s^{-2}									
Code	Minimum RPM		Maximum RPM			Cross-Cutting			
						Front		Rear	
	Front	Rear	Front	Rear		SW	HW	SW	HW
A ^{a}	3.23	3.77	4.07	3.50	A ^{abc}	2.73	2.78	5.04	4.92
B ^{a}	2.36	3.62	3.87	4.65	B ^{ab}	2.79	3.09	4.20	4.65
C ^{d}	2.84	2.79	4.36	2.47	C ^{a}	2.28	2.65	3.65	3.02
D ^{b}	2.66	2.58	4.99	6.64	D ^{e}	3.73	3.88	10.21	11.93
E ^{a}	2.97	2.76	2.58	5.04	E ^{ab}	2.73	2.50	4.98	4.42
F ^{c}	2.17	3.49	3.76	4.12	F ^{c}	5.40	5.92	4.43	5.12
G ^{a}	1.76	3.72	3.33	6.79	G ^{ab}	2.52	2.84	5.37	5.12
H ^{a}	3.51	2.33	3.60	3.08	H ^{bc}	3.57	3.52	5.76	6.11
I ^{b}	3.23	2.92	3.08	3.98	I ^{d}	6.29	6.57	6.15	5.25

SW = Corsican pine; HW = European beech. Superscript letters in CODE indicate similar values (LSD's test).

In the case (*i*), the multifactor analysis of variance highlights that the a_{hv} (m s^{-2}) is significantly affected by the RPM rates (*p*-value < 0.000), the chainsaw model (*p*-value 0.001), and the accelerometer position (rear vs. front handle) (*p*-value < 0.000). The higher effect is due to the RPM rate (57.76% of the variability) followed by the accelerometer position (29.08%) and the chainsaw model (3.41%).

The Fisher's least significant difference (LSD) procedure was applied to determine which a_{hv} means are significantly different from each other. The LSD test indicates that 11 pairs show statistically significant differences at the 95.0% confidence level and five homogenous groups within which there are no statistically significant differences of a_{hv} (Groups: C, H, I, E, and F; H, I, E, F and B; E, F, B, and G; B, G, and A; B, G, A and D). According to the LSD test, the pair difference is significative for the models A vs. C, A vs. H, A vs. I, B vs. C, C vs. D, C vs. G, D vs. E, D vs. F, D vs. H, D vs. I and G vs. H. A particular case is I which resulted in a high level of vibration in rear position in both RPM test condition. This situation was affected by the critical condition of vibration isolators.

The minimum RPM rates result in a similar level of a_{hv} in front handle position for almost all the chainsaw models (less than 4 m s^{-2}). In the case of the rear handle, almost all the chainsaw models exceeded the value 4 m s^{-2}, and only C and H resulted lower.

In the case (*ii*), the cross-cutting test aimed to evaluate a_{hv} on front and rear handles positions, due to the different type of wood and the different chainsaw models.

The multifactor analysis of variance indicates a p-value < 0.000 for the front and rear handle position and for the chainsaw model. These factors have a statistically significant effect on a_{hv} at the 95.0% confidence level. In the case of the types of wood factor, the p-value resulted higher than 0.05 and thus is not significant.

The Fisher's least significant difference (LSD) procedure was applied to determine which a_{hv} means are significantly different from which others. The LSD test indicates that 23 pairs show statistically significant differences at the 95.0% confidence level and four homogenous groups within which there are no statistically significant differences of a_h are identified (Groups: C, G, and E; G, E, B, H and A; F and I; D)

The chainsaws F and I have generated similar vibration values for both handles without differences between softwood and hardwood (Figure 4), as shown by the LSD test. The other chainsaws reported a significant difference between the rear and front handle position: on average +44% during cross-cutting of softwood and +38% for hardwood. Anyway, the differences considering the type of wood used result in being slightly not significant (p-value 0.055), probably due to the high effect due to the chainsaw type. Consequently, the vibration values during the cross-cutting of Corsican pine and European beech were not statistically different, disproving the experimental hypothesis, despite comparing a softwood with a hardwood species.

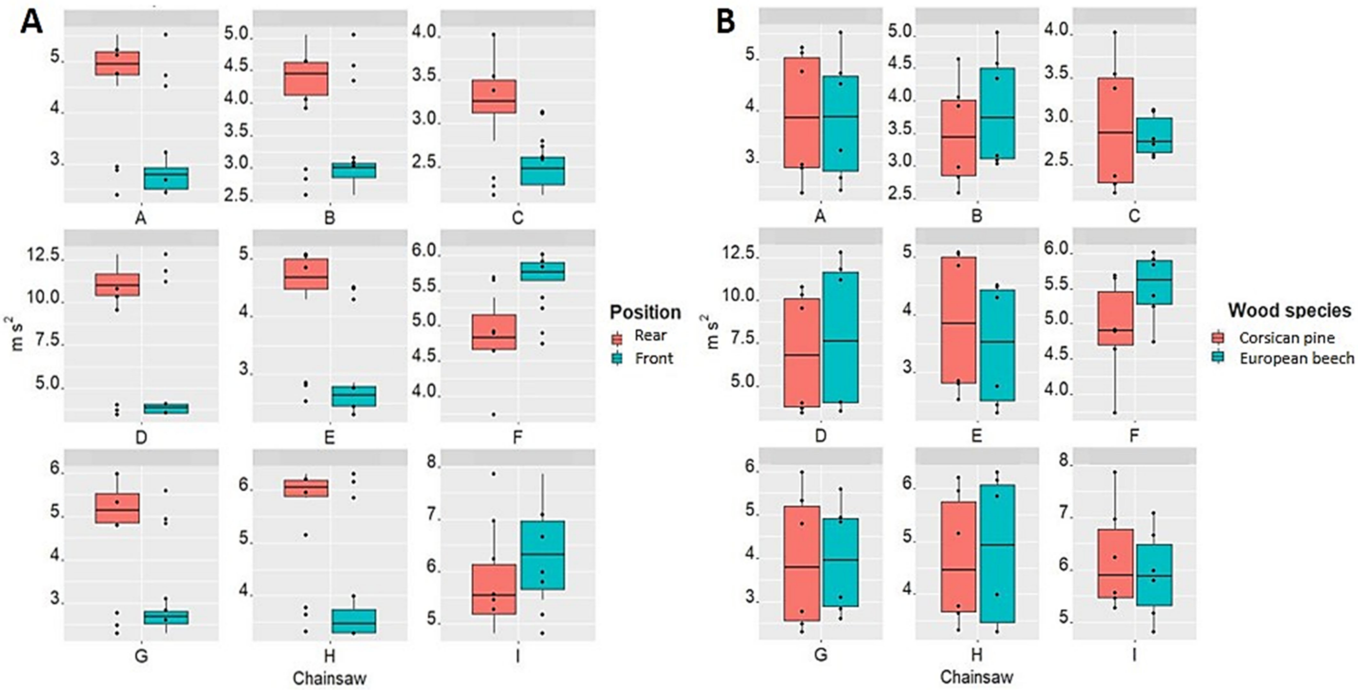

Figure 4. The graphical representation of the vibration peak level a_{pl} during minimum and maximum RPM (case *i*) (**A**) and during cross-cutting operation (**B**) (case *ii*) where A–I represent the chainsaw models.

The vibration amplitude, which is the characteristic that describes the severity of the vibration, can also be represented by the peak level (a_{pl}). The a_{pl} can be used to indicate the acceleration shocks.

In the case (*i*) for the evaluation of the a_{pl} on front and rear position according to the minimum and maximum RPM rates, the multifactor analysis of variance highlights that the a_{pl} (m s^{-2}) is significantly affected by the RPM rates (*p*-value < 0.000), the chainsaw model (*p*-value = 0.038), and the accelerometer position (rear vs. front handle) (*p*-value = 0.011). The higher effect is due to the RPM rate (67.13% of the variability) followed by the chainsaw model (18.31%) and the accelerometer position (12.77%).

Additionally, for the a_{pl}, the evaluation of the effect of the type of wood (Corsican pine—softwood and European beech—hardwood) during the cross-cutting operation has been evaluated.

The effect is clear for chainsaw model (*p*-value < 0.000) and for the accelerometer position (front and rear) (*p*-value < 0.000), while wood type is significant but slighter than the previous effects (*p*-value = 0.017).

The Fisher's least significant difference (LSD) procedure was applied to determine which a_{pl} means are significantly different from which others. The LSD test indicates that 19 pairs show statistically significant differences at the 95.0% confidence level and five homogenous groups within which there are no statistically significant differences of a_{pl} (Groups: C, E, B, G, and A; E, B, G, A and H; A, H and F; F and I; D).

The Table 3 reports L_{Aeq} and L_{Cpeak} according to two cases: (*i*) the minimum and maximum RPM rates, and (*ii*) the different type of wood (Corsican pine—softwood and European beech—hardwood) during the cross-cutting operation.

Table 3. Noise measurements in terms of L_{Aeq} and LC_{peak} (dB(A)).

	L_{Aeq}			L_{Cpeak}	
Code	**Min RPM**	**Max RPM**	**Code**	**Min RPM**	**Max RPM**
A [cd]	82.04	99.95	A [b]	101.66	116.07
B [ab]	75.74	95.36	B [a]	91.24	110.63
C [ab]	72.68	100.69	C [b]	98.48	114.94
D [d]	85.83	100.85	D [b]	101.74	113.81
E [bcd]	78.32	102.29	E [b]	100.81	116.19
F [d]	85.39	105.03	F [c]	108.15	119.32
G [cd]	76.66	99.47	G [b]	96.72	112.46
H [a]	73.71	98.43	H [a]	97.51	113.69
I [a]	80.62	89.91	I [a]	100.93	104.63
Cross-Cutting Operation					
Code	L_{Aeq} **SW**	**HW**	**Code**	L_{Cpeak} **SW**	**HW**
A [b]	88.59	90.82	A [a]	105.64	106.41
B [a]	85.92	86.44	B [a]	100.31	100.84
C	89.02	89.81	C [a]	102.87	103.12
D [ab]	88.11	88.19	D [a]	103.11	103.78
E [bc]	90.01	90.29	E [b]	103.94	105.24
F [d]	92.92	94.55	F [d]	111.87	112.17
G [b]	88.31	91.52	G [a]	102.88	103.19
H [bc]	89.19	91.71	H [b]	105.82	107.11
I [bc]	90.31	91.44	I [b]	108.51	109.42

SW = Corsican pine; HW = European beech. Superscript letters in CODE indicate similar values (LSD's test).

In the case (*i*), the multifactor analysis of variance highlights that the L_{Aeq} is significantly affected by the RPM rates (*p*-value < 0.000) and the chainsaw model (*p*-value 0.002). The higher effect is due to the RPM rate (84.49% of the variability) followed by the chainsaw model (16.45%).

The Fisher's least significant difference (LSD) procedure was applied to determine which L_{Aeq} means are significantly different from which others. The LSD test indicates that 16 pairs show statistically significant differences at the 95.0% confidence level and four homogenous groups within which there are no statistically significant differences of L_{Aeq} (Groups: H, I, C, and B; B, C and E; C, E, A and G; E, A, G, D and F).

Again, in the case (*i*), the multifactor analysis of variance highlights that the L_{Cpeak} is significantly affected by the RPM rates (p-value < 0.000) and the chainsaw model (p-value < 0.000). The higher effect is due to the RPM rate (77.85% of the variability) followed by the chainsaw model (21.07%).

The Fisher's least significant difference (LSD) procedure was applied to determine which L_{Cpeak} means are significantly different from which others. The LSD test indicates that 23 pairs show statistically significant differences at the 95.0% confidence level and three homogenous groups within which there are no statistically significant differences (Groups: B, I and H; C, D, G, E and A; F).

According to the evaluation of the L_{Aeq} and L_{Cpeak} in relation to the different types of wood (Corsican pine—softwood and European beech—hardwood) during the cross-cutting operation (case *ii*), the same statistical approach of the case *i*) is applied.

The multifactor analysis of variance highlights that the L_{CAeq} is significantly affected by the chainsaw model (p-value < 0.000) and not significantly affected by the wood tree species (p-value 0.967). The effect due to the chainsaw model is estimated in 81.40% of the total variability.

The Fisher's least significant difference (LSD) procedure was applied to determine which L_{CAeq} means are significantly different from which others. The LSD test indicates that 15 pairs show statistically significant differences at the 95.0% confidence level and four homogenous groups within which there are no statistically significant differences (Groups: B and D; D, A, G, I, E and H; I, E, and H; F).

By considering L_{Cpeak}, the multifactor analysis of variance highlights that the L_{Cpeak} is significantly affected by the chainsaw model (p-value < 0.000) and not significantly affected by the wood tree species (p-value 0.449). The effect due to the chainsaw model is estimated in 72.84% of the total variability.

The Fisher's least significant difference (LSD) procedure was applied to determine which L_{Cpeak} means are significantly different from each other. The LSD test indicates that 24 pairs show statistically significant differences at the 95.0% confidence level, and four homogenous groups within which there are no statistically significant differences (Groups: B; C, G, D and A; E, H and I; F).

The noise test indicates significant differences between the chainsaw models by considering minimum and maximum RPM. In the case of minimum RPM, the displacement of each chainsaw examined has not completely influenced the acoustic levels products.

In fact, the chainsaws F (2.3 kW) and I (2.1 kW) have major noise values respective to models with a higher engine displacement; this result is not supported during the maximum speed where the more powerful chainsaws generated higher noise. As can be seen in Table 3 and Figure 5, during the cross-cutting operations, each chainsaw produced high acoustic levels. LA_{eq} values are in all the cases above 87 dB(A) with some of them even reaching 100 dB(A). Indeed, peak values turn out to be high, even though they never exceed the peak as required by the law in force.

Compared to the European legislation and to the noise exposure assessment standards [42], the results of this study indicate that in most of the observed tasks, the exposure to noise exceeded the 80 dB(A) lower exposure action level. The noise levels for the study sample were normally distributed, with the majority of the "noisy" equipment operated in the region of 90 dB(A) to less than 85 dB(A) [43]. This situation should be considered to permit a correct application of PPE during this use. There are four general types of passive hearing protection devices: earplugs, semi-insert or ear canal caps, earmuffs, and helmets. In particular, headphones could be used, as some studies have already tested their ability to reduce the noise levels that reach the operator [31–42]. Considering the occasional, not continuous use of these sampled chainsaws, Table 4 evaluated the noise and vibration emissions considering different daily exposure values to three different reference periods: 4, 6, and 8 h.

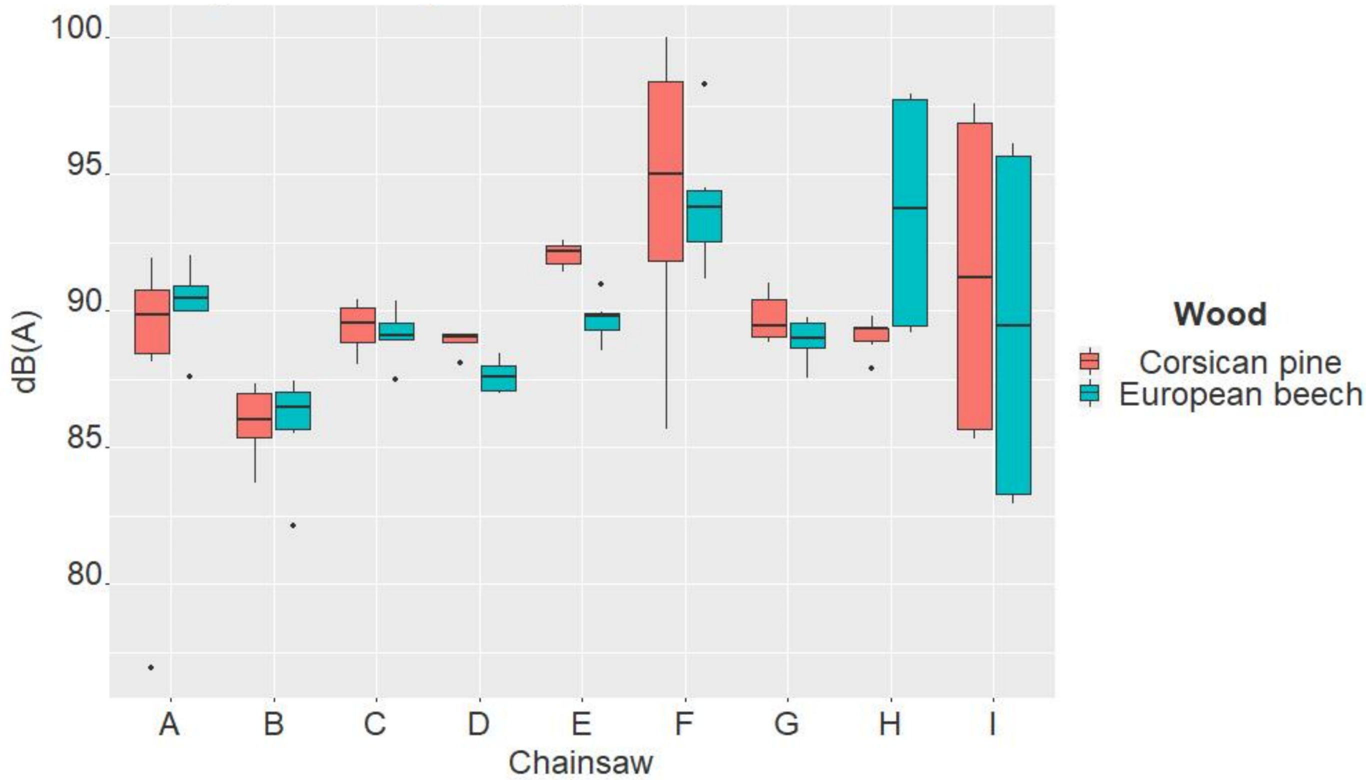

Figure 5. Average 8 h A-weighted equivalent continuous noise level during cross-cutting phase.

Table 4. The noise and vibrations emissions of tested chainsaws considering different daily exposure values (4, 6, and 8 h scenarios).

Chainsaw Code	Noise dB(A) L_{EX}						Vibration m s^{-2}					
	4 h		6 h		8 h		4 h		6 h		8 h	
	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW
A	85.6	87.8	87.3	89.6	88.6	90.8	4.7	5.4	5.8	6.6	6.7	7.6
B	82.9	83.4	84.7	84.9	85.9	86.4	4.6	4.8	5.7	5.9	6.5	6.8
C	86	86.8	87.8	88.6	89	89.8	3.8	3.5	4.6	4.3	5.3	4.9
D	85.1	85.2	86.9	87	88.1	88.2	7.5	8.2	9.3	10.1	10.7	11.6
E	87	87.3	88.8	89	90	90.3	5.0	5.6	6.2	6.9	7.1	7.8
F	89.9	91.5	91.7	93.3	92.9	94.6	5.7	5.8	7.0	7.1	8.1	8.2
G	85.3	88.5	87.1	90.3	88.3	91.5	5.0	5.2	6.2	6.3	7.1	7.3
H	86.2	88.7	87.9	90.5	89.2	91.7	5.1	5.4	6.3	6.6	7.2	7.6
I	87.3	88.4	89.1	90.2	90.3	91.4	5.9	6.3	7.2	7.7	8.3	8.9

SW = Corsican pine; HW = European beech.

Table 4 grouped the noise and vibrations emissions of tested chainsaws starting from the high values monitored during the cross-cutting operation for each different log. Compared to the European legislation and to the noise exposure assessment standards [13], the results indicate that each chainsaw exceeded the 80 dB(A) minimum action level, indiscriminately between wood type and hourly exposure. In the exposure interval of 4 and 6 h, only the chainsaw B did not exceed the daily threshold of 85 dB(A) in both wood types. However, the noise exposure based on 4 h showed values nearest to 87 dB(A) respective to 6 and 8 h, where the values went beyond the maximum allowable daily exposure threshold.

The differences in daily noise (L_{EX}) between chainsaws due to engine power or years of use have not highlighted important distinctions. This is a symptom of how noise remains a risk factor for human health strictly connected in the use of the chainsaw, whatever the model, the years of use, and the engine power.

Similarly to noise values, the daily vibration exposure value A (Table 4), normalized to three-different-hour reference periods, exceeded in all sampled chainsaws with the daily exposure action value of 2.5 m s^{-2}, limiting threshold beyond which it is mandatory to reduce exposure to this physical agent. Higher values were obtained in three different models of chainsaws (D, F, and I) in each different daily exposure. It could be assumed that the exposure values have been influenced by the years of use of the chainsaws but, in reality, a cause of a technical nature of the chainsaw itself seems more plausible. In fact, other chainsaws, with the same period of years of use, have showed lower vibration values. For example, chainsaw C, despite having about 12 years of use and a high engine power, generated lower vibration values than all the models tested. Therefore, the results showed that the differences in power and years of use between the different chainsaws confirm that the levels of exposure to these two physical risk agents (noise and vibrations) are highly variable and depend mainly on the type of chainsaw construction.

5. Discussion

Noise and vibration are closely linked [44]. The study evaluated together these two physical agents to determine the potential levels of acoustic and vibrations pressures on operator working occasionally in felling and bucking operations in agroforestry.

Noise and vibrations levels generated by a chainsaw are significant issues on agroforestry farms because they are not always considered a hazardous problem due to the short period (days/year) dedicated to wood harvesting.

As a consequence, the use of appropriate control measures and protection strategies, as well the evaluation of the vibration and noise exposition levels, are precautions to reducing the workload, noise, and musculoskeletal disorder risks.

In the case of professional use of the chainsaw, this is common daily maintenance, and the chainsaw periodically replaced to ensure the efficiency of sawing and reduce vibration and noise exposition levels. In the case of small-scale agroforestry context, chainsaws are hardly replaced, therefore the exposition to these physical agents increases.

Therefore, despite the technical progress developed by manufacturers to contain exposure to these risk agents, in small agroforestry the exposure limits are constantly exceeded. As reported by Landekić et al. [23], every chainsaw in professional forestry must undergo a verification process every three years in Croatia, and maintenance and replacement of parts must be in accordance with the manufacturers' recommendations. In addition to the replacement or valid maintenance of chainsaw, Calcante et al. [45], confirmed that reducing exposure to noise and vibration levels can be improved not only with the technological progress of the engine design, but above all by adopting advanced fuels that lead to a more efficient combustion process and consequently to reduce the vibration amplitudes.

The results obtained in the specific condition of the agroforestry farms in southern Italy partially reflect what was identified by previous studies [30,33], which considered chainsaws of the same age and in new conditions. In fact, in our study, it is clear that the vibration levels depend on the chainsaw model and occur according to the accelerometer position (front and rear handles), while the results of vibration levels on different wood types are significant, but slighter than the results when using different chainsaw models. In the case of Kováč et al. [30] (Norway spruce wood versus Scotch pine wood), and Rottensteiner et al. [33] (Norway spruce wood versus European beech wood and Black poplar wood), the impact of wood density is determined in terms of vibrations due to wood tree species and the consideration of the chainsaw as new. However, differences in years in the use of chainsaws seem to have not had an influence in terms of vibration exposure, as comparable values were measured despite the difference in age of use, as has been confirmed by Landekić et al. [23]. The study evaluated vibration levels separating 30 chainsaws into three groups of ages with an interval of years from three to ten years. In their study, the authors indicated that the daily vibration exposure was not affected by the years of use comparing three different types of professional chainsaws. This consideration supported the result of our study that added more information and data in the field of the safety and health of operators. In fact, as foreseeable, the daily vibration exposures A(6) and A(8) abundantly exceeded the limit value of 5 m s^{-2}, the sign indicated by several authors [15,23] to also be the low or total absence of maintenance. Instead, the scenario imagined with daily exposure of only 4 h, reduces the potential impact of vibrations for many of the chainsaws tested; perhaps it would be useful to indicate the maximum time of use per day for these types of chainsaws with a limit of 4 h.

As reported by EU Directive 2002/44/EC [19], vibration exposure is an important indicator in defining occupational safety measures, and each action must be developed to reduce this vibration hazard to a minimum. In terms of noise generated, the high values generated by each chainsaw exceeded the exposure limit of 85 dB(A), however this value was expected, as it was widely declared by the constructor (Table 1).

However, it is important to remember that after overtaking this value, it is necessary to take measures to eliminate negative values of noise to protect the health of workers. Almost all chainsaws overtake the daily exposure level A(4), and the noise value is in the range of 85–90 dB(A) for softwood and 85–91.5 dB(A) for hardwood. In this case, evaluating the aged chainsaws used and the non-continuous use, it is possible to control the noise with the reduction at the receiving point by wearing personal protective equipment (PPE) to control of the sound field. In fact, earmuffs or similar hearing protectors reduce the perceived noise level, thereby eliminating the danger of deafness. Another possible solution can be the reduction of time use in chainsaw work, as already suggested, for the reduction of vibration exposures.

Several and detailed previous studies [16,23,46] have aimed to compare the values of vibration and noise declared by constructed respect the occupational exposure limits without considering how these values can change over the years and even decades from their first use. This study added more information with respect the study conducted by Landekić et al. [23] that considered only three types of used professional chainsaws. Instead, at a non-professional level there is still a lack of information which translates into greater risk for operators, even if they work occasionally. Compared to other studies that have shown that engine power is the main cause of high noise levels [15,30,32,45], in this analysis, the data showed that years of use and association with low maintenance, can affect noise levels. If work of a chainsaw operator, even if occasional, is characterized by a large physical load and high risk of accidents, it also endangers his health in other ways, of which vibrations and noise are the most important [47]. In fact, Kovac et al. [30], suggested how inappropriate chainsaw operations, i.e., absence of maintenance and lack of safety equipment, may worsen the effects of noise and vibration.

Although the results of our study could be seen in the light of some important limitations, including for example the small representative sample of chainsaws used, the data obtained confirm previous but few studies that have examined used chainsaws many years after their first use [15,23]. Therefore, this information supports the need for continuous control of these tools, which are erroneously considered not harmful to human health only for their occasional use in small-scale agroforestry practices. In addition, these considerations are also supported by Calvo et al. [38], who provided reliable information on the service life and maintenance cost of chainsaws used in forest operations, estimating a service life of 8 years.

6. Conclusions

This study stands out for evaluating the variability in terms of exposure to vibrations and noise in the use of the chainsaw, as well as in its usual conditions of operators involved in the management of agroforestry systems. Some occupational health disorders, such as hearing losses, repetitive stress syndromes, and certain musculoskeletal trauma, are the subject of study and research among relevant international agencies, such as FAO and ILO, in countries with significant forestry sectors. In fact, wood harvesting exposes the operators to occupational disturbance levels and, in this perspective, this research is one of few studies focused on the monitoring the vibro-acoustic impacts on used chainsaws in small agroforestry companies. Among all nine samples of chainsaws examined, in fact, the chainsaw with fewer years of use, despite being the one with the highest engine power (kW), generated similar or sometimes lower noise levels compared to less powerful chainsaws. This consideration could be useful to focus once again on the importance of valid and correct maintenance, also and above all for small agroforestry companies that occasionally use these aged tools. In general, the study has confirmed the important role of correct maintenance of chainsaws. It has been verified that the use of aged and unprofessional chainsaws increases the risk factor due to the occurrence of noise and vibrations, but which are not strictly influenced by the type of wood sawn. The results of this work should be interpreted as being indicative as they account for a descriptive case study which can prove its utility and replicability in similar conditions in all agroforestry farms in which the use of chainsaw is low frequent. It is advisable to consider this aspect to start information programs suitable for semi-professional and occasional operators in the use of chainsaws in order to address the operators to better maintenance the chainsaw, reduce the risk of work-related diseases, and increase the level of safety. In further research, it would be interesting to repeat the experiment in other work phases (e.g., felling and delimbing) or testing the same chainsaws before and after valid and specialized maintenance. Despite different health impacts, noise and vibration hazards have similar sources, behave similarly and, from a prevention perspective, the controls have a similar approach. An improvement in the maintenance of used chainsaws may be the first step to reducing the exposures. This solution can be done only with periodic education and training on noise and vibration hazards in ensuring that a safety management program is an integral part of the work environment. In particular, for organizational measures, in addition to the use of PPE, such as gloves and handles which reduce the vibration transmitted to the hand-arm system, rest pauses should be scientifically designed to ensure cardiovascular recovery, and also to limit the exposure to noise during the operational time.

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4.9 Wood Technology and Non-Destructive Testing

Article 8
A tomographic approach to assessing the possibility of ring shake presence in standing chestnut trees

Andrea R. Proto[1], Maria F. Cataldo[1], Corrado Costa[2], Salvatore F. Papandrea[1], Giuseppe Zimbalatti[1]

[1]Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy

[2]Consiglio per La Ricerca in Agricoltura E Analisi Dell'economia Agraria (CREA), via Della Pascolare 16, 00016 Monterotondo, RM, Italy

*Correspondence: andrea.proto@unirc.it; ORCID 0000-0003-4630-898; Tel.: +39 (0) 965.1694275

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A tomographic approach to assessing the possibility of ring shake presence in standing chestnut trees

Andrea R. Proto[1] · Maria F. Cataldo[1] · Corrado Costa[2] · Salvatore F. Papandrea[1] · Giuseppe Zimbalatti[1]

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Abstract
Ring shake is a widespread phenomenon affecting a great number of species of both softwood and hardwood and is found in trees grown in temperate and tropical climates. Chestnut (*Castanea sativa* Mill.) represents one of the most important hardwood timbers that is very often affected by ring shake. This defect seems to be the only real limit to the spread and use of chestnut wood worldwide on a scale closer to the availability of this wood. The aim of this study was to examine the potential of tomographic measurement as a non-destructive method for predicting the possibility of the presence of ring shake in standing chestnut trees. For this reason, the experiments were carried out in a chestnut coppice stand where one hundred chestnut standards were monitored using an acoustic tomographic device, and subsequently harvested by a local company and cross-sectioned corresponding to the acoustic tests. This work proposed an applied approach to predicting and determining wood quality (sound wood vs. defective wood) from tomographic data. The model, based on a non-linear approach, showed that sonic tomography can identify ring shake in a tree trunk without affecting its biological activity, overcoming the difficulties of predicting ring shake using only visual inspection.

1 Introduction

Several technologies were introduced in the early twentieth century in Europe and North America to assess wood quality in standing trees in response to the numerous requests by wood products manufacturers and forest managers worldwide. A significant effort has been devoted to developing robust non-destructive technologies (NDT) that are capable of predicting the intrinsic wood properties of individual trees and assessing wood quality at the stand and forest scale. Wood quality can be assessed by several techniques, such as the use of penetrometers and drilling resistometers, acoustic methods and imaging (Pellerin and Ross 2002). Drilling resistance measurement is a semi-destructive method commonly used for wood defect detection where a thin steel probe penetrates into the wood. Low resistance in a resistance profile typically indicates decay, cavities, or large internal cracks (Wu et al. 2018), but one problem with this technique is that the results are restricted to a single perforation, with no scanning of the cross-section. The acoustic method is based on the observation of stress wave propagation. In general, stress waves travel faster in high-quality wood than in deteriorated and low-quality wood (Divos and Szalai 2002; Wang et al. 2007). Based on this fundamental conclusion and signal acquisition of stress wave propagation velocity in wood cross-sections, the horizontal distribution of the stress wave velocity in wood can be analysed (Fang et al. 2011; Li et al. 2014; Du et al. 2018). A typical approach for measuring wave propagation velocity in standing trees involves inserting two sensor probes into the sapwood and introducing stress wave energy into the tree trunk from a point source through a hammer impact (Proto et al. 2017). This procedure is referred to as a single-path stress wave timing measurement, and the stress wave velocity obtained suggests the physical condition of the tree. An important limitation of this method, as reported by Wang et al. (2005), is the absence of a standard reference velocity for data interpretation for each tree. A single-path stress wave measurement can only detect internal decay that is above 20% of the total cross-section area (Wang et al. 2007). To remedy the several limitations of single-path stress wave timing tools and to define the extent and location of any

✉ Andrea R. Proto
andrea.proto@unirc.it

[1] Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy

[2] Consiglio Per La Ricerca in Agricoltura E Analisi Dell'economia Agraria (CREA), via Della Pascolare 16, 00016 Monterotondo, RM, Italy

internal decay, sonic tomography has been introduced, and its applicability to standing trees has been evaluated positively. Acoustic tomography technology simultaneously uses multiple sensors that function both as signal emitters and receivers, evenly distributed around the cross-section of the tree trunk, to measure the variation in acoustic transmission speeds in multiple directions. Computer projection software then uses the acoustic wave data matrix to create an image (a tomogram) of the acoustic wave velocity for the cross-section of the tree (Wu et al. 2018). The use of acoustic tomography technology is beneficial for appropriate tree management in urban communities; in fact, an acoustic tomographic device permits the acquisition of data from the inner part of the trees, and the tomograms allow the determination of the stability of the trees to minimize the risk of tree failure. Numerous previous studies have determined, using this tomograph method, different types of structural defects, such as heartwood and sapwood decay, internal and lateral cracks, ring shake and hollows in urban trees (Bucur 2003; Nicolotti et al. 2003; Deflorio et al. 2008; Lin et al. 2008; Feng et al. 2014; Rinn 2015). Ostrovský et al. (2017) demonstrated that tomograms were 83% accurate for the determination of area and location of defects in the laboratory using green sample discs from extensively damaged trees in an urban environment. Several years after its use became widespread in urban forestry, some researchers have turned this NDT technique from urban forestry to the wood products industry for determining wood properties; however, the potential of this technology for assessing the quality of high-value hardwood trees in production forests has not been fully investigated (Wang et al. 2005).

Ring shake is a widespread phenomenon affecting a great number of species. In chestnut (*Castanea sativa* Mill.), in fact, ring shake seems to be the only real limit to the spread and use of chestnut wood worldwide, on a scale closer to the availability of this wood in the countries of the Mediterranean basin (Macchioni and Pividori 1996). The study of the internal state of this species has a long tradition in Italy and throughout Europe due to the high economic value of its wood products. It is one of the most important forest tree species; it grows commonly in hilly and mountainous areas, where it is primarily used as timber in construction and furniture. Ring shake defect is a type of wood crack that develops as a circular failure on the tangential plane in the ligneous tissue along the annual growth ring in standing trees (Owen and Wilcox 1982; Chanson et al. 1989). Many studies (Bourgeois 1992; Macchioni and Pividori 1996; Fonti et al. 2002a, b; Becagli et al. 2002–2004; Spina and Romagnoli 2010) have focused on describing the anatomical features of the ring shake phenomenon and on the possible causes that determine their occurrence using destructive techniques and laboratory analysis. The defect of ring shake occurrence greatly reduces the value of the timber assortment; in the worst cases, the incidence of ring shake is so high that only a few logs of a stand can be brought to the sawmill (Fonti et al. 2002a). In fact, Chanson et al. (1989) and Fonti et al. (2002b) reported the presence of ring shake in 39–60% of trees in sample plots observed immediately after felling at several locations in France, Italy, Switzerland, and Spain. Mutabaruka et al. (2005) carried out a study to assess the value of external tree characteristics in predicting ring shake. The study by Birbilis et al. (2018), in accordance with that of Romagnoli and Spina (2013), has shown that it is possible, based on the age and diameter of the trees, to successfully predict the presence of ring shake. Mariño et al. (2010) have reported on detecting pith location in chestnut lumber by non-destructive evaluation in laboratory tests using a different tomographic device, while Dündar et al. (2016) examined the potential of ultrasonic velocity as a rapid and non-destructive method for predicting the dimensional stability of the chestnut specimens commonly used in the flooring industry. Opinions diverge on whether ring shake is already present in standing trees, with several authors believing that it might be present at least in standing trees or in green wood discs (Bonenfant 1985; Leban 1985; Cielo 1988; Chanson et al. 1989; Fonti 1997). Giudici et al. (1998) used ultrasonic measurement on stems; Götz and Mattheck (1999) tested a fractometer on wood samples taken directly from standing trees. Fonti et al. (2002a) detected ring shake directly on green wood discs in 70% of the entire observed sample, while ring shake developed in the remaining 30% during the drying process, particularly concentrated in those wood discs that were already affected by the defect in their green state. Therefore, the purposes of this study were to determine the best non-destructive parameters for predicting ring shake in standing chestnut trees and the accuracy of the tomographic techniques.

2 Materials and methods

2.1 Study sites and tree samples

The test site was situated in Southern Italy (Calabria region), in the municipality of Cardinale in the Serre Massif. In Calabria, chestnut occupies 101,600 hectares, 21.1% of the regional woodland surface, divided into high forests (47.3%) and pure coppices (52.7%). The majority of chestnut orchards (88.3%) are private property, and the remaining 11.7% are under public ownership. The study area covers a total of 15 hectares with an altitude ranging from 610 to 780 m. The climate is temperate, with an annual mean temperature of approximately 13.5 °C, and the annual rainfall is 930 mm unevenly distributed through the year, with the minimum precipitation occurring in the summer. The study site was coppiced with first-class standards derived from coppice shoots growing from the previous cut. The shoots were approximately 14 years old, whereas the standards were 28 (II cycle) and 42 (III cycle) years old. The breast height (DBH) was measured using a classic diameter calliper, and tree height was measured with a vertex IV hypsometer. Based on these measurements, one hundred chestnut standards of the III cycle with regular cross-sections (cylindrical body) were selected, and each tree was marked with a red plastic tag and assigned a tracking number for conducting the tomographic study and for the subsequent felling phase (Fig. 1a, b). The choice of this population was dictated not only by their favourable characteristics for production silviculture but also by the assured presence of ring shake in the trees, identified through inquiries among local foresters. The main characteristics of the study sites are shown in Table 1.

Table 1 Study area characteristics and dendrometric parameters

Parameters	Unit measure	Value
Altitude—range a.s.l	m	610–680
Slope—range	%	15–20
Average basal area for tree	m^2	0.102
Average basal area for hectare	$m^2\ ha^{-1}$	26.14
Volume for hectare	$m^3\ ha^{-1}$	214.15
Coppice shoots diameter	cm	20.12
Standard diameter	cm	33.03
Number of stump	$n\ ha^{-1}$	370
Shoots—number of trees	$n\ ha^{-1}$	1720
Standards—number of trees	$n\ ha^{-1}$	65

2.2 Field acoustic tomography test and laboratory measurements

All 100 standards were first non-destructively tested using a commercial ArborSonic 3D acoustic tomograph device (Fakopp Enterprise Ltd., Hungary) and the sample trees were monitored at a height of approximately 50 cm above the ground (Macchioni and Pividori 1996; Spina and Romagnoli 2010). The sampling height was chosen because it is the most susceptible to ring shake defects. At this height, the circumference was measured by an operator using a tape measure; this data was inserted in the software (ArborSonic3D software, ver. 6.2.), which calculated the positions of the sensors that were used to map the approximate geometric form of the cross-section. The tests were performed in accordance with the manufacturer's (Fakopp Enterprise Ltd. 2019) and software's instructions and these test procedures are explained in many similar papers (Deflorio et al. 2008; Johnstone et al. 2010; Alves et al. 2015; Ostrovský et al. 2017; Marra et al. 2018; Trenyik et al. 2018). Eight sensors were used for each tree and the travel times (in µs) generated from each sensor were captured by the other sensors. Every measurement was repeated three times on each sensor (repetitions) in order to obtain averaged travel times to reduce uncertainties from individual testing. After using the last sensor as a transmitter, the recording stopped, the measurement was saved and the software, applying a filtered back projection evaluation (Buza and Göncz 2015), constructed the two-dimensional tomographic image adapting to the anisotropy condition (Maurer et al. 2006; Dikrallah et al. 2010). The velocity of wave movement was automatically calculated based on the time registered for the passage of the impulse between sensors. The tomograms in the software displayed the relative sound transmission speeds on a four-colour discrete scale, and the operator associated different speeds with different colours. The colour of the lines from every sending to every receiving sensor visualizes the virtual speed: green means the stress wave travelled fast. Yellow, red and purple lines indicate that the waves circumvented the defect and did not travel straight through it. During testing, each sensor position was marked so that the original location in the stem disc could be traced in order to assess the condition of the wood at the area of sampling. The tomographic acquisitions lasted 5 consecutive days (June 2016) to guarantee similar environmental conditions.

After the acoustic measurements had been taken, the 100 trees were subsequently harvested by a local company and cross-sectioned corresponding to the acoustic tests. A 5-cm thick disc was collected from each stem (Fig. 1c) and taken to a laboratory where the physical characterization (ISO 3130, 3131, 4469, 4858) was performed. The physical

Fig. 1 In situ acoustic tomography test on a standing tree (**a**) and successive harvesting phase (**b**) and collection of a wood disc (**c**)

characteristics were determined to compare the physical properties of trees affected by ring shake and those that are not (shaken trees and healthy trees). In particular, the following parameters were measured: density at 12% moisture content (ρ_{12}); basic density (ρ_y), which is the ratio between the oven-dried weight and green volume; total shrinkage (radial (β_r), tangential (β_t), and volumetric (β_v) shrinkage) coefficients measured from the maximum water content to oven-dried moisture content. The data were processed to align the propagation velocity data with the corresponding region, either healthy or defective. Each wood disc was subdivided into four regions (A, B, C and D), or quadrants like a Cartesian plane, where 1 ↔ 5 and 3 ↔ 7 paths represented *x*-axis and *y*-axis respectively, using the same orientation as for the installation of the tomographic sensors to permit the correct localization of the defects on the reciprocal paths. The presence of ring shake was evaluated with a visual inspection in laboratory identifying the critical year (ring position), and the extent was measured on the wood discs as the ratio between the arc of the circle of the shake and the corresponding total circumference (Spina and Romagnoli 2010). At the end, its location on the wood disc was used to overlay the paths generated by tomography.

2.3 Data analysis

Acoustic reconstruction based on the transmission velocity of a stress wave can be performed in different ways depending on the type of defect. For this reason, in this study, the velocity of the acoustic wave transmission measured from each chestnut tree was studied and used to predict the presence of ring shake with respect to the typical application of two-dimensional tomograms to detecting cavities or decay. The proposed methodology aims to find a velocity reference value to detect the defective region considering the relationship between stress wave velocity and its propagation direction, with the assumption that the tree has a regular cross-section (Li et al. 2014; Rinn 2015; Espinosa et al. 2017). The acoustic velocities obtained from different angles (± 67.5°; 45°, 22.5° and 0°) were compared, and the ratio between the tangential velocity and the radial velocity was analysed. In particular, the orientation angle represented the position of the receiver point relative to the source point, with $\theta = 0$ representing the velocity in the radial direction, i.e., the angle between an emitter sensor and the diametrically placed receiver sensor. A total of 2800 paths, excluding repeated data, were registered, and the comparison between the paths of stress wave measurements on one cross-section (sound wood vs. defective wood) was applied. Using the tomographic technique, a complete data matrix was obtained through the measurement of stress wave transmission time with the aim of intercepting the localization of ring shake using the intersection of the paths generated simultaneously during the test.

2.4 Statistical approach

The statistical analyses were based on an artificial intelligence approach. The analysis was performed on the matrix composed of 2 sets of variables for the 100 samples. The first was composed of mean velocity, and the second was composed of Vt/Vr values. Both datasets represent values at 0°, ± 22.5°, ± 45°, and ± 67.5°. Both datasets include tree circumference and diameter and wood density values. The Vt/Vr dataset does not include 0° values reporting equal values for all the samples. The models were developed using a non-linear classification Artificial Neural Network (ANN) approach. The ANN was developed based on an input layer (*x*-block) to estimate the binary output layer (sound wood *vs*. defective wood; *y*-block). In detail, the eight average velocities of wave movement, having the same propagation direction (i.e. 1 → 2, 2 → 3, 3 → 4, etc.), were copied from the ArborSonic3D software to a MS Excel spreadsheet and in each row, the Vt/Vr values were calculated as the ratio between the tangential velocities (+ 67.5°, ± 45° and ± 22.5°) and the radial velocity (source point 0°). This operation was repeated for each tree monitored and separated between sound wood and defective wood. The ANN model was developed using a probabilistic neural network (PNN). PNN is a feedforward neural network that is widely used in classification and pattern recognition (Specht 1990). In the PNN algorithm, the parent probability distribution function (PDF) of each class is approximated by a Parzen window and a non-parametric function (Specht 1990). Then, using the PDF of each class, the class probability of a new input data is estimated, and Bayes' rule is then employed to allocate the class with the highest posterior probability to the new input data. Using this method, the probability of misclassification is minimized (Zeinali and Story 2017). This type of ANN was derived from a Bayesian network (Friedman et al. 1997) and a statistical algorithm called kernel Fisher discriminant analysis (Cheung and Cannons 2003). In a PNN, the operations are organized into a multi-layered feedforward network with four layers: the input layer, in which each neuron represents a predictor variable; the pattern layer, which contains one neuron for each case in the training data set; the summation layer, which contains one pattern neuron for each category of the target variable; and the output layer, which compares the weighted votes for each target category accumulated in the pattern layer and uses the largest vote to predict the target category. The PNN was trained with a back-propagation learning algorithm. From the 100 observations, to avoid overfitting, only 75 samples (75%) were used to construct the models. The remaining 25 samples (25%) were then used to test the performance of the models (internal test). The partitioning of the two datasets was optimally chosen with Euclidean distances, based on the algorithm developed by Kennard and Stone (1969), which selects objects without a priori knowledge of a regression model (i.e., the hypothesis is that a flat distribution of the data is preferable for a regression model). The training of the ANN was carried out using a learning equal to 0.5 and a momentum equal to 0.1. The training procedure was repeated 1,000,000 times, and the best-performing PNN was selected based on the independent test set. The percentages of correct classification on the model and the test sub-sets were reported. A variable impact neural network analysis was performed to assess the relative importance of each variable (Abdou et al. 2012). Operatively, this index is similar to the linear regression variable importance in the projection (VIP) scores (Chong and Jun 2005; Febbi et al. 2015). The ANN analysis was performed using Palisade Neural Tools 7.6.

3 Results

After cutting the stem disc with a chainsaw, in several cross-sections, some ring shake decay, visually invisible on the external surface of the trees, was observed from the visual inspection only after a few weeks, in the laboratory, showing the typical aspect. Of the 100 trees examined, 61 standards were affected by ring shake, and only 39 were intact. The laboratory measurements described in Table 2 show several of the monitored characteristics of chestnut wood. The mean and standard deviation (SD) values confirm that the physical properties and density were high in healthy trees, whereas shrinkage values were low in shaken trees. In particular, the values of radial, tangential, and volumetric shrinkage of the shaken trunks were different from those of the healthy trees.

Table 2 Physical properties of trees: sound wood (SW) and defective (D)

Property	Tree type	Mean	SD	N
β_r	SW	3.29	0.84	39
	D	3.15	0.76	61
β_t	SW	6.93	0.82	39
	D	6.45	0.78	61
β_a	SW	0.42	0.36	39
	D	0.37	0.47	61
β_v	SW	10.41	1.29	39
	D	10.24	0.98	61
ρ_{12}	SW	601.79	51.15	39
	D	597.21	43.18	61
ρ_y	SW	509.64	41.24	39
	D	501.29	37.81	61

β_r radial shrinkage (%), β_t tangential shrinkage (%), β_a, axial shrinkage (%), β_v, volumetric shrinkage (%), ρ_{12} density at 12% moisture content (kg/m^3), ρ_y basic density (kg/m^3)

The results separated and catalogued the paths derived from sound and defective wood to evaluate the comportment of the stress wave in detail. The mean, standard deviation, and range of the acoustic velocity measurements on standing trees are reported with the different and sequential paths generated by the eight sensors on sound wood (Table 3) and defective wood (Table 4). The data obtained in sound wood confirmed that the velocity in the radial direction Vr (with $\theta = 0°$) was the highest, and the velocity in the tangential direction Vt (with $\theta = \pm 67.5°$) was the lowest. The average speed in the radial direction (1944 m s^{-1}) was approximately 3.2%, 5.8% and 8.7% higher than that for the paths generated by angles of 22.5°, 45° and 67.5°, respectively. In sound wood, the standard deviation was low in each of the 28 paths registered from the 39 trees examined, which suggests a strict interval in which the acoustic signal travels between two sensors indifferently from various angles.

During the tests conducted on trees affected by ring shake, the tomographic software recorded 210 paths indicating slow speeds with respect to the others on the same tree cross-section. On average, each defective tree showed 3–4 slow paths, and the majority (96%) was collected with an angle of 0° and 22.5°. The high values of the standard deviations registered on paths generated (Table 4) with respect to the other two tangential directions (45° and 67.5°), confirmed the possibility of finding this defect in the radial direction, or with a small directional angle between the source point and receiver point. The mean of the acoustic velocity measurements registered in these 210 paths were 1403 m s^{-1}, 1434 m s^{-1} and 1507 m s^{-1} for the paths generated by angles of 45°, 22.5° and 0°, respectively. The tomograms generated from defective wood showed a typical round form with a red/yellow area in the centre, which could indicate severe heartwood decay damage, but the examination of the disc conducted in the laboratory showed that the defect was ring shake, not heartwood decay (Fig. 2). Purple lines, in fact, are never shown on tomograms because no trees were hollow or deeply damaged. The presence of a red (dark) area inside the yellow (light grey) shape, for example tree n. 45, indicated a lower speed of transmission with respect to the closest angle. In the laboratory, this deterioration was confirmed with an accentuated detachment of the annual ring. In particular, in the A region, a small ring shake was identified with a yellow colour, while in the C region, an additional ring shake was located deeper in the tree. In fact, the ring shake acted as a barrier that cut off the linear propagation of the acoustic waves. As a result of the geometric shape of the ring shake (round), the acoustic tomogram produced by the software erroneously indicated the presence of heartwood decay or internal cracks. Figure 3 shows the paths of stress wave measurements (a) before the software generated the tomogram and (b) the subsequent superimposition on the corresponding cross-section of tree no. 87, where the paths

Table 3 Acoustic velocity data of sound wood

Paths 67.5°				Paths 45°				Paths 22.5°				Paths 0°			
	Speed m s^{-1}				Speed m s^{-1}				Speed m s^{-1}				Speed m s^{-1}		
Way	Min	Max	Mean (σ)	Way	Min	Max	Mean (σ)	Way	Min	Max	Mean (σ)	Way	Min	Max	Mean (σ)
1↔2	1599	1946	1796 (±67)	1↔3	1687	2039	1844 (±74)	1↔4	1711	2058	1883 (±73)	1↔5	1727	2095	1936 (±77)
2↔3	1572	1878	1769 (±84)	2↔4	1664	1972	1814 (±75)	2↔5	1680	2012	1855 (±86)	2↔6	1735	2069	1931 (±78)
3↔4	1579	1897	1774 (±74)	3↔5	1622	2017	1838 (±92)	3↔6	1723	2024	1884 (±74)	3↔7	1737	2079	1942 (±75)
4↔5	1580	1933	1765 (±87)	4↔6	1612	1961	1830 (±78)	4↔7	1754	2043	1884 (±71)	4↔8	1798	2113	1964 (±69)
5↔6	1616	1945	1764 (±74)	5↔7	1678	1956	1812 (±69)	5↔8	1699	2032	1883 (±68)				
6↔7	1553	1893	1769 (±95)	6↔8	1674	1988	1848 (±75)	6↔1	1587	2034	1860 (±98)				
7↔8	1620	1894	1783 (±72)	7↔1	1699	1982	1822 (±69)	7↔2	1765	2026	1891 (±72)				
8↔1	1611	1931	1773 (±65)	8↔2	1643	1964	1836 (±70)	8↔3	1724	2045	1908 (±84)				

Standard deviations are given in parentheses

Table 4 Acoustic velocity data of defective wood

Paths 67.5°				Paths 45°				Paths 22.5°				Paths 0°			
	Speed m s^{-1}				Speed m s^{-1}				Speed m s^{-1}				Speed m s^{-1}		
Way	Min	Max	Mean (σ)	Way	Min	Max	Mean (σ)	Way	Min	Max	Mean (σ)	Way	Min	Max	Mean (σ)
1↔2	1742	2046	1862 (±51)	1↔3	1420	2066	1889 (±126)	1↔4	1325	2021	1809 (±249)	1↔5	1416	2222	1976 (±223)
2↔3	1761	1991	1874 (±46)	2↔4	1509	2072	1920 (±71)	2↔5	1328	2105	1803 (±244)	2↔6	1354	2194	1806 (±295)
3↔4	1806	1983	1865 (±40)	3↔5	1485	2211	1927 (±80)	3↔6	1345	2250	1834 (±233)	3↔7	1411	2207	1883 (±270)
4↔5	1789	2073	1870 (±47)	4↔6	1851	2570	1945 (±89)	4↔7	1382	2087	1857 (±197)	4↔8	1327	2194	1860 (±285)
5↔6	1782	2065	1874 (±49)	5↔7	1861	1995	1929 (±32)	5↔8	1327	2104	1867 (±226)				
6↔7	1799	2197	1873 (±67)	6↔8	1891	2113	1950 (±46)	6↔1	1364	2224	1818 (±253)				
7↔8	1721	2138	1876 (±65)	7↔1	1374	2190	1902 (±109)	7↔2	1321	2069	1790 (±244)				
8↔1	1798	2051	1875 (±48)	8↔2	1457	2097	1924 (±87)	8↔3	1367	2239	1823 (±247)				

Standard deviations are given in parentheses

7↔2, 7↔3, 7↔4, and 8↔5 in the C region intercepted the ring shake. In the laboratory, the location and extent of ring shake on defected trees were measured and reported in Table 5. In particular, in this table, the exact position (region and annual ring) of the defect was correlated with the corresponding paths (speed, direction and angle) to demonstrate the accuracy of model predictions. For example, in the case of tree no. 49, a major arc of circumference generated by ring shake intercepted more slow paths. For this reason, the study involved a complete examination of the paths and their interactions between the sensors, and the statistical analysis conducted with two sets of variables confirmed the necessity of evaluating an accurate travel time reading for each path. The results used in the construction of an applicative model

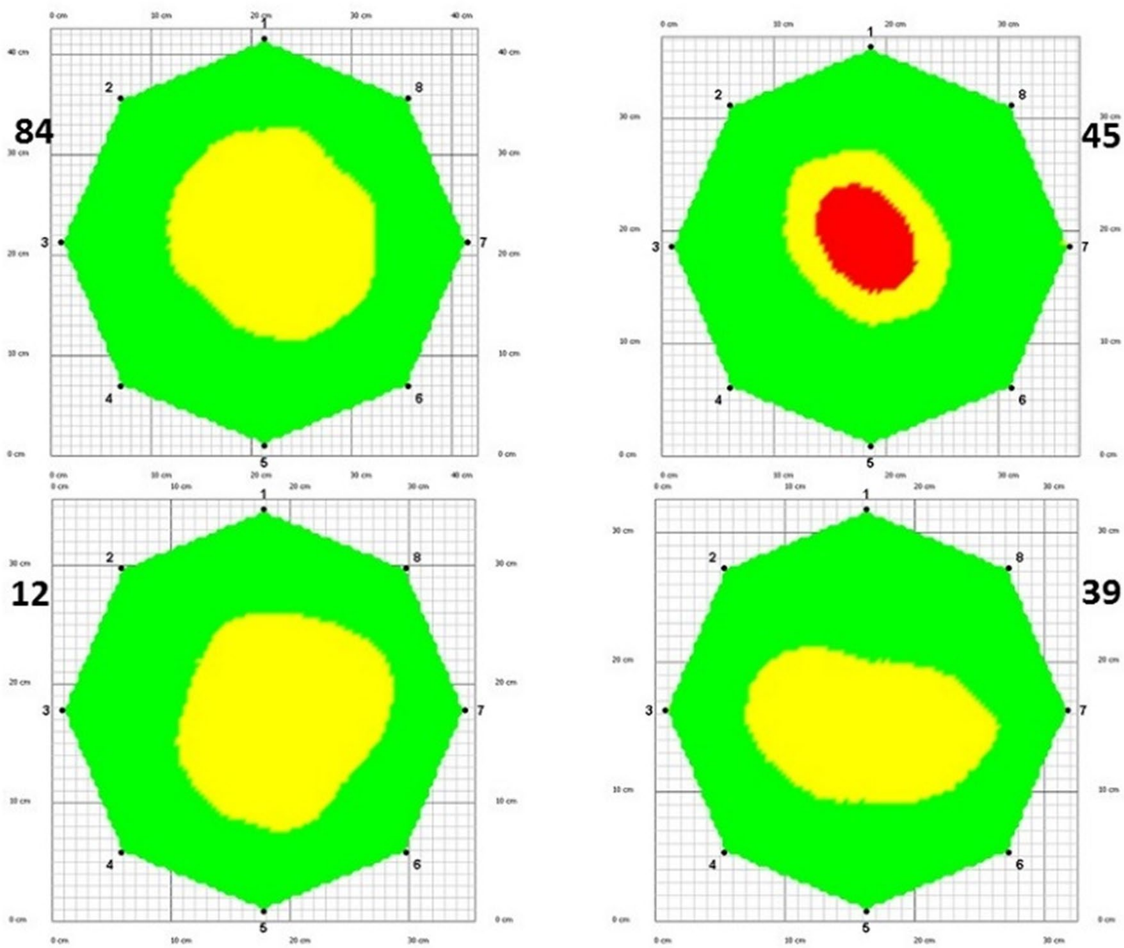

Fig. 2 Sonic tomographic images of cross-sections in four different sampled chestnuts showing internal defects

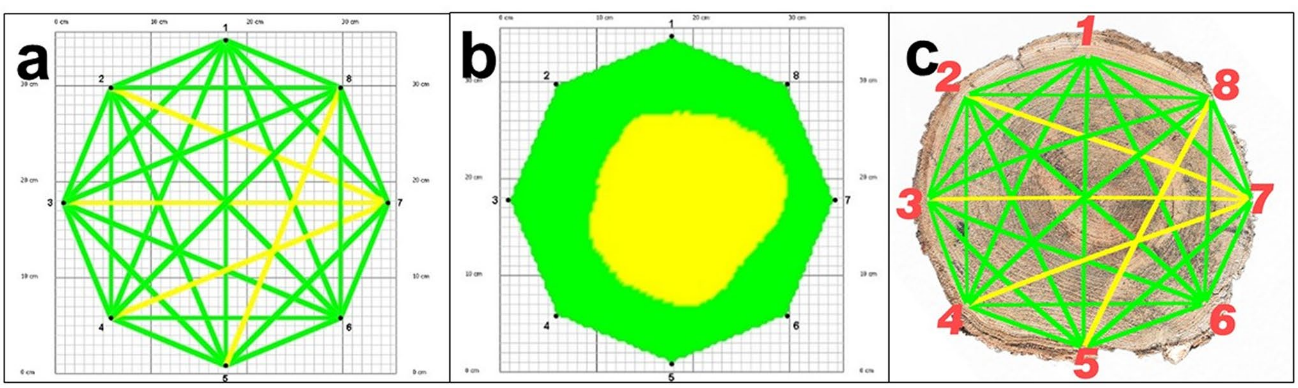

Fig. 3 Comparison of the 28 independent paths generated (**a**), the corresponding sonic tomogram (**b**) and the superimposed paths on the cross-section (**c**)

used to predict sound wood vs. defective wood from mean velocity and Vt/Vr data, are summarized in Table 6. The PNN model reported a perfect classification (by percentage of correct classification) of all the samples, including those in the 25% test set. The relative variable impact (Figs. 4,5), which indicated the importance of the different variables in the non-linear classification process, showed that in the Vt/Vr dataset, the more important variables are the ones

Table 5 Location and extent of ring shake on several trees sampled

Sample (no.)	Diameter (cm)	Region	Path	Angle (°)	Speed (m s^{-1})	Extent of the defect (%)	Ring position (years)
86	37	C	1↔5 5↔8	0° 22.5°	1434 1329	13	24th
91	41	A	2↔5 2↔6 7↔2	22.5° 0° 22.5°	1425 1354 1321	17	29th
70	38	A, B	2↔5 3↔6 3↔7 8↔3	22.5° 22.5° 0° 22.5°	1398 1364 1412 1396	19	31th
49	39	A	1↔3 2↔5 2↔6 7↔2 8↔3	45° 22.5° 0° 22.5° 22.5°	1420 1453 1461 1417 1449	22	33th
88	40	C	3↔7 4↔7	0° 22.5°	1457 1397	14	30th

Table 6 Characteristics and principal results of the PNN model used to determine sound wood vs. defective wood samples using mean velocity and Vt/Vr datasets

	Mean velocity	Vt/Vr
No. samples	100	100
No. classes (*y*-block)	2	2
Mean sensitivity	1	1
Mean specificity	1	1
Efficiency	1	1
Random probability, %	50	50
Mean classification error, %	0	0
Mean % correct classification calibration/validation set (75%)	100	100
Mean % correct classification test set (25%)	100	100
Mean incorrect probability (test set)	0.00	0.01
Std. deviation of incorrect probability (test set)	0.00	0.06

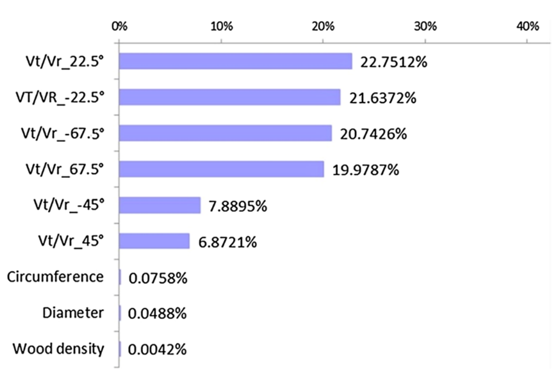

Fig. 4 Relative variable impacts, Vt/Vr

at ± 22.5° and ± 67.5°, while in the mean velocity dataset, the most important variables are at 0°, ± 67.5°, ± 45°.

4 Discussion

This study was designed to evaluate the accuracy of a tomographic technique on standing chestnut trees, to determine the best non-destructive parameters for predicting ring shake. In each of the sound wood trees examined, the measured stress wave transmission times were in good agreement with the theoretical analysis of several studies (Watanabe and Payton 1997; Payton 2003; Schubert 2007). In fact, the correct relationship between the velocity ratio Vt/Vr and the angle θ has been statistically shown as a parabolic curve, with a coefficient of determination $R^2 = 0.94$, and the coefficients of the second-order polynomial regression were $a = -0.0094$, $b = 0.0754$, and $c = 0.841$ (Fig. 6). To the best of the authors' knowledge, there is no study that evaluates NDT techniques for predicting ring shake in standing chestnut trees, but several researchers have addressed accurately the effective prediction of sonic tomography using simultaneous NDT and destructive tests; therefore, comparison of the results reported here with those available in the literature has been partially difficult. Some studies (Deflorio et al. 2008; Brazee et al. 2011; Liang and Fu 2012) used acoustic tomography and destructive measurements to detect internal decay. Recently, Marra et al. (2018) demonstrated how acoustic tomography and electrical resistance tomography, used in combination, can be used to non-destructively quantify the extent of internal decay and the associated carbon loss. Burcham et al. (2019) estimated the accuracy of sonic tomography using colours associated with intermediate sonic velocities comparing the destructively measured

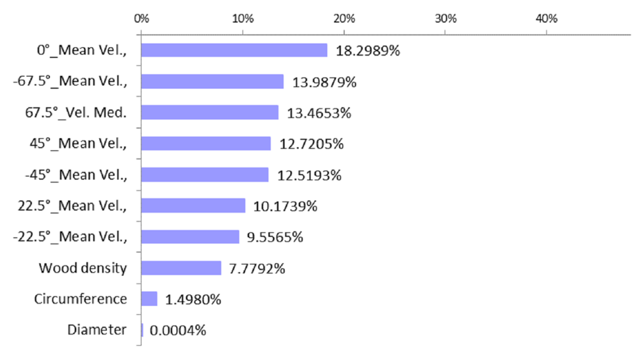

Fig. 5 Relative variable impacts, mean velocity

internal condition of the corresponding cross sections. Starting with the type and characteristics of the defect, the type of ring shake identified in this study can be defined as "healthy ring shake" because visible anomalies in the wood tissue or wounds caused during harvesting or external phenomena were not observed (Chanson et al. 1989; Macchioni and Pividori 1996; Fonti et al. 2002a). As opposed to traumatic ring shake, healthy ring shake has a mechanical origin and may appear, in standing trees (Chang 1972; Ferrand 1980; Chanson et al. 1989; Cielo 1988; Birbilis et al. 2018), with the detachment between cells at the ring boundary between the earlywood zone of the annual ring and the latewood zone of the previous one in the compound middle lamella layer between cells. In this study, the results confirmed what Giudici et al. (1998) found in their research: the discontinuity created by ring shakes caused slower transmission speeds observed on damaged trees. In the literature, this kind of fracture was often reported as a breakage of vessel members and fibre detachment in the area between two annual rings in standing trees, or after felling. It is called green wood ring shake (Chang 1972; Ferrand 1980; Chanson 1988; Cielo 1988; Fonti and Macchioni 2003). The

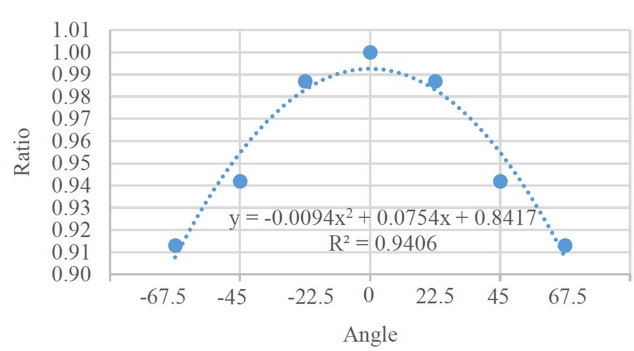

Fig. 6 Parabolic curve created by the average velocity ratio (Vt/Vr) generated by a measured average of 39 sampled trees

occurrence of the ring shake defect is not related to a particular cell type but to the effect of growth stresses imposed on the transversal/radial wood plane (Fonti and Frey 2002; Fonti and Sell 2003; Fonti and Giudici 2005; Birbilis et al. 2018). The range of stress velocities in sound wood samples was similar to the data obtained by Ostrovský et al. (2017), who used the same acoustic tomography technique for wood cross-sections on three chestnut trees. On standing trees, to the authors' knowledge, only Li et al. (2014), using a sonic tomograph, have determined the velocity patterns in eight healthy black cherry trees using the difference in values from four other defective trees. For each measure, Li et al. (2014) used 12 sensors at three different heights and validated the theoretical analysis of the wave velocity paths by applying the results obtained. Most studies have reported that sonic tomography underestimates the size of decay and overestimates the size of cracks (Gilbert and Smiley 2004; Liang et al. 2007; Wang et al. 2007; Deflorio et al. 2008; Liang and Fu 2012; Marra et al. 2018; Burcham et al. 2019), and under certain circumstances, the tomograms of trees with cracks, ring shake or cavities may look similar (Göcke et al. 2008). For this reason, Dackermann et al. (2014), Espinosa et al. (2017), Qin et al. (2018), and Du et al. (2018) have developed different methods to improve the accuracy of tomography techniques and overcome the overestimation problem. Unlike previous studies that evaluated the final accuracy of tomograms to reduce the over- and underestimation of the damaged area, this study applied the statistical accuracy of the Vt/Vr ratio to localize the exact area of the internal defect in the tree using the intersection between the different speeds of transmission. The high number of samples tested guarantees the solidity of the data and the homogeneity of the results, returning exactly the values collected on the standing trees without any necessary laboratory experimentation. This work proposed an applied approach to predicting and determining wood quality applying the ratio Vt/Vr, and the model, based on a non-linear approach (Assirelli et al. 2018), is able to perfectly predict wood quality by returning a correct classification of both validation and test sets. In particular, this PNN statistical model, tested on the Vt/Vr dataset, revealed more important variables necessary to consider before assessing the presence of ring shake. Starting from a correct statistical evaluation of the Vt/Vr ratio, the technique proposed in this study can be improved with the development of a specific application (software or app) capable of evaluating immediately in the field after the acoustic test where wood properties do not limit the use of Vt/Vr ratios as a predictor. This approach returns a ready-to-use dataset and can optionally be integrated into tomography software as second option to use it. The novelty of the present approach is based on a statistical model elaborated comparing the different propagation directions and analysing the velocity of each path. This study has not used a theoretical velocity model as proposed by Li et al. (2014) but rather the intersection between the different velocity patterns identifying the defect with respect to the healthy area. The use of eight sensors, although it required a few more minutes to conduct the test, permits the generation of a database able to identify defective regions in cross-section tomographic images. The use of a single-path stress method, for example, would not have allowed to localize the defect in a specific area of the cross-section but only to identify a slower path with respect to others generated not simultaneously in the same cross-section. In fact, the results from the current study suggest that destructive sampling may not be necessary to confirm the results of the NDT testing as long as the minimum number of sensors, at least eight, is used. The physical chestnut wood properties observed in the Calabrian Region site were in agreement with the reported mean values for chestnut wood in Italy (Nardi Berti 2006; Sarlatto et al. 2006; Spina and Romagnoli, 2010; Romagnoli and Spina, 2013) and confirmed that ring-shaken trees show lower shrinkage in accordance with several studies (Macchioni 1995; Romagnoli and Spina, 2013). In accordance with a previous study by Birbilis et al. (2018), this research demonstrated that ring shake rarely occurs in juvenile wood and usually occurs in adult wood between the 20thand 40th growth rings. For this reason, eight sensors generate a sufficient number of paths to intercept ring shake in this location; a lower number of sensors applied to this technique might not be enough to locate correctly the damaged paths. In addition, a smaller number of sensors, for example, 4 or 6, applied to trees having at least 30 cm of diameter, creates a data matrix that is able to detect a defect in a circle with minimum detectable defect sizes of 4% and 8%, respectively (Divos and Szalai 2002). Considering that ring shake is only an arc of a circle, the probability of detecting this defect reduces considerably with a lower number of sensors, and the image resolution is thus a function of the number of sensors. Another important aspect to be considered is the shape of the image that the software produces; in fact, compared to other types of decay, ring shake is shown as an irregular circle with clearly distinguishable colours.

5 Conclusion

The objective of this study was to develop a methodological approach using a NDT, i.e., conventional sonic tomography, based on fast/slow paths to assess the presence of ring shake in standing chestnut trees. The results confirmed that sonic tomography can identify several defects in a tree trunk, including ring shake, without affecting its biological activity, overcoming the difficulties of predicting using only visual inspection. These technologies can be applied directly to standing trees wherever quality chestnut wood has to be cultivated for production processes, but experts are still needed to perform an accurate diagnosis. This technique can represent a very important solution for companies because, in a short time, it can detect data from several points of the stem and possibly determine which trees are unsuitable for harvesting, because there are usually no external symptoms indicating this internal defect. In terms of the commercial importance of the species in Europe, the research is aimed at understanding the factors that cause ring shake in order to evaluate new preventive measures to minimize the risk of ring shake occurrence (Fonti et al. 2002b), and it would be of great value for public organizations and private owners to be able to evaluate the impact of ring shake in different forest stands in order to ascertain, which sites are likely to be most productive and obtain better quality material (Spina and Romagnoli 2010). In fact, the evaluation of potentially high quality forest trees requires a reliable and valid method for determining the correct economic value. Therefore, the method developed can be considered as a field method if supported by further studies, and this approach can be reliable for detecting not only ring shake but different structural defect types, too. Further research, using measurements at different tree heights or applying diverse tools to impedance tomography or ultrasonic devices, can confirm that non-destructive technologies can be used not only in urban forestry but also in important wood commercial sectors. In the field of NDT technologies, as well as in other fields of research, the use of these tools requires extensive experience with testing techniques because of the difficulty in interpreting the data. Only with an accurate interpretation is it possible to effectively translate the tomography data into an understanding of the type, location and dimensions of the internal defects in standing trees.

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4.10 Wood Technology and Non-Destructive Testing

Article 9
Comparative evaluation of inspection techniques for decay detection in urban trees

Salvatore F. Papandrea[1], Maria F. Cataldo[1]*, Giuseppe Zimbalatti[1], Andrea R. Proto[1]

[1]Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy.

*Correspondence: maria.cataldo@unirc.it (M.F.C.); Tel.: +39-(0)965-169-4275

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Salvatore F. Papandrea, Maria F. Cataldo *, Giuseppe Zimbalatti, Andrea R. Proto

University Mediterranean of Reggio Calabria, Department of AGRARIA, Feo di Vito, 89122, Reggio Calabria, Italy

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ABSTRACT

A crucial problem associated with urban trees is the need ensure citizens' safety. It requires the development and application of rapid and precise diagnostic techniques for detecting decay and other types of structural defects in trees to prevent falling due to strength failure or damage caused by internal decay. Significant effort has been devoted to developing robust non-destructive technologies, such as specialized sensors, capable of predicting the intrinsic properties of the wood of individual trees. In this study, the authors used four different devices with its sensors to measure decay: a microsecond timer, an electric resistivity tomograph, an acoustic tomograph and a resistograph. An inspection protocol combined stress wave, electrical resistance, and drilling resistance to detect internal defects on Mindi trees (*Melia azedarach* L.) located in the city of Reggio Calabria in Southern Italy. The percentages of the decayed wood areas, calculated by the different instruments, were compared to establish at which degree the use of simple and rapid instruments can guarantee reliability in detecting the extent of damaged woody tissues. This study's experimental results indicate high correlations between the resistance drilling and the stress wave methods. These high correlations may provide the opportunity to replace the resistograph with the microsecond timer or the acoustic tomograph, both of which are less invasive tools for detecting defects in standing trees. Compared to the resistograph, the electrical resistivity tomograph proved to be the least sensitive instrument for detecting wood decay.

1. Introduction

Green areas in cities are acquiring an increasingly important role in urban architecture. Within urban communities, trees are valuable assets that provide ecological, aesthetic, social, and economic benefits. In fact, urban trees play a significant role in our daily life and are valuable assets to communities and a healthy environment [1]. However, at the same time, they pose a potential risk to people and property when they become structurally unstable [2]. A crucial problem associated with urban trees is the need to know and evaluate their health to ensure citizens' safety and security. The internal defect in tree stem or branch weakens the health of forest, declines the quality and value of timber, and poses a risk of public safety in urban communities [3]. In recent years, trees' potential to cause harm has been increasing because of climate change effects, mainly related to windstorms and tree diseases that cause trees to fall [4,5]. Accidents related to trees' and branches' sudden falls keep administrations' and individuals' attention on the problem of tree safety. For this reason, public and private owners are called to quantify and monitor their trees' risk to public safety [5]. Consequently, the detection, evaluation, and management of hazardous trees has become a major concern for urban foresters and park managers [6]. For this reason, the theories and application protocols for evaluating trees' stability are the subject of a wide debate involving researchers and technicians. A thorough inspection of trees' branches, stems and root collars is essential in detecting hazardous conditions [6]. Tree risk assessment is a methodical process for identifying, analysing and evaluating risk [7,8], and the Visual Tree Assessment method [9] represents an internationally recognized procedure for tree health assessment. Arboriculturists consider visual tree assessment an essential practice that serves as the starting point for evaluating tree defects and providing basic information regarding tree growth performance and stability [10]. The method involves four phases: (*i*) visual inspection; (*ii*) any instrumental investigation that highlights the presence of structural defects; (*iii*) assignment of the subsidence propensity class or phytostatic risk categories and (*iv*) definition of operational note to restore the tree's static balance or, in extreme cases, to recommend its felling. Visual

* Corresponding author.
E-mail addresses: salvatore.papandrea@unirc.it (S.F. Papandrea), maria.cataldo@unirc.it (M.F. Cataldo), gzimbalatti@unirc.it (G. Zimbalatti), andrea.proto@unirc.it (A.R. Proto).

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inspection is aimed at identifying all visible components of a tree and any symptoms indicative of structural defects that could compromise its stability. The instrumental investigation quantitatively describes any anomalies found. This kind of analysis can make use of the different available investigation methods: identification of discontinuities in tissues by means of sonic or ultrasonic systems, measurement of wood density with penetrometric systems, evaluation of the wood's mechanical characteristics with destructive tests, electrical resistivity, radar and other techniques [11–17]. Concerns related to public safety support the development and application of rapid and precise diagnostic technologies to detect decay and other types of structural defects in trees [2]. Destructive testing destroys or changes the part examined, while non-destructive methods, do not leave any permanent traces. Among the second group can be found methods based on the propagation of electromagnetic waves including ultrasound methods [18,19]. Between the two categories, there is the semi-desctrucitive methods category in which tests are characterized by a low impact on the object. In this group, among others, fall penetration methods, leaving traces in the form of holes with a small diameter (hardness tests, resistance drilling tests) [20,21]. Significant effort has been devoted to developing robust non-destructive technologies that are capable of predicting individual trees' intrinsic wood properties [22]. The assessment of wood via stress waves is one of the oldest and simplest methods available [23]. A typical approach for measuring wave propagation velocity in standing trees involves inserting two sensor probes (a transmit probe and a receiver probe) into the sapwood and introducing stress wave energy into the tree trunk from a point source through a hammer impact [24,25]. This procedure is referred to as a single-path stress wave timing measurement, and the stress wave velocity obtained is related to the physical condition of the tree. The single-path method is fast, economical, and easy. Acoustic methods have been found to be very effective for detecting the internal decay of urban trees [26]. The concept of detecting decay using ultrasound or sound waves is based on the observation that stress wave propagation is sensitive to the presence of degradation in wood [27]. In general, stress waves travel faster in high-quality wood than in deteriorated and low-quality wood [28,29]. The health of a tree can be assessed also by means of penetrometers and drilling resistance tools. Resistance drilling measures the relative resistance (drilling torque) of the material as a rotating needle is driven into the wood at a constant speed and changes in wood resistance are displayed on a graph as changes in mechanical resistance. Areas of prolonged low resistance indicate decay, cavities, or cracks [27]. Furthermore, drilling does not require the removal of the bark, and the width of the hole in the tree is barely visible making it the least harmful invasive method.

Many authors have already worked on detecting wood anomalies in trunks or standing trees, applying in most cases a single method and in fewer cases using and comparing two or more techniques with the aim of defining a fast method to identify potential risk in urban forests. Nicolotti et al. [30] reported application of electric, ultrasonic and georadar tomography for detection of tree decay and the comparison of these methods with the traditional penetrometer in an urban environment. Brazee et al. [31] studied the determination of internal decay comparing acoustic and electrical impedance tomography. Wang et al. [29] and Rinn [32], for similar studies, used acoustic tomography subsequently verified by resistograph testing. Qin et al. [33] conducted health assessment of *Cinnamomum camphora* tree logs by combining the acoustic-laser technique and acoustic tomography. The acoustic-laser technique uses the acoustic excitation generated by a loudspeaker designed to vibrate the object with frequencies up to 20,000 Hz, and a laser beam to measure the vibrational frequency response. The difference in the response signal can identify whether the localized region is intact or defective. Their results demonstrated that the acoustic-laser technique could identify the presence of near-surface trunk defects that are normally overlooked by the conventional acoustic tomography measurements with random sensor distribution. Lin et al. [34] detected deterioration in royal palm combining the use of ultrasonic tomographic and resistance drilling techniques and found a high correlation between the amount of decay detected by ultrasonic tomography and the amount actually present in cross-sections of discs and living palms according to the drill-resistance profile. Several years later, two of the authors [11] from that study compared acoustic velocity and electrical resistance tomography for evaluation of peripheral-inner wood demarcation in urban royal palms, suggesting combining these methods with drilling resistance profiling.

This study's aim was to determine the precision of four different methods in detecting and quantifying decay in Mindi trees (*Melia azedarach* L.) in an urban context in the metropolitan city of Reggio Calabria (Italy). In particular, the research was aimed at (*i*) calculating the amount of deteriorated wood with a microsecond timer, acoustic tomography, electric resistivity tomography and resistograph and (*ii*) verifying, by comparing the resistographic results with the results obtained by all three instruments, the results' reliability in determining the amount of deteriorated woody tissues.

2. Materials and methods

2.1. Study area and test devices used

The tests were conducted on 75 mindi trees (*Melia azedarach* L., Meliaceae) located along the edges of some streets in the metropolitan city of Reggio Calabria (Italy; Fig. 1). Mindi trees, in Italy, is one of the most widespread species used in urban architecture; in fact, it is often planted in parks, gardens and alongside paths as an ornamental tree. Table 1 describes some physical characteristics of the Mindi wood measured at the wood technology laboratory. The media and the standard deviation (SD) values confirm what has been reported in various studies regarding wood density and shrinkage [35]. It is a small to medium size, deciduous tree characterised by a large trunk and many branches. In this study, various measurement methods were applied to detect internal defects in standing trees and four devices were used: a Fakopp microsecond timer (Fakopp Enterprise, Agfalva, Hungary), an ArborSonic 3D acoustic tomograph (Fakopp Enterprise Ltd., Hungary), a PiCUS TreeTronic (Argus Electronic Gmbh, Rostock, Germany) and an IML-Resi PD400 Resistograph (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany). As reported by Proto et al. [22], the samples trees were monitored at a height of approximately 50 cm above the ground.

2.2. Microsecond timer

To investigate if inside the trees there were wood defects, after a preliminary visual inspection, the microsecond timer device (Fakopp Bt.

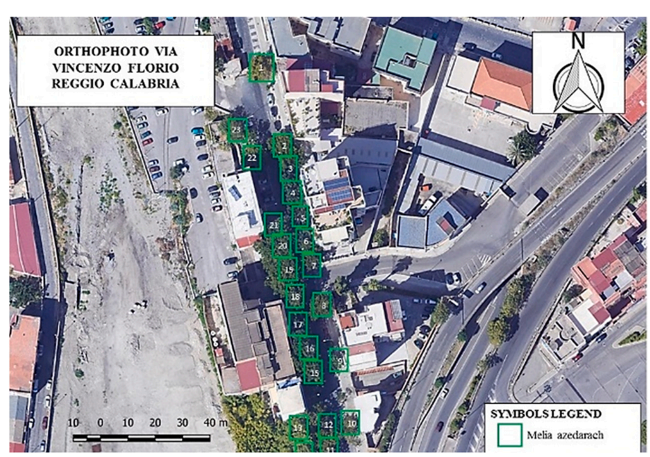

Fig. 1. The location of a first sample of 23 trees monitored in the municipality of Reggio Calabria.

Table 1
Physical properties of *Melia azedarach* trees.

Property	Unit of measure	Mean	SD	N
β_r	%	3.75	2.25	50
β_t	%	6.25	2.15	50
β_a	%	0.38	1.17	50
β_v	%	10.48	3.51	50
ρ_{green}	Kg/m^3	750	2.74	50
ρ_{12}	Kg/m^3	534	1.45	50
ρ_y	Kg/m^3	460	3.96	50

β_r radial shrinkage (%), β_t tangential shrinkage (%), β_a axial shrinkage (%), β_v volumetric shrinkage (%), ρ_{green} density green wood (kg/m^3), ρ_{12} density at 12% moisture content (kg/m^3), ρ_y basic density (kg/m^3).

Agfalva, Hungary) was used to generate single-path stress waves on the trees. This tool consists of needles attached to accelerometers, used as mediators, that penetrate the bark and reach a tree's sapwood. A hammer is used to tap the start sensor to generate a stress wave in the tree stem in the radial direction. The two sensors transmit with a frequency of about 23 kHz and pick up the start and stop signals, and the wave transmission time is displayed on an LCD screen with a 1-μs resolution. Following the instructions dictated by the instrument's manufacturer, the trunks were tested by aligning the two probes on the trunk in a north-south (NS) level position for the first test and in a west-east (WE) level position for the second test. The tests were repeated several times for each pair of sensors to derive average values from at least three readings. Through the sound wave's speed, it is possible to immediately establish whether there is a cavity or degraded wood in the area between the two sensors. The principle on which the analysis is based is simple: if there is a cavity or decayed wood, the sound waves produced by the hammer's impact do not propagate along the straight line joining the sensors, but rather go around the cavity remaining in the sound wood. Accordingly, the waves take more time to reach the sensor block in the presence of decay [36–38].

2.3. Acoustic tomograph

The same 75 trees were non-destructively tested using the ArborSonic 3D acoustic tomograph device (Fakopp Bt. Agfalva, Hungary). The tests were performed in accordance with the manufacturer's and software's instructions, and these test procedures are explained in many similar papers [39–42]. Eight high sensitivity SD02 piezo-sensors with measurement error of ± 3 microseconds were used on each standing tree one placed at each of the eight different cardinal and intercardinal points. The travel times (in μs) generated by each sensor were captured by the other sensors, thus determining the acoustic velocity. Every measurement was repeated three times (repetitions) on each sensor to obtain averaged travel times, thus reducing uncertainty related to individual tests.

2.4. Electrical resistivity tomography

The electrical resistivity tomography (ERT) was used to measure the electrical resistivity (reciprocal to electrical conductivity) for the same 75 trees. The measurement was conducted with the Picus Treetronic device (Argus electronic GmbH, Rostock, Germany). The test applied eight electrodes, evenly placed around the trunk in a horizontal plane using a dipole–dipole configuration at a low-frequency current of 8.3 Hz. Each electrode was clipped and attached to a nail (with a 2-mm diameter) that had been tightly forced into the bark and sapwood. Upon completion of the electrical resistivity measurements at each level, a tomogram was constructed for the cross-section using Picus Q72 software. The electrical resistance between the sensors is calculated using the voltage and current values and the distance between the sensors [43–45]. The outcome is a tomogram: a two-dimensional image where the distribution of electrical resistance values in the stem cross-section is depicted using a relative colour scale. Red-coloured areas represent the areas with relatively increased resistance, whereas blue-coloured areas represent areas with relatively decreased resistance. The image consists of a grid of tessellating triangles, with each triangle having its own electrical resistance reading.

2.5. Resistograph

The drilling resistance test was conducted using an IML-Resi PD400 (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany) resistograph equipped with a 400-mm-long and 3-mm-thick steel drill (tip diameter 3 mm, shaft diameter 1.5 mm). A drilling resistance tool consists of a power drill unit, a small-diameter spade-type drill bit and an electronic device that can be connected to the serial interface input of any standard personal computer. The method is based on measuring the drilling resistance along a small needle path when a needle is driven into a tree with a constant force [46]. This system produces a chart showing the relative resistance over the needle's travel path. Areas of sound wood have varying levels of resistance, whereas voids and areas of decay show no resistance, so the user can determine areas of low, mild and high decay levels [47]. During the drilling measurement process, the relative drilling resistance, feeding force and speed parameters can be continuously measured as a function of the drill bit's position along the drilling path [48]. Measurements were performed at the height of the trees of approximately 50 cm above the ground. The perforation was set at 2 cm m^{-1} forward speed (feed speed) with a rotation rate of 3500 rpm along the radial direction of the trees' stems, producing a trace chart at a 0.1-mm sampling interval. Like the microsecond timer tests, the drilling resistance tests were conducted drilling the trunk in a NS level position for the first test and in a WE level position for the second test. The test results were transmitted to a computer and processed with dedicated software (Fig. 2).

2.6. Data processing and statistical analysis

Following all the measurements with the different tools, the study proceeded to assess the percentage of the degraded wood area in correspondence with the inspected section. During the microsecond timer tests, the velocities of single-path stress waves (VW) were obtained in a north-south level position (VW-NS) and a west-east level position (VW-WE). The distance between the two sensors, determined by a tape measure, was used to calculate the propagation speed (in m/s) of the stress wave into the wood between the two sensors. The percentage of wood deterioration detected by the microsecond timer (DZ_{VW}) was obtained from the ratio between the reference value [49] of the velocity of the stress waves V_0 (the average value found in the healthy wood) and the value of the stress waves measured for each deteriorated tree (V_d) following Eq. (1):

$$DZ_{VW} = \frac{V_0 - V_d}{V_0} \times 100 \quad [\%] \tag{1}$$

As explained below in the dedicated drilling test presentation, since the study's purpose was to compare the results obtained from all the instruments used for decay detection with the resistographic results, of all the paths recorded by both electrical and acoustic tomography, only the paths between sensors 1–5 and 3–7 were considered in the study. These paths in the trunks coincided with the NS and WE positions (i.e. the same paths monitored with the resistograph and microsecond timer tools). For the tomographic data (acoustic and electrical), the percentage of the decayed wood area was obtained with the same approach used for the microsecond timer. Particularly, concerning the acoustic tomography, because the ArborSonic 3D software provides the velocities of the path of the acoustic wave between sensors, the percentage of the decayed wood areas was calculated with the Eq. (2):

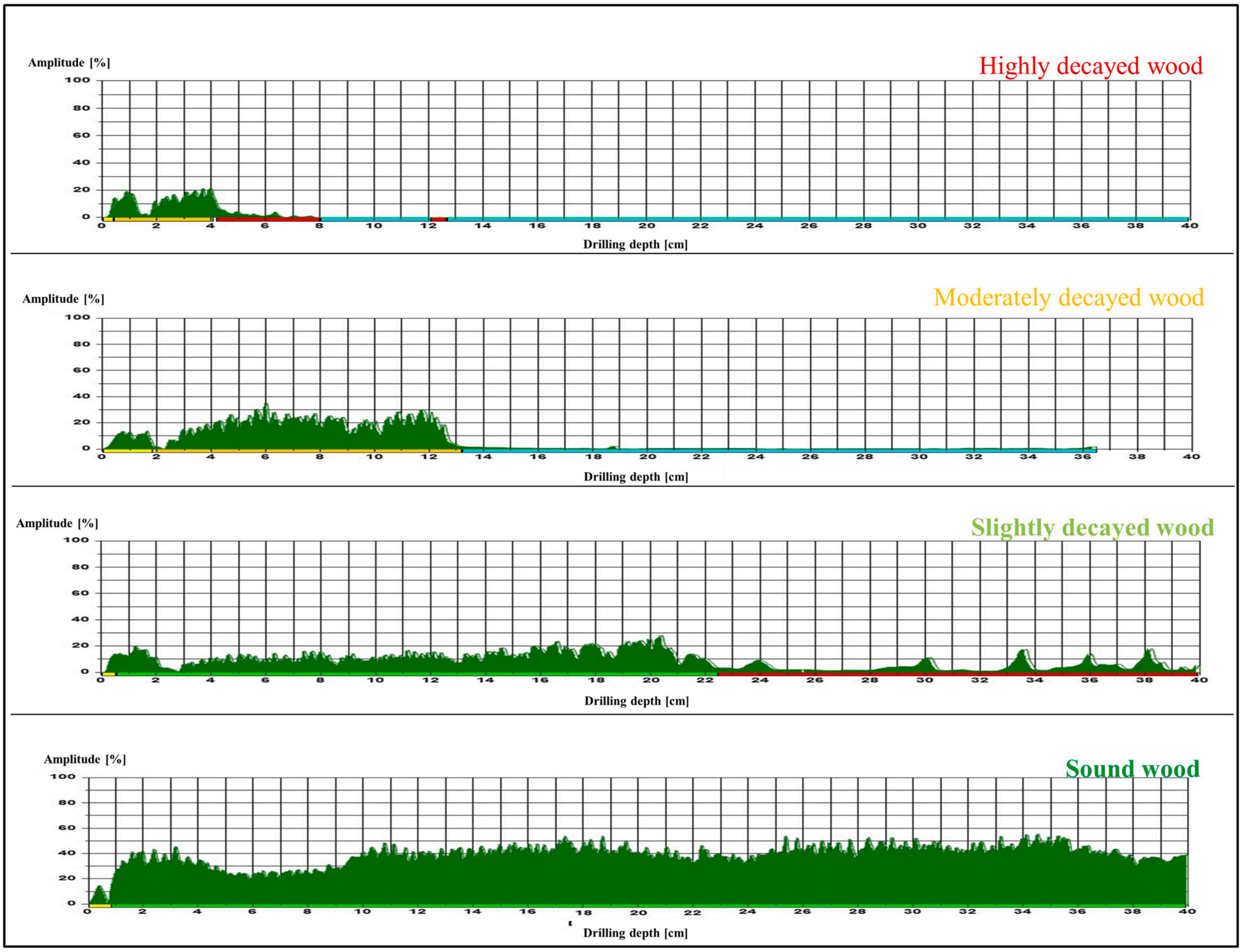

Fig. 2. Drilling resistance record measured on trees belonging to different classes of damaged wood.

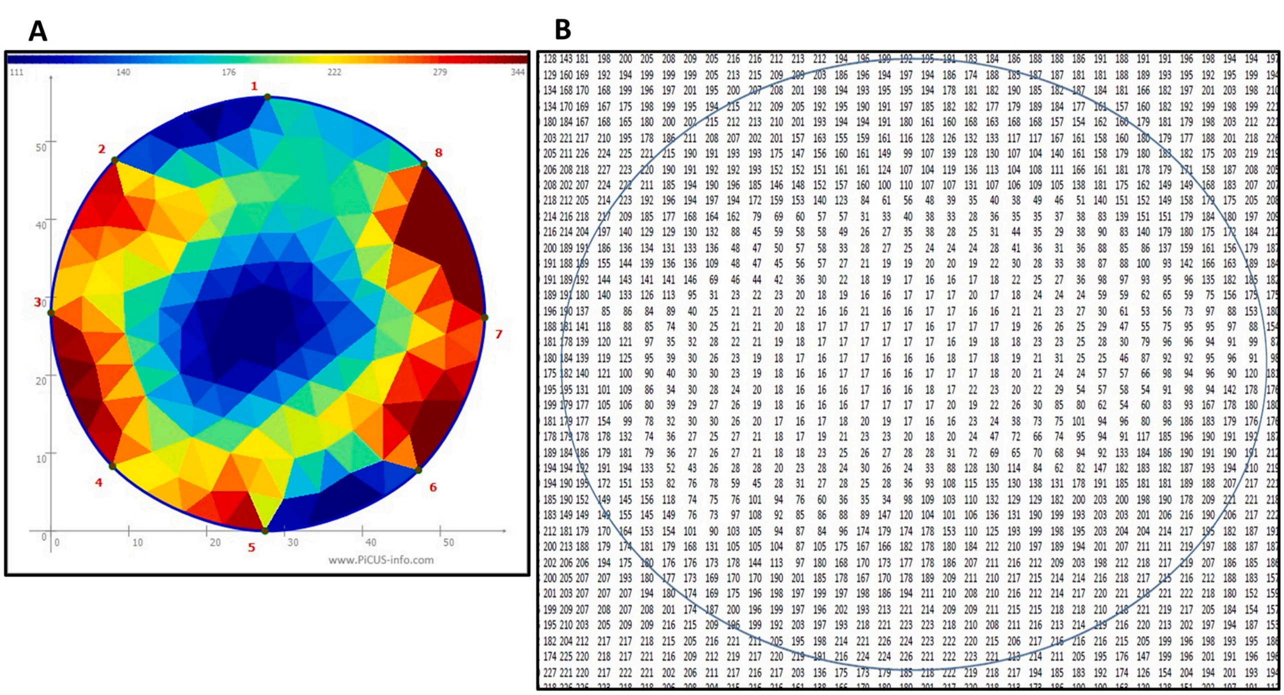

Fig. 3. An original electrical tomogram (A) and a corresponding electrical resistivity grid (B).

$$DZ_{TS} = \frac{V_{a0} - V_{ad}}{V_{a0}} \times 100 \quad [\%] \tag{2}$$

where DZ_{TS} is the extent of decayed wood as a percentage of the total trunk area surveyed by acoustic tomograph, V_{a0} is the average value of the velocities of the acoustic waves found in the healthy wood and V_{ad} is the velocity of the acoustic waves found in the sensing direction in the decayed section.

Regarding electrical resistivity tomography, several studies have used image analysis to interpret tomographic results [31,50,51]. However, due to the relativity of the colour scale for each tomogram, this study has focused on the values of electrical resistivity of each triangle in order to accurately calculate the image resistance values of the resistance tomography. To achieve this, the colour image was first converted to grayscale and then the pixel values in the graph were converted to resistance values using the MATLAB software (MathWorks, Natick, MA, USA) [52,53], ultimately creating a grid of electrical resistivity values (Fig. 3). In this study, only the electrical resistances values found in the pixels of the NW and WE positions of the tomogram were considered, so that they could be compared with the other instruments' results. The severity of decay detected with the electrical resistivity tomograph was calculated following Eq. (3):

$$DZ_{E} = \frac{R_0 - R_d}{R_0} \times 100 \quad [\%] \tag{3}$$

where DZ_E is the extent of decayed wood as a percentage of the total trunk area surveyed by electrical resistivity tomograph, R_0 is the average value of the healthy wood's electrical resistivity and R_d is the average electrical resistivity value in the sensing direction in the decayed section.

For the drilling tests, the software used for resistograph analysis was PD-tools Pro V. 1.22. Similar to Reinprecht and Šupina's [49] approach, the extent of damaged zone determined by resistograph (DZ_R) was computed in a percentage using Eq. (4):

$$D_{ZR} = \frac{d_R}{L} \times 100 \quad [\%] \tag{4}$$

where L is the diameter of the tree, and d_R is the total length (mm) of the tree's significantly damaged zones. The distinction into various damage classes was achieved using a threshold of about 33% of wood deterioration [54], considering the percentage of decayed wood recorded by the two paths of the resistograph. The damaged zones along the radial direction of trees were obtained in a NS level position (DZ_R-NS) and in a west-east level position (DZ_R-WE).

Since the resistograph provides accurate data through a mechanical measurement given by the resistance of the woody tissues against the drilling, the data are recorded in the characteristic form of a graph, which can describe the trunk's internal conditions. In fact, following the same theory of Johnstone et al. [55], wood decay was believed to occur when there was significant "yield" on the graph in relation to the rest of the trace and a lack of "peaks" on the graph associated with growth increments, without reference to the cut stem. This tool's results have therefore been taken as a reference for comparison with other tools that provide inaccurate path data through techniques that exploit wood's ability to transmit acoustic, electrical, and stress waves. Table 2 shows the abbreviation codes used to describe the damaged zones detected by the different tools used in this research.

SPSS software version 20.0 (IBM Corp., Amonk, NY, USA) was used for statistical data analysis. To determine the differences in the decay detection results among the applied techniques compared to the resistograph measurements, the authors evaluated the relationships between the percentage of the damaged zones of trees (DZ) determined by resistograph (DZ_R) and those reported by the other tools (DZ_{VW}, DZ_{TS} and DZ_E for damaged zones detected with microsecond timer, acoustic tomography and electric resistivity tomography, respectively) using linear correlations [49].

Table 2
List of acronyms used to describe the detected damaged zones.

Abbreviation codes	Description
Dzr-NS	Damaged zones along the radial direction of trees, determined by resistograph device on north-south position
Dzvw-NS	Damaged zones along the radial direction of trees, determined by microsecond timer device on north-south position
Dzts-NS	Damaged zones along the radial direction of trees, determined by acoustic tomography device on north-south position
Dze-NS	Damaged zones along the radial direction of trees, determined by electrical resistivity tomography device on north-south position
Dzr-WE	Damaged zones along the radial direction of trees, determined by resistograph device on west-east position
Dzvw-WE	Damaged zones along the radial direction of trees, determined by microsecond timer device on west-east position
Dzts-WE	Damaged zones along the radial direction of trees, determined by acoustic tomography device on west-east position
Dze-WE	Damaged zones along the radial direction of trees, determined by electrical resistivity tomography device on west-east position

3. Results

The basic descriptive statistics of the results regarding the percentage of degraded areas obtained by all the tools used in this research are shown in Table 3. The data demonstrate the diversity among the values found with the drilling tests and the other instruments. According to the percentage of damage found with the resistograph throughout the investigated section, the trees were catalogued into three different damage categories: slightly, moderately, and highly (Table 4). A fixed threshold value (33%) for the extent of deterioration was defined to classify the defective classes [54].

Tight relationships were observed between the damage percentage detected by microsecond timer (DZ_{VW}) and the damaged zones inside the trees determined by the resistograph (DZ_R). The linear correlation between DZ_R-NS and DZ_{VW}-NS provided an R^2 value of 0.918 (Fig. 4) and that in the west-east direction (DZ_R-WE and DZ_{VW}-WE) obtained a highly similar value: 0.919 (Fig. 5). Similar results were obtained from the correlations between DZ_R-NS and DZ_{TS}-NS and between DZ_R-WE and DZ_{TS}-WE, with R^2 values of 0.875 and 0.882, respectively. A lower correlation was found between DZ_R and DZ_E for both the NS path and the WE path. In fact, between the damaged zones detected by the resistograph and the electrical tomography, there were R^2 values lower than 0.7.

Fig. 6 shows that the difference in decay detection by resistograph compared to the other instruments increased as the extension of the decayed wood increased. Different correlation levels were observed between the percentage of decayed wood detected by the resistograph and those determined by the microsecond timer, the ArborSonic 3D and the TreeTronic for both the NS direction and the WE direction (Table 5).

The observed results for the low-decay wood category showed that the DZ_R and D_Z values detected with the other instruments always

Table 3
Descriptive statistics of the damaged zone (%) detected by the various tools for the NS and WE paths.

	N	Minimum	Maximum	Mean	Std. Deviation
Dzr-NS %	75	0.00	75.00	30.61	24.41
Dzr-WE %	75	0.00	74.00	31.57	24.62
Dzvw-NS %	75	0.00	53.89	22.19	17.18
Dzvw-WE %	75	0.00	55.03	22.02	17.41
Dzts-NS %	75	0.00	50.03	19.48	16.61
Dzts-WE %	75	0.00	55.31	20.65	16.59
Dze-NS %	75	0.00	45.00	15.83	13.33
Dze-WE %	75	0.00	52.85	18.64	15.61

Table 4
Descriptive statistics of the wood categories distinguished by the percentage of decayed wood detected by the resistograph.

Wood categories		N	Minimum	Maximum	Mean	Std. Deviation
Sound wood	Dzr-NS %	13	0.00	0.00	0.00	0.00
	Dzr-WE %		0.00	0.00	0.00	0.00
Slightly decayed wood	Dzr-NS %	25	2.00	28.00	14.94	7.54
	Dzr-WE %		2.00	26.66	15.40	7.37
Moderately decayed wood	Dzr-NS %	21	25.00	59.27	41.75	10.56
	Dzr-WE %		30.00	59.00	45.11	10.08
Highly decayed wood	Dzr-NS %	16	60.00	75.00	65.34	4.323
	Dzr-WE %		56.45	74.00	64.73	6.197

showed a significant correlation in both the NS and the WE directions. The microsecond timer and the acoustic tomograph reached the level of 0.01, whereas the correlation was significant at the level of 0.05 for the electrical resistivity. Even in the case of medium-decay wood, the DZ_R and D_Z detected by the microsecond timer (DZ_{VW}) were significantly correlated at 0.01 levels in both directions. On the other hand, for the acoustic tomograph, it was found the correlation of the obtained data was highly significant at 0.01 for the NS path and at 0.05 for the WE path. Regarding the high-decay wood class, there was a decrease in the significance of the correlation between the results obtained with the resistograph and those obtained using the other three instruments. With the exception of the data collected by the acoustic tomograph, which showed a high correlation with the resistograph at only the NS path, the other instruments did not demonstrate any significant correlation.

4. Discussion

Non-destructive testing methods and tools do not always provide extensive information on trees' internal integrity, and this study is focused on determining the precision of four different tools and methods in detecting and quantifying decay in standing trees: microsecond timer, acoustic tomography, electric resistivity tomography and resistograph. All the instruments used in this study demonstrated the ability to effectively detect standing tree trunks' internal decay, but determining the size of damaged zones to identify hazardous trees has been challenging using fast diagnostic techniques. The proposed inspection protocol can support urban tree diagnosis managers in detection, providing highly accurate estimates and tree stability characterisation. In fact, this approach has eliminated the typical inherent limits of each considered tool. Although the resistograph's key features are its modest cost, digital data collection, high-resolution data and ease of field use [56], it has the disadvantage of drilling into the tree, penetrating up to 150 cm. The resulting deep hole in the xylem exposes the tree to fungal spores after

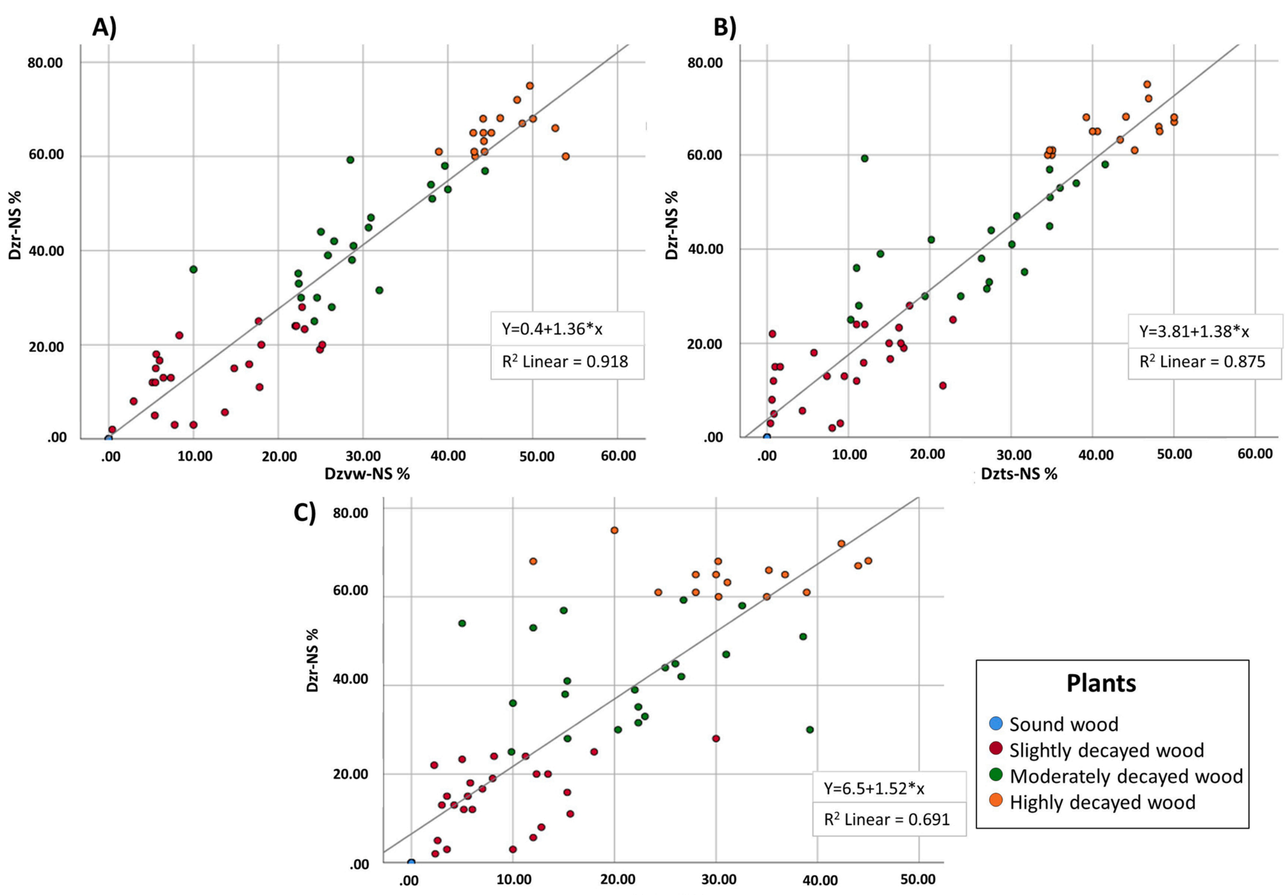

Fig. 4. The relationships between the percentages of damaged area measured by the resistograph and those measured using the other instruments in the NS direction: (A) resistograph and microsecond timer device, (B) resistograph and acoustic tomography device and (C) resistograph and electrical resistivity tomography device.

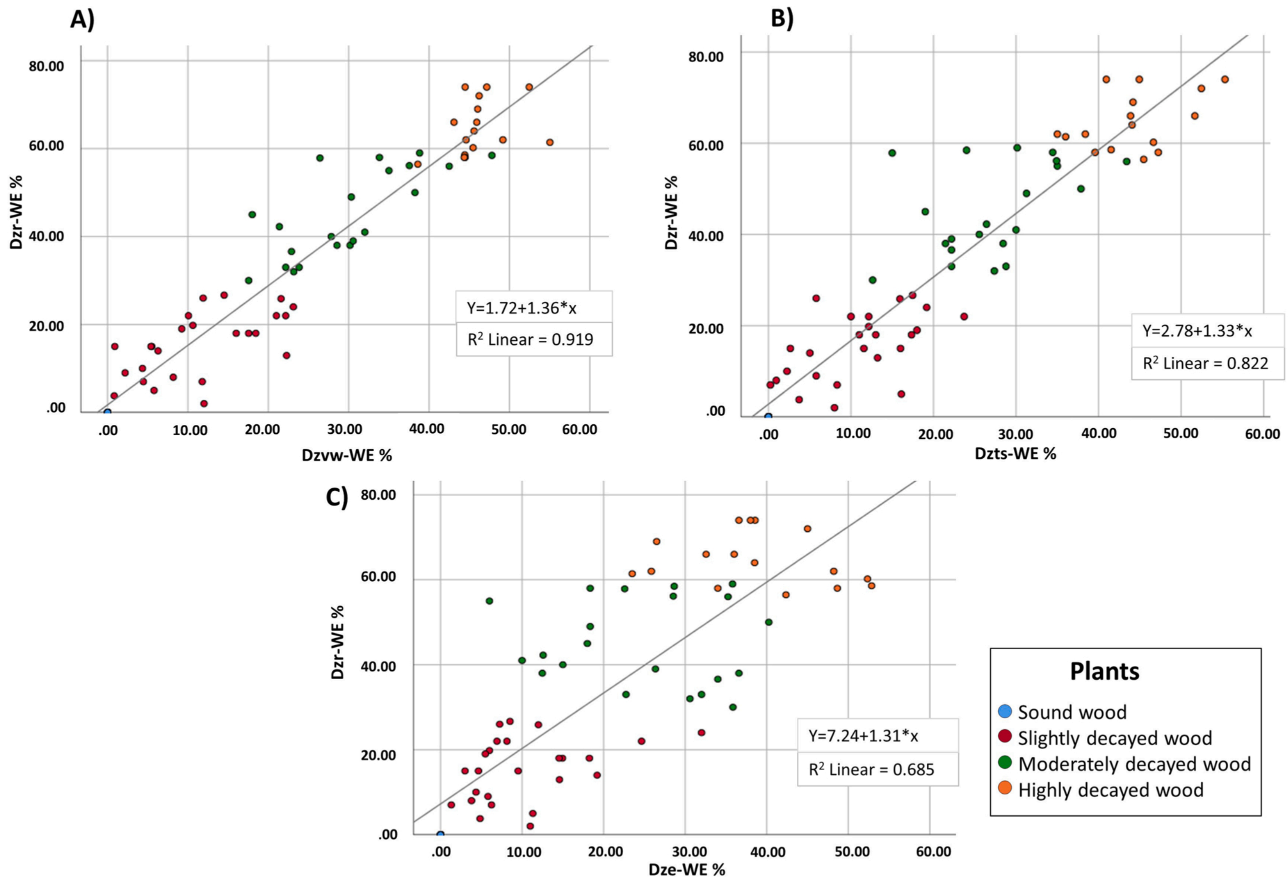

Fig. 5. The relationship between the percentages of damaged area measured by the resistograph and the other instruments in the WE direction: (A) resistograph and microsecond timer device, (B) resistograph and acoustic tomography device and (C) resistograph and electrical resistivity tomography device.

measurement [30,57]. Additionally, this method requires considerable time to take each measurement. Using devices with invasive techniques often requires a high level of specialised knowledge and experience [58]. Furthermore, this method provides strictly accurate measurements. Given the strong correlation between their results, the resistograph could be replaced by the microsecond timer, which is a less invasive tool that does not place the tree at risk of biotic attacks, and which guarantees a good detection of anomalies inside the trunks [59]. Regarding the mark left by the measurement, the use of tomographic equipment requires the insertion of standard 5-cm nails through the cortex; these wounds are minor and can heal quickly [31] compared to the deep hole created by the resistograph. It is interesting to note that using the microsecond timer has detected degraded areas even with extensions of less than 0.5% of the wave path in the sensing direction in the surveyed section, whereas the resistograph was less precise. However, the microsecond timer does not allow reconstruction of the entire cross-sectional area. In fact, although it was found to be highly sensitive in detecting wood decay along the single path, the single path stress wave measurement can detect only internal decay that occupies over 20% of the total cross-sectional area [29]. Therefore, several measurements are required to be able to detect defects throughout the study section. The resistograph is portable and easy to handle in the field and in the laboratory, although like the microsecond timer it does not allow reconstruction of the entire cross-sectional area. Additionally, drilling does not require removal of the bark, and the hole in the tree is barely visible. Hence, testing using this tool is considered minimally invasive. However, replacing the resistograph with the microsecond timer would ensure effective preliminary detection of wood decay with even milder wounds on the trunk and very short measurement times due to its easy handling and use. The high correlation demonstrated by this research between the resistograph and the microsecond, at first view, provides the opportunity for preliminary detection of defects in standing trees using only the stress wave method, which is usually cheaper and faster. This association between the two instrumental methods agrees with previous experiments by da Costa et al. [60], who found relationships between the stress wave timer and visual damage analysis in various species' woods.

The sonic tomograph also provided accurate results, albeit slightly less accurate than those of the microsecond timer. As confirmed by other studies, sonic tomography has proven highly effective in detecting the decay of trees' internal tissues [1,40–43,61–65], even in the early stages of wood decomposition [30]. Furthermore, it is a highly accurate non-destructive method in locating anomalies and in estimating their size and shape [22,66]. However, the use of the sonic tomograph, given the greater complexity and duration of its data detection procedure compared to the resistograph and the microsecond timer, is suggested only in case of the need to detect more-detailed data in trees with known internal decay levels and in those that must be monitored over time.

In this study, the electrical resistivity tomograph proved to be the least sensitive instrument for detecting wood decay. Evaluation of the electrical resistivity tomogram can be complicated by each tree species' specific resistance distribution, which may change from season to season [43]. Therefore, electrical resistance tomography requires considerable field practice to correctly interpret image [44,67].

The urban foresters assigned the duty of safety management of these often massive tree structures in close proximity to buildings, roads and people must analyse and apply this new information to their practice [68,69].

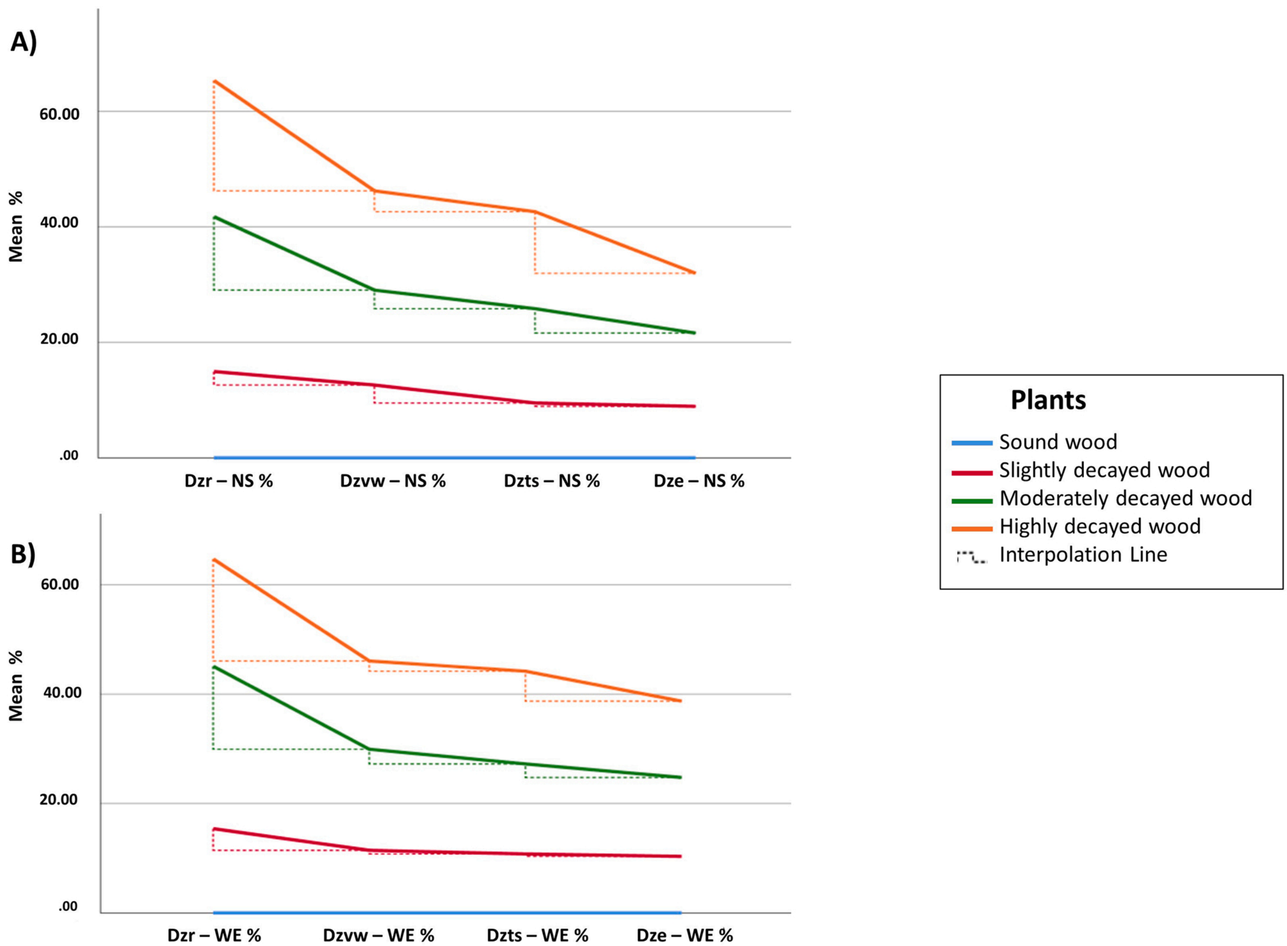

Fig. 6. Mean wood decay detected by the different tools on the (A) NS and (B) WE directions.

Table 5
Correlations between the damaged zones detected by the resistograph and those detected by the microsecond timer, acoustic tomography and electrical resistivity tomograph tools in the NS and WE directions.

			Dzvw-NS %	Dzts-NS %	Dze-NS %
Slightly decayed wood	**Dzr-NS %**	Correlation	0.669 * *	0.525 * *	0.421 *
		Sig.	0.000	0.004	0.018
Moderately decayed wood	**Dzr-NS %**	Correlation	0.700 * *	0.563 * *	0.127
		Sig.	0.000	0.004	0.292
Highly decayed wood	**Dzr-NS %**	Correlation	0.364	0.643 * *	-0.054
		Sig.	0.083	0.004	0.422
			Dzvw-WE %	**Dzts-WE %**	**Dze-WE %**
Slightly decayed wood	**Dzr-WE %**	Correlation	0.588**	0.552**	0.360*
		Sig.	0.001	0.002	0.038
Moderately decayed wood	**Dzr-WE %**	Correlation	0.746**	0.466*	-0.064
		Sig.	0.000	0.017	0.392
Highly decayed wood	**Dzr-WE %**	Correlation	0.330	0.419	-0.236
		Sig.	0.106	0.053	0.190

* *Correlation is significant at the 0.01 level.
*Correlation is significant at the 0.05 level.

5. Conclusions

Green areas in cities are acquiring an increasingly important role in urban architecture. To the best of the authors' knowledge, this study is the first designed experiment in which a potential inspection protocol in instrumental methodology has been proposed. This approach can be functional to favor the choice and use of one or multiple diagnostic sensors according to the technical-professional needs for a quick and precise evaluation of the failure of the trees. Nevertheless, the visual analysis of an expert technician is preliminarily fundamental [55]. The merit of this study is that it builds up on a reasonably wide dataset collected in the field; seventy-five monitored trees and each with four different NDT tools. Therefore, this research accounts for operational variability, contributing a more precise approach to describing sizes and locations of damaged areas. The study showed that the drilling resistance and single path stress wave equipment identified the different sizes of defects, and being considered rapid tools, they offer a benefit in terms of quality and accuracy of the analyses, even if they are unable to define the entire stem cross-section. However, considering that most arborists apply only the limited visual assessment because tomographic and resistographic tools are considered excessively expensive, the use of an impulse hammer, such as the one used in this study, is much less expensive than the other two methods, and it can provide higher accuracy in detecting decay than the visual method. At the same time, visual assessment remains a fundamental and irreplaceable element in the diagnosis process. Finally, as an attempt at determining the validity of a risk assessment method, this study provides some insights into different methodological approaches' accuracy (stress wave, wood resistance and electrical impedance) as methodical processes for identifying and evaluating tree failure risk that are adopted in different regions of the world. Future research on this topic should aim at a broader assessment of tree risk to better define the accuracy of the entire defect investigation process such as internal wood decay with particular regards to actual damage or injury when the initially used visual technique is insufficient to make management recommendations [8]. Certainly, knowing the level of detail that different sensors can reach in the interception of internal defects of the wood in the trunk of standing trees, will be able to support the decisions of the professionals in choosing the right tool according to their needs and economic capabilities.

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CRediT authorship contribution statement

Salvatore F. Papandrea: Methodology, Investigation, Software, Formal analysis, Writing – original draft. **Maria Francesca Cataldo**: Software, Formal analysis, Writing – original draft. **Giuseppe Zimbalatti**: Supervision. **Andrea R. Proto**: Methodology, Investigation, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Salvatore F. Papandrea: Methodology, Investigation, Software, Formal analysis & Writing - original draft. **Maria Francesca Cataldo**: Software, Formal analysis & Writing - original draft. **Giuseppe Zimbalatti**: Supervision. **Andrea R. Proto**: Methodology, Investigation, Supervision, Project administration, Writing - review & editing.

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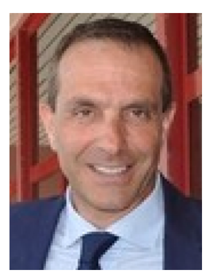
Salvatore Francesco Papandrea is a Ph.D. student of the doctoral course in Agricultural, Food and Forestry Science at the Department of AGRARIA - Mediterranean University, Reggio Calabria, Italy. His interest areas are wood harvesting, forest wood supply chain, renewable energy sources, power system analysis, agro-forestry mechanization, power system control and instrumentation in power systems.

Maria Francesca Cataldo earned Bachelor and Master of Forest and Environmental Science at the Department of AGRARIA of Mediterranean University, Reggio Calabria (Italy), in 2014 and 2016 respectively, and a Ph.D. in Agricultural, Food and Forestry Sciences in 2021. She is currently working at the Laboratory of Wood Technology and Forestry Mechanization, to determine the effects of silvicultural practices on wood quality and environmental resources conservation through sustainable forest management. Her research interests focus on engineering and forest management, including the application of NDT, sensors, and instrumentation for wood investigations.



Giuseppe Zimbalatti, full professor in agricultural and forestry machinery at the Department of AGRARIA - Mediterranean University, Reggio Calabria, Italy. He authored or co-authored about 130 papers. His scientific research interests include agricultural and forestry mechanization and to the supply of timber, analyzing the technological and organizational, ergonomic and safety, ecological and environmental aspects of the supply chains.

Andrea Rosario Proto is currently working as professor in the Department of AGRARIA - Mediterranean University, Reggio Calabria in Italy. He received his Ph.D. in forestry engineering in 2006. Actually, he is coordinator of the Laboratory of Wood Technology and Forestry Mechanization, doctoral supervisor and master supervisor. His research interests include the non-destructive technologies (NDT) for evaluating wood and wood-based materials from the assessment of standing trees to in-place structures, acoustic wave device-based sensor, forest wood supply chain, wood residues combustion, biofuel and renewable energy sources. He has published more than 50 scientific research papers as the first author or corresponding author.

4.11 Wood Technology and Non-Destructive Testing

Article 10
The Predictive Accuracy of Modulus of Elasticity (MOE) in the Wood of Standing Trees and Logs

Salvatore F. Papandrea[1], Maria F. Cataldo[1] *, Bruno Bernardi[1], Giuseppe Zimbalatti[1] and Andrea R. Proto[1]

[1]Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy

*Correspondence: maria.cataldo@unirc.it (M.F.C.); Tel.: +39-(0)965-169-4275

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Article

The Predictive Accuracy of Modulus of Elasticity (MOE) in the Wood of Standing Trees and Logs

Salvatore F. Papandrea , Maria F. Cataldo *, Bruno Bernardi , Giuseppe Zimbalatti and Andrea R. Proto

Department of AGRARIA, Mediterranean University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy
* Correspondence: maria.cataldo@unirc.it; Tel.: +39-(0)965-169-4202

Abstract: The characterization of poplar wood assumes a strategic position to increase the competitiveness of the entire forest wood supply chain. From this aspect, the identification of wood quality represents a primary objective for researchers and private landowners. The quality of wood can be defined via traditional visual methods based on the experience of technicians or using traditional tools, such as incremental drills and sound hammers. The traditional properties of these traits, based only on visual characteristics, can outline a classification based on the macroscopic properties of wood with the aim of defining the volume of recoverable wood. However, this approach does not provide a good indicator of the physical or mechanical properties of wood. Mechanical tests of wood require the felling of trees with the correlated preparation of the specimens. A different solution to determine wood quality is based on the application of non-destructive technology (NDT). In this context, the aim of the present study was to determine the predictive accuracy of non-destructive analysis of the MOEd in standing trees and logs of a 22-year-old poplar clone and to examine the relationship with MOEs in sawn specimens. This relationship was also studied at three different stem heights. We non-destructively measured poplar trees and green logs using TreeSonic and Resonance Log Grader and compared the results with those obtained via a destructive method using a universal testing machine. The results showed that for clone I-214 poplar trees, the dynamic elastic moduli of standing trees and logs were validly correlated with the static elastic modulus. These results suggest that it is possible to evaluate the mechanical properties of poplar wood directly from standing trees using non-destructive techniques (NDT) and that this tool can be easily used to presort material in the forest.

Keywords: acoustic tools; wood technology; mechanical properties; quality; non-destructive testing; stress-wave; *Populus*

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1. Introduction

As sylviculture aims to guarantee and perpetuate the productivity of forest stands, the commercial volume of trees, and their ecological sustainability, wood-based products are the principal economical source used to realize these purposes. Therefore, wood quality represents a primary objective for the entire wood supply chain. Several authors have focused their studies on wood qualities and properties, paying attention to various aspects, such as the influence of forest stand characteristics on physical, mechanical, and chemical wood characteristics [1,2], or the practical wood implications derived from quality characteristics [3]. Other researchers have investigated the potential of various methods and techniques of wood quality evaluation [4–6]. Wood quality can be defined as a set of characteristics that make woody materials economically valuable for their end uses. For several years, researchers in wood processing industries have been constantly looking for ways to increase the value and quantity of their products [7]; therefore, assessing wood quality has become an important practice for forest operations [8]. With the growing demand for wood-based products, the determination of quality and defects in the wood of standing trees is one of the most important operations in forestry management and forest product industries [9]. The importance of measuring wood properties has been discussed in several studies [3,10,11], which have highlighted the feasibility of various methods applied in standing trees or after the felling phase. Wood quality can be defined by the traditional visual methods based on technicians' experience and timber characteristics using traditional tools, such as increment borers and sounding mallets. Visual inspection of a tree's "body language" represents a classic means of estimating the presence of defects and anomalies [12]. In standing trees, a circular stem, a regular growth form, and other features are visually evaluated; after felling, visual inspection of the width and regularity of tree rings, number and size of knots, and eccentric pith on the cross-sectional log face occurs. Traditional appraisal of these traits, founded only on visual characteristics, can delineate a classification based on macroscopic wood properties, sometimes permitting definition of the volume of timber that can be recovered; however, this approach does not provide a good indicator of the physical or mechanical properties of the wood. For example, the traditional technique for determining wood density in standing trees is to extract increment cores from trees and measure their volume and mass of wood in a laboratory [13]; mechanical testing of wood requires felling of trees with the correlated preparation of test specimens. These measurements are therefore slow, relatively destructive, expensive, and time-consuming [14–16]. Therefore, the development of a fast screening method for standing trees has always been desirable [17,18]. Non-destructive testing (NDT) technology is a valid system of evaluation of some major wood characteristics. In the last two decades, NDT tools have contributed considerably to the characterization of wood quality in standing trees, cut logs, and sawn lumber [18]. In general terms, non-destructive testing of materials is a technique for detection and evaluation of the stress that materials can undergo (mainly physical and mechanical) without failure or changes in their overall characteristics [19]. Pioneering studies on non-destructive testing (NDT) techniques in wood technology are numerous and have been used to define their capability of predicting the intrinsic wood properties of individual trees and assessing wood quality at the stand and forest scale. Wood quality can be assessed by numerous techniques, such as the use of penetrometers and drilling resistometers, acoustic methods, and imaging visions [20,21]. As reported in numerous studies, these methods are fast, easy, inexpensive, applicable to field tests, and could be employed to improve log sorting and optimized cross cutting of tree stems to achieve optimal industrial use [22,23]. These technologies have become well-established as material evaluation tools, and their use has become widely accepted for quality control in the wood industry [3,24]. The NDT techniques applied to wood differ considerably from those applied to homogeneous materials [9,11,21]. In particular, acoustic analysis of wood features has been executed with methods based on transit time, resonance frequency, ultrasound, and wavelength spectral analysis [25,26]. In particular, the acoustic approach is based on the principle of stress wave propagation, which was developed to predict the mechanical properties and grading of timber and wood products [20,27,28] to evaluate the strength of standing trees, logs, and lumber [29–32], as well as for silvicultural management of standing trees [33–35]. In standing trees, the determination of the propagation velocity of acoustic waves is carried out via the time of flight (TOF method) of a generated wave with an actuator (usually one impact with a hammer) [36], whereas in logs or lumber, the propagation velocity can be measured by stationary acoustic waves generated with a resonance method through spectral analysis [36,37]. Wave propagation in wood is a dynamic process that is internally related to the physical and mechanical properties of wood [38]; based on this correlation, it is possible to estimate some wood quality indicators. One of the most important mechanical properties that can be measured by NDT methods is Young's modulus, i.e., the modulus of elasticity, which describes the stiffness of the material and strongly affects the acoustic properties of wood [39,40]; a high modulus of elasticity (MOE) value indicates a high resistance of wood to deformation [41]. MOE is one of the most important properties of wood and a major determinant of potential end-use products [2]. MOE is a measure of how much a wood member resists bending when a load is applied; thus, a higher MOE value indicates higher stiffness and greater suitability for structural products [42]. Wang and Simpson [43] evaluated the potential of acoustic analysis as presorting criteria to identify wood quality through the assessment of the dynamic modulus of elasticity (MOEd). This parameter is well-correlated with the static MOE (MOEs), which is measured by testing the piece to failure, with a slow process in the laboratory involving expensive equipment that is not very portable. Brüchert et al. [44] investigated the possibility of wood quality prediction from standing trees to sawn timber in coniferous species, and Vaughan et al. [42] determined the correlations between dynamic and static MOE value of small, clear wood samples. In previous studies, mechanical properties were validated by comparing them with the protocols envisaged by national and international standards, revealing a correlation between various methods and indicating a degree of accuracy between static bending and acoustic measurements [45]. However, all of these non-destructive methodologies must be supported by real values in order to guarantee the accuracy of the data obtained, and it is necessary to apply the dataset of these correlations (MOEd vs. MOEs) to more commercial wood trees.

Among the numerous and important species worldwide, the poplar represents one of the most important commercial wood species. The *Populus* species promotes local economic sustainable development based on the processing and use of wood resources, and the poplar wood industry chain represents a competitive bioeconomy worldwide. The widespread planting of poplars in Europe and throughout the world is primarily due to its rapid growth and adaptability to a range of soil and climate conditions [29]. For this reason, several studies have been conducted in recent years to characterize poplar wood, such as in terms of density, compliance coefficients [45], acoustic emission and propagation [46,47], and modulus od elasticity (MOE) [48,49] from standing trees using acoustic waves, also considering some parameters that affect wood characteristics, e.g., stand location, clones, season [50], or timber size [51]; however, only a few studies have tested the predictive accuracy of MOE until failure of the wood extracted from the same trees [52,53]. In Iran, Madhoushi and Daneshvar [9] found a correlation between the MOEd and the MOEs in sawn wood and standing trees of eastern cottonwood (*Populus deltoides*). In Spain, Gallego et al. [52] and Casado et al. [51] showed high values of the linear regression coefficients between non-destructive and destructive methods in young plantations of clone I-214 (*Populus* × *euroamericana* (Dode) Guinier) using an oscilloscope for standing trees and logs [52] and longitudinal vibrations on poplar lumbers [51]. In China, Zhou et al. [54] tested a resonance tool to sort Chinese poplar (I-72) logs for laminated veneer lumber products, finding a strong correlation between resonance-based acoustic velocities and dynamic MOE.

However, there is still a significant lack of knowledge regarding the predictive accuracy of modulus of elasticity of poplar clone I-214; therefore, the aim of this study was to determine, by non-destructive analysis, the MOEd in standing trees and logs of the 20-year-old poplar clone I-214 and to examine the relationship with the MOEs in sawn specimens. This relationship was also studied at three stem heights, from base to top. No previous studies have been conducted with respect to the application of NDT stress waves in standing trees and logs in Italy; consequently, a further goal of this study was to incorporate, encourage, and expand these methods for forest management and wood technology in poplar species.

2. Materials and Methods

2.1. Description of the Site

The poplar trees used in this study were selected in an area that falls within the municipality of Francica in the province of Vibo Valentia in the Calabria region (Italy), on private land, where traditional crops in the area were once cultivated. The area under consideration was planted with poplar clone I-214; this choice was made thanks to the productive and qualitative characteristics of the species. The site extends over an area of about 3 hectares (Table 1, Figure 1; 38°36′15′′ N–16°08′76′′ E), which is mainly flat, with only a slight slope in some places. The geometry used for the realization of this plantation was 6 m × 6 m. Furthermore, the necessary pruning was carried out over the years.

Table 1. Main characteristics of the stand.

Species	*Populus × euroamericana*
Clone	I-214
Latitude (°)	38°36′15″
Longitude (°)	16°08′76″
Age	22
Trees per ha	400
Mean DBH (cm)	30
Mean height (m)	20.41

Figure 1. Site map located in Calabria region (southern Italy).

2.2. Description of Standing Tree Measurement

For this study, 25 standing poplar trees were selected, and two non-destructive methods were used. The time of flight (TOF) of the acoustic stress waves was determined over a length at 3 different heights, thus obtaining H1 (30–130 cm), H2 (130–230 cm), and H3 (230–330 cm) (Figure 2A). The TOF of the sound wave was acquired using a TreeSonic instrument (Fakopp, Sopron, Hungary), and the acoustic velocity was determined. Before harvesting the tree, the breast diameter and total height of the selected trees were measured. Two SD-02 Fakopp piezoelectric sensors with a resonance of about 20 kHz were used to obtain the velocity of propagation along the direction of the fibers and nailed to the outermost part of the trunk of the tree. Furthermore, according to previous works [3,31,37,55], the sensors were always placed 100 cm from each other, and the tips were inserted 2 cm into the wood. To obtain an adequate propagation of the longitudinal waves, the tips penetrated the bark of the trunk at an angle of 45° to the vertical axis of the tree. During field acoustic measurements, the probes were aligned within a vertical plane on the same face [3]. For the recording, a control unit was used that received the signals generated by a percussion hammer weighing 100 g on the upper sensor. Ten readings in the same position were recorded for each tree, and the consequent stress wave times were then converted to mean acoustic velocity for each tree using Equation (1):

$$VelTre = \frac{d}{\Delta t} \quad (1)$$

where *VelTre* is the acoustic velocity in the longitudinal direction (m s^{-1}), *d* is the distance between the two sensors (m), and Δt is the difference in arrival time of the signal to both transducers (s).

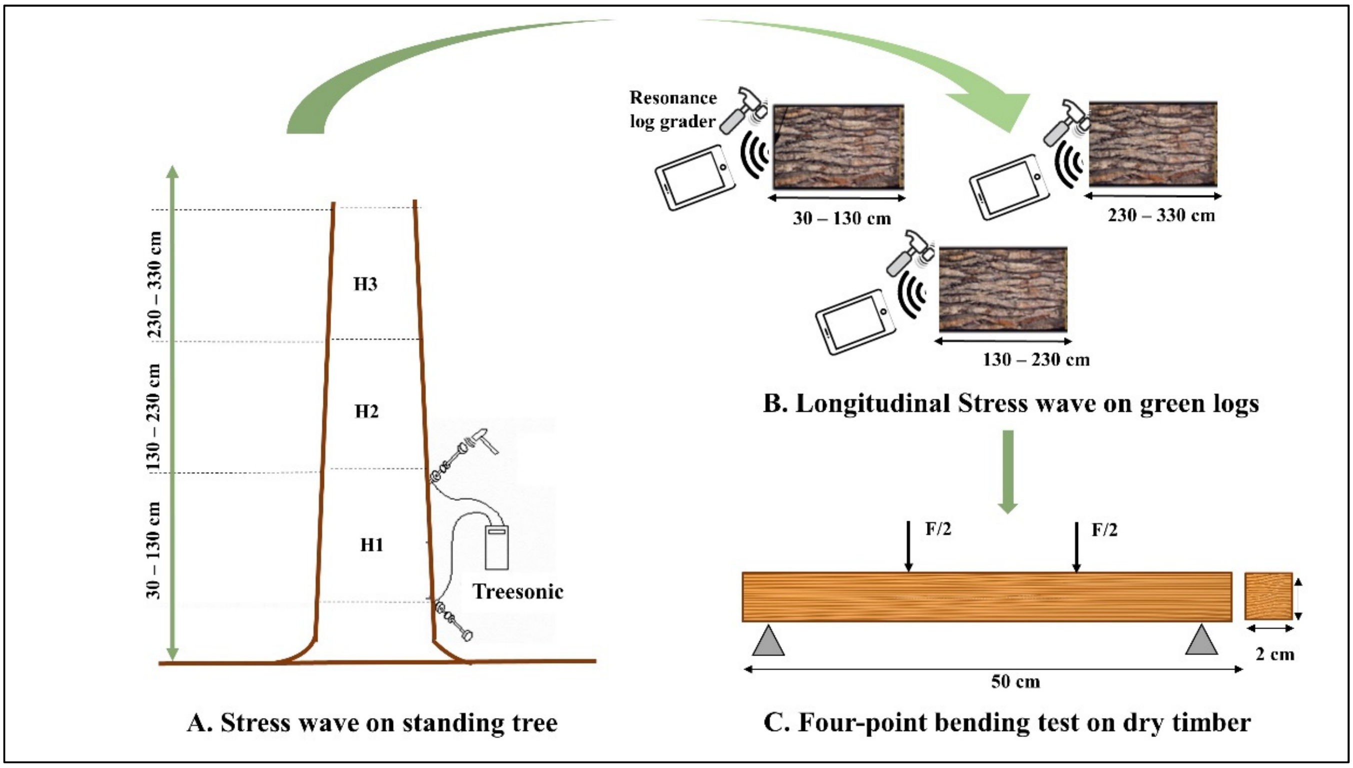

Figure 2. Measurement setup: (**A**) on standing trees; (**B**) on green logs; (**C**) on conditioned specimens.

2.3. Description of Log Measurements

After taking standing tree measurements, the trees were felled, and from each tree, three logs (length 100 cm) were separated and classified into three groups: H1: 30–130 cm, H2: 130–230 cm, and H3: 230–330 cm—as defined above. After about 3 weeks from the felling, measurement of the acoustic velocity in the longitudinal direction on the logs was carried out with a resonance log grader (Fakopp, Sopron, Hungary) (Figure 2B). The resonance longitudinal velocity of the logs was calculated using Equation (2):

$$VelGra = 2\,f\,L \quad (2)$$

where *VelGra* is the acoustic velocity in the longitudinal direction (m s^{-1}), *f* is the fundamental frequency (Hz), and *L* is the log length (m).

An acoustic resonance test was performed on each log; the measurement consisted of hitting a point of the section surface of the log with a 100 g percussion hammer and recording the response sound signal with a microphone. From the response signal, the first longitudinal resonance frequency was obtained as the first peak of the spectrum. Based on the frequency, dedicated software made it possible to obtain the propagation speed in the log with greater precision. As reported by other studies [52,56], during the recording phases of the sound wave, the log was raised from the ground at the central point so as to reduce the damping effect of the ground and obtain a cleaner sound wave.

2.4. Determination of Moisture Content (MC), Density, and Dynamic Elastic Modulus (MOEd)

To determine the water content (MC) under green and dry conditions (12%), the dry oven method was applied, according to EN 408 [57]. The samples were sized and conditioned in the cell according to the regulations before being subjected to mechanical tests. Furthermore, the mass and dimensions of the wood samples were recorded to determine the density. The mean value determined for wood density at 12% MC was 395 kg m^{-3} (±5.4).

Velocities obtained from the previous measurements (*VelTre*; *VelGra*) were adjusted to a reference moisture content (MC) of 12% based on the works of Sandoz [58,59]. An adjustment factor of 0.8% per 1% MC below fiber saturation point (FSP) was applied (Equation (3). It is well known that the influence of MC on non-destructive testing results is much stronger below than above the FSP. According to Sandoz [59], this influence is at least eight times more with respect to sound velocity. A similar effect was reported by Unterwieser and Schickhofer [60] and Rais et al. [61] with respect to longitudinal vibration. Therefore, because green logs had an average MC of 88%, the correction was applied for a reduction in MC from 30 to 12%. MOEd was then calculated from density and velocity, which were previously adjusted to 12% according to Equation (4):

$$Vel_{12} = \frac{Vel_u}{0.8} \tag{3}$$

where Vel_u is the velocity measured at a certain (u) moisture content level.

$$\text{MOEd} = \rho \, Vel_{12}^2 \tag{4}$$

where MOEd is the dynamic MOE in the longitudinal direction (N mm^{-2}), and ρ is the wood density (kg m^{-3}). Therefore, MOEdTre was obtained on standing trees, and MOEdGra was obtained on logs.

2.5. Determination of Mechanical Testing and Static Elastic Modulus (MOEs)

For each group (H), 50 specimens were used for the bending test in the laboratory of Wood Technology and Forest Mechanization of the AGRARIA Department of Reggio Calabria. The specimens were conditioned in a climatic cell at 20 ± 2 °C and 65% (±5%) relative humidity (RH) to reach an equilibrium moisture content (EMC) of 12%. A four-point bending test was performed using a 300 kN universal testing machine (METRO COM, Novara, Italy), in accordance with European Standard 408:2010 + A1 [57]. Data were acquired with DINA 960 XP, 4.3 version (METRO COM, Novara, Italy) software. The supports were placed at a distance equal to 18 times the width, and the two load points were placed at a distance from each support equal to 6 times the width (408:2010 + A1) [57]. The speed of the crosshead was 3.6 mm/min. During the test, the values of the load and the bend were registered. A static diagram of the test is presented in Figure 2C.

2.6. Data Analysis

Statistical data analysis was performed using SPSS software version 20.0 (IBM Corp., Amonk, NY, USA). First, descriptive statistical analysis was carried out for the velocities of the stress wave on standing trees (*VelTre*) and logs (*VelGra*), and of the calculated dynamic and static elastic moduli (MOEdTre, MOEdGra, and MOEs). In particular, for each group (H), MOEs were expressed as an average value of the 50 specimens tested in the laboratory. Subsequently, a two-tailed linear correlation analysis was performed between the static modulus of elasticity (MOEs) and sound stress wave velocities acquired with Treesonic (*VelTre*) and Resonance Log Grader (*VelGra*). The same approach was applied to calculate the linear correlation between the static modulus of elasticity (MOEs) and the dynamic modulus of elasticity obtained with TreeSonic on standing trees (*VelTre*) and Resonance Log Grader on logs (*VelGra*), both for the whole trunks and for the parts divided according to the three designated heights.

3. Results

Different measurements of wood with their descriptive statistics are summarized in Table 2. They relate to the stress properties of the acoustic wave of the static and dynamic modulus of elasticity obtained with non-destructive and destructive instruments, distinguishing the data collected for the three heights of the stem (H1, H2, and H3). The TOF measured in the same part of the standing stem and logs with the two different tools (TreeSonic and Resonance Log Grader) were similar for all three cases. The same trend was observed for the MOEd; the highest difference between the mean values of MOEdTre and MOEdGra for the three heights was around 6%. Static MOE values compared to the means of MOEd were 25%–30% higher. In general, all analyzed parameters increased, rising from the bottom to the top of the stem. According to the tests carried out on standing trees, starting from section H1 (30–130 cm from the ground), the average value of the acoustic velocity detected by the TreeSonic device was 3865.15 m s^{-1}; in section H2 (130–230 cm from the ground), it increased by 8.8%; and finally, in section H3 (230–330 cm from the ground), it was 4425.26 m s^{-1}, increasing by 12.9% from the first to the third section. The MOEd estimated by the TreeSonic followed the same trend, increasing by 17.45% and 25.5% from the first to the second section and from the first to the third section, respectively (Figure 3). With regard to tests on logs carried out by Resonance Log Grader, the results were close to those obtained with the TreeSonic device for the same log subdivision (H1, H2, and H3), as shown in Figure 2, both for acoustic velocity and for the MOEd. Finally, even the static elastic modulus derived from the specimens of the three sections confirms how it increased as the height of the stem increased, increasing from 8248.51 N mm^{-2} for section H1 to 9091.2 N mm^{-2} (+9.3%) and 10,364.78 N mm^{-2} (+20.4%) for section H3.

Table 2. Descriptive statistics of the stress velocities of the sound wave (m s^{-1}) on standing trees (*VelTre*) and logs (*VelGra*) and of the calculated dynamic and static elastic modules (MPa). The variables were split along the three designated stem heights (H1-H2-H3).

H		N	Minimum	Maximum	Mean	Std. Deviation	CV
H1	*VelTre*	22	3125	4556	3853.75	333.4	8.65
	VelGra	22	3598	4196	3876.55	144.24	3.72
	MOEdTre	22	3782.82	8040.51	5793.94	987.06	17.03
	MOEdGra	22	5014.63	6820.04	5828.8	434.21	7.44
	MOEs	22	6574.2	10,145.52	8248.51	909.63	11.02
H2	*VelTre*	22	3250	5321	4226.6	509.29	12.04
	VelGra	22	3500	4500	4110.18	275.77	6.70
	MOEdTre	22	4091.5	10,967.37	7015.81	1667.72	23.77
	MOEdGra	22	4745.18	7844.07	6572.04	852.49	12.97
	MOEs	22	7166.7	11,908.6	9091.2	1300.55	14.30
H3	*VelTre*	22	3828.5	5985	4425.26	719.79	16.26
	VelGra	22	3900	5741	4413.18	430.97	9.76
	MOEdTre	22	5677.67	13,875.37	7777.24	2740.8	35.24
	MOEdGra	22	5891.76	12,767.07	7612.99	1591.12	20.90
	MOEs	22	7914.9	14,958	10,364.78	2118.74	20.44

Considering the acoustic stress wave velocities and the static modulus of elasticity, Table 3 shows the global linear correlation among the data collected during the surveys. The sound stress wave velocities detected with the TreeSonic instrument on the entire tree were strongly correlated with the measurements made with the Resonance Log Grader on the logs, as well as with the results of the static modulus of elasticity. The MOEs demonstrates a strong two-tailed correlation with a confidence interval of 0.01 both with *VelGra* and with *VelTre*. In general, *VelGra* and *VelTre* were also strongly correlated with each other.

The same trend can be observed (Table 3) for the dynamic and static moduli of elasticity; furthermore, the two dynamic moduli of elasticity, MOEdTre and MOEdGra, were also correlated with each other, with a Pearson correlation coefficient of 0.607.

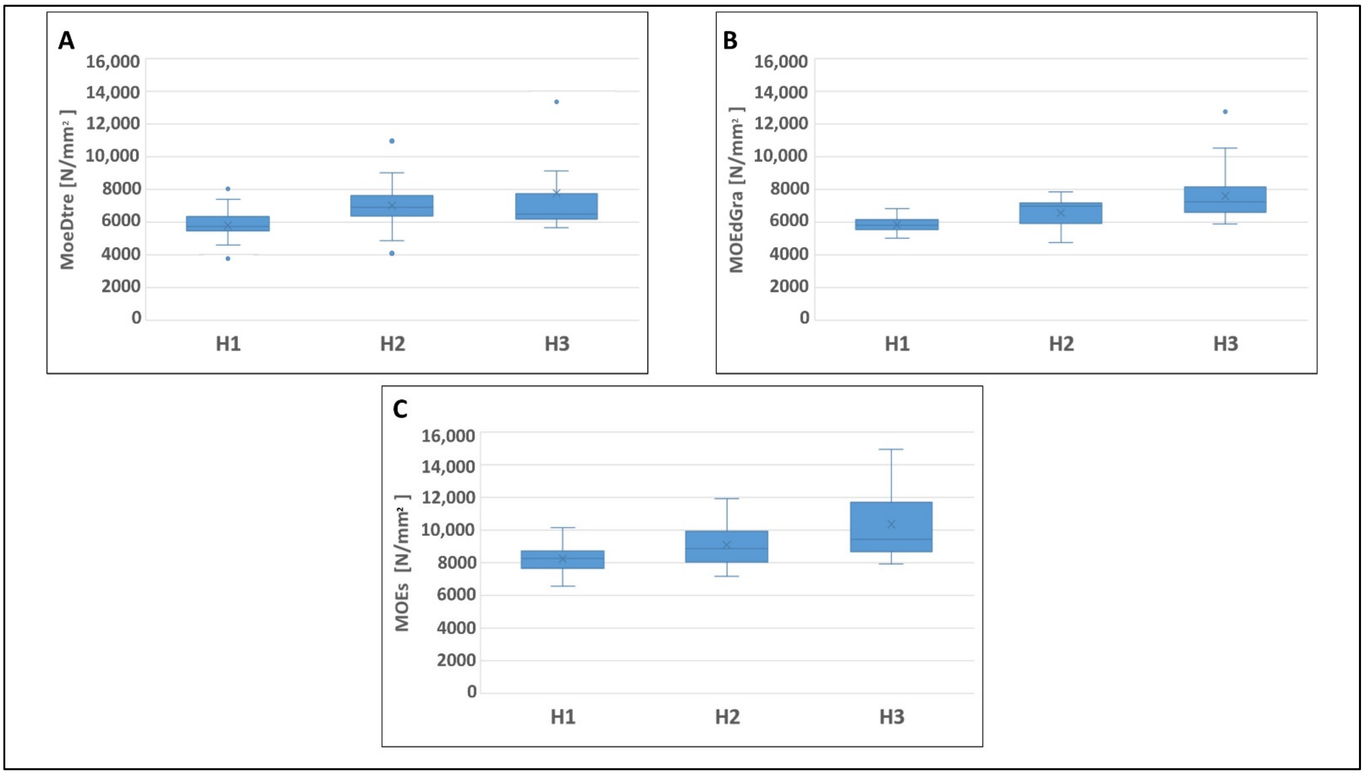

Figure 3. Graphical representation of the modulus of elasticity (MOE) assessed with (**A**) Treesonic on standing trees, (**B**) Resonance Log Grader on green logs, and (**C**) universal testing machine DINA 960 XP (METRO COM, Italy) on conditioned specimens.

Table 3. Two-tailed linear correlation between the static modulus of elasticity (MOEs) and sound stress wave velocities acquired with TreeSonic (*VelTre*), Resonance Log Grader (*VelGra*) and dynamic modulus of elasticity obtained with TreeSonic (MOEdTre) and Resonance Log Grader (MOEdGra).

		N	*VelTre*	*VelGra*	MOEdTre	MOEdGra
MOEs	Pearson Corr.	66	0.690 **	0.726 **	0.708 **	0.728 **
VelGra	Pearson Corr.	66	0.627 **	1	-	-
MOEdGra	Pearson Corr.	66	-	-	0.607 **	1

** Correlation is significant at the 0.01 level (two-tailed).

The correlations between the static modulus of elasticity and the dynamic modulus estimated by the TreeSonic on the different height sections varied according to section. The results (Table 4) observed in the H1 section (the bottom-most section of the tree) showed that the MOEs was not strictly correlated with the MOEdTre, with a Pearson correlation coefficient of 0.279, whereas section H3 showed the highest correlation index between the two moduli of elasticity, i.e., static and dynamic (Pearson correlation coefficient of 0.775).

Table 4. Two-tailed linear correlation divided by the three designated heights between the static elastic modulus and the dynamic elastic modulus obtained with TreeSonic and Resonance Log Grader devices.

H			N	MOEdTre	MOEdGra
H1	MOEs	Pearson Corr.	22	0.279	0.439 *
H2	MOEs	Pearson Corr.	22	0.466 *	0.287
H3	MOEs	Pearson Corr.	22	0.775 **	0.759 **

* Correlation is significant at the 0.05 level (two-tailed); ** Correlation is significant at the 0.01 level (two-tailed).

As shown in Table 4, comparing MOEdGra and MOEs, the H3 section showed the highest Pearson correlation index of 0.759 for a confidence interval of 0.01. Figure 4 shows the linear correlations between the acoustic stress wave velocities of the standing trees (Figure 4A) and the logs (Figure 4B), as well as the static modulus of elasticity. Specifically, the relationship between the speeds of stress wave *VelTre* and the MOEs had an R^2 value of 0.476, whereas the correlation between *VelGra* and the MOEs shows an increase in the R^2 value equal to 0.527. The graph highlighted in Figure 4 shows a linear correlation with R^2 value of 0.501 with regard to the MOEdTre and the MOEs, whereas a slightly closer linear correlation was observed between the MOEdGra and the MOEs, with an R^2 value of 0.530. Even if the correlation value considered in these graphs is global for the entire tree (not subdivided by sections) it is possible to observe in Figures 4 and 5 that section H3 tended to have higher values with respect to the dynamic modulus of standing trees and logs with the static modulus of elasticity calculated from similar specimens.

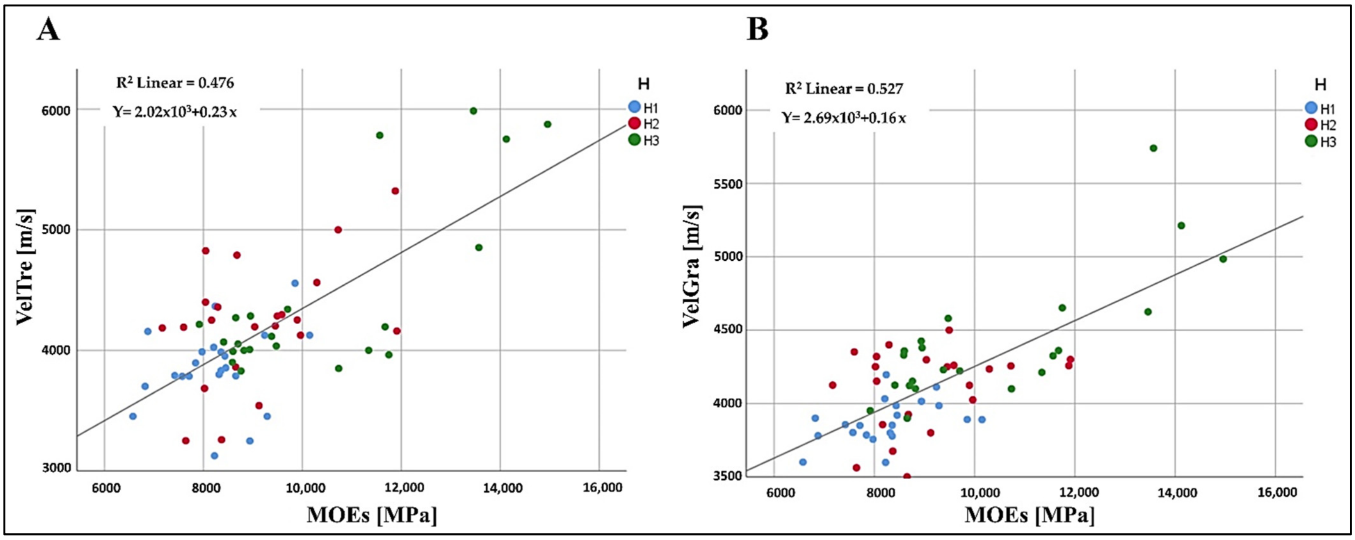

Figure 4. The relationships between the static modulus of elasticity and the sound wave stress velocities acquired from standing trees (**A**) and logs (**B**).

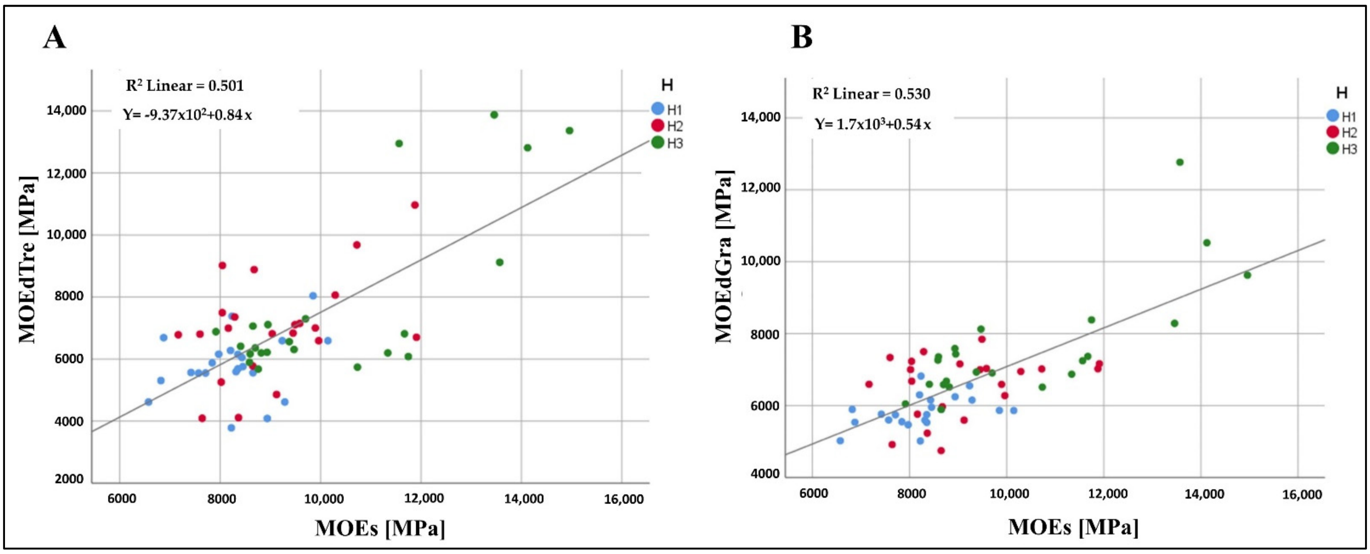

Figure 5. The relationships between the static modulus of elasticity and the dynamic modulus of elasticity obtained from standing trees (**A**) and logs (**B**).

4. Discussion

Many factors could affect the propagation velocity of acoustic waves through wood, such as the level of wood defects, the percentage of bark, and the relative uniformity of the logs in the section [62]. However, as observed in a study conducted by Danilović [63], pruned trees up to 5 m in stem height have fewer defects (knots) than non-pruned trees. The low standard deviation measured by the TOF and resonance methods could be explained by the thin bark and the homogeneity of the wood [46,50,63] resulting from pruning; therefore, the dynamic elasticity moduli obtained by tests in the present research show a small difference (3%) between the average values of the elastic modulus between standing trees and logs.

As confirmed by the research of Rescalvo et al. [50] and Gallego et al. [52], there is a significant correlation between the propagation velocity of acoustic stress waves of standing trees obtained using the TOF method and the propagation velocity measured on the logs by means of the resonance method, generally with standing tree acoustic speeds being slightly higher (faster velocities) than those measured on logs cut from trees [20].

In general, the stress wave speed in the longitudinal direction increases slightly with the height of the stem, as observed in this study. This trend could be justified by the higher moisture content in the basal part of the trunk; previous studies [20,64] have reported that humidity is one of the causes of reduced wave speeds in trees. Furthermore, these results are consistent with previous results reported by Ishiguri et al. [65] and Madhoushi and Daneshvar [9], who showed that the speed of the stress wave depends on the position of the stem but also because variation in the modulus of elasticity along the stem depends on the species [66,67]. In some species, such as pine [68], a similar trend was reported to that found for poplar [9].

Compared to this research, Gallego et al. [52] reported slightly inferior values, possibly because for MOE calculation, they applied a basic density at 0% moisture content (MC), so the density used in that study was equal to 330–350 kg m^{-3}. Regarding increasing velocity in log wood, compared to standing trees, the relationship between acoustic velocity and green density was defined, and the reduction in green density is proportional to the loss of moisture and to the increase in velocity squared [8].

Furthermore, in accordance with [69,70], in this study, we found highly significant correlations between tree velocity and the MOE of logs. Some authors [38,71] found that there is a relationship between the elastic modulus of standing trees and logs and the static elastic modulus of sawn timber, measuring elastic modulus in the longitudinal direction on the standing trees. The relationship between acoustic measures in trees and logs was very similar to that reported by Gallego et al. [52] who tested a similar clone with different acoustic tools in the same comparative study. In other studies with similar species of the *Populus* genus, the authors identified a significant correlation between static and dynamic MOE with a deviation of 10.4% [48].

The resulting difference between the average value of the MOEs and the MOEd is about 26%. This result disagrees the results reported by other authors. Leite et al. [72] and Chauhan and Sethy [73] reported a higher MOEd relative to MOEs, but Hoduosek et al. [74] reported a lower MOEd value. In accordance with the results of the present study, Gallego et al. [52] and Hernández et al. [45] reported a static modulus of elasticity higher than the MOEd for the same species and clone. Hernández et al. [45] observed differences of more than 20%, on average, between dynamic and static modulus, advising caution in predicting mechanical properties of wood based on density in *Populus* × *euroamericana* clones at young ages. Hoduosek et al. [74] also attributed this trend to sample dimensions, especially length [75], and opined that measured values of MOEd are mostly lower than those of MOEs due to the relationship between frequency and sample dimensions.

Therefore, it is fundamental to correctly define the size of specimens and lumber used in comparative tests to determine the prediction accuracy; for example, Casado et al. [51] identified an overestimation of accuracy for medium-sized lumber and a valid correlation for smaller wood specimens. The results of this research are therefore supported by several studies that showed that the degree of concordance of the velocity relationship for standing trees and logs provides a valid support to identify mechanical properties of poplar wood. Based on these results, the accuracy of the resonance tool was also supported and can be used to evaluate mechanical properties after the felling and cross cutting phases on site as a presorting activity based on wood quality. In fact, compared to the use of TreeSonic, the Resonance Log Grader tool is faster, as its use does not require predetermination of the physical characteristics of the wood (for example, the density); consequently, the detection of the speeds is rapid and immediate.

Therefore, the present study provides strong evidence that both the time-of-flight (for standing trees) and resonance acoustic (for logs) tools can provide aggregated cross-sectional quality information.

5. Conclusions

The aim of the work conducted in this study was to determine, by non-destructive analysis, the MOEd of standing trees and logs of the 22-year-old poplar clone I-214 and to examine the relationship with the MOEs in sawn specimens. The purpose was to determine the predictive accuracy of the modulus of elasticity, starting from the TOF of acoustic stress wave (on standing trees with the TreeSonic device) and resonance (on logs with the Resonance Log Grader tool) tools. The results showed that both non-destructive methods applied in this study are valid for estimating the MOEd, with resulting values differing slightly between methods, as reported, and confirming the prediction performance for determination of static MOE. The choice of one or the other method is at the discretion of the operator, but above all, should be determined according to the phase in which it is decided to carry out the surveys and the products to be obtained.

Therefore, the present study supplies strong evidence that both investigated tools can provide quality information on forest stands. The information obtained with the acoustic techniques can be useful for the prediction of the real elastic modulus and is relevant for adapting both the cutting models from the design of the cut itself with the use of Treesonic and the selection of the logs, thanks to the Resonance Log Grader, by forestry companies or sawmills. Given the variability of use of poplar wood in the production of panels or as veneers, these NDT techniques are adaptable for selection in all segments of the forest wood supply chain in order to facilitate and make the evaluation process more efficient. Moreover, the information obtained by acoustic techniques may be relevant in adapting cutting patterns to logs of lower stiffness and favoring the segregation of logs into batches and altering the cutting patterns for lower stiffness logs in order to produce timber that will not be rejected during the grading process.

Considered the relative ease and rapidity of applying non-destructive instrumentation to both standing trees and logs, such a method could support foresters in determining whether trees from a timber sale or just some part of them might be suitable for structural products or whether they should be directed towards bioenergy, pallet stock, or other existing, lower-value markets [42]. However, for the correct interpretation of the observed data, sufficient knowledge of the characteristics of the investigated tree species is required in order to understand which factors could influence the measurements. The development of new applications for existing technologies is ongoing, with continuous advances and refinements. In the field of NDT technologies, as well as in other fields of research, the use of these tools requires extensive experience with testing techniques due to the difficulty in interpreting data. Only with accurate interpretation can this technology assist in managing wood quality, assessing forest value, and improving the timber quality of forest stands [3]. If correctly integrated into forest inventories, these methodologies allow a large number of measurements to be carried out in the field in a short time and with a satisfactory level of accuracy.

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Abbreviations

The following acronyms are used in this manuscript:

NDT	non-destructive test
TOF	time-of-flight of wave
MC	moisture content
FSP	fiber saturation point
MOE	modulus of elasticity
MOEd	dynamic modulus of elasticity
MOEs	static modulus of elasticity
VelTre	sound stress wave velocities obtained with Treesonic on standing tree
VelGra	sound stress wave velocities obtained with Resonance Log Grader on log
MOEdTre	dynamic modulus of elasticity on standing tree
MOEdGra	dynamic modulus of elasticity on log

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5. Conclusion and Future Perspectives

This PhD thesis has developed three different approaches to evaluate the wood supply chain in the Calabria Region focusing attention on forests and logging operations, ergonomic conditions in forest operations, and wood technology and non-destructive testing.

In particular, the primary object of this study was to determine the various parameters that influenced the rate of productivity and economic costs of forestry machinery used during forestry utilization in Bulgaria, which is particularly suited to forestry. The importance of this study was motivated to establish whether forest management operations and machines could be recommended for more efficient and sustainable harvesting in the forest conditions of the Calabria Region.

In general, the first results have shown that a good organization on-site, in particular, planning an optimal road network to reduce the extraction distance, managing the arrangement of the wood assortments already during felling, using innovative machines, can limit the time consumption related to the extraction operations, during the total time of the work cycle. It has been observed how productivity increases thanks to the use of innovative forestry machinery; in this case, it has been seen how:

- The use of "Yarder tower processors" compared to other machines, was production, cost-efficient, and minimally labor intensive in logging operations in coniferous forests on steep terrains, managed by the shelterwood system.
- The "combi–forwarder" provides high productivity and cost efficiency compared to many extraction machines, which makes it very suitable for logging operations in deciduous forests in mountainous conditions.

These machines are perfectly adaptable to the orography of the Calabrian territory. Even the use of imposing machines such as Forwarders and Harvesters, in some sites that allow them to be manoeuvrable, could be efficient in Southern Italy. When site conditions do not permit the use of forestry machinery, especially large and heavy machinery, particularly in situations such as areas restricted by closures or recognized as nature reserves, the use of tower yarders or cable cranes may be the best applicable solution. Furthermore, the productivity of some forestry machines in forests damaged (*Salvage Logging*) by abiotic or biotic factors was evaluated and the results revealed that the operational costs of salvage logging are higher than traditional stand cutting but necessary to recover the future economic value of the forest. In fact, salvage logging benefits can exceed the economic limit in these forests that should be managed to guarantee ecological and productive aspects.

The second activity is related to the determination of ergonomic conditions in forestr operations. In particular, the research carried out concerned: the determination of significant differences in terms of forest operator exposure to noise and hand-arm vibration due to the use of chainsaws; the study of working postures during the measurement of forest assortments by comparing three different measurement options, i.e., say traditional measurement, scanning from a smartphone, and scanning from a commercial laser scanner.

The results obtained from the study performed on postures during wood measurements demonstrate that updated technology is needed, and can help improve ergonomic conditions, in many forestry applications, including wood measurement. While such technology is already available, its use in wood measurement tasks is still in its infancy, being implemented primarily as an occasional test to demonstrate its effectiveness. For these reasons, ergonomic assessments are needed to validate their sustainability in use, assuming a full or complementary scale implementation.

Some occupational health disorders, such as hearing loss, repetitive stress syndromes and some musculoskeletal injuries, are the subject of study and research at important international agencies, such as FAO and ILO, in countries with significant forest sectors. Indeed, the harvesting of wood exposes the operators to levels of an occupational nuisance. In this perspective, few studies focused on monitoring vibro-acoustic impacts on chainsaws used in small agroforestry enterprises. The results obtained from the determination of the significant differences in terms of forest operator exposure to noise and hand-arm vibrations due to the use of chainsaws demonstrate the correct maintenance of chainsaws over time has an important role in exposure to noise and vibrations by the forestry operator, especially for small agroforestry companies that occasionally use these dated tools.

The objective of the third part of this Ph.D. was to develop a methodological approach using a non-destructive technology (NDT), to evaluate some qualitative characteristics of wood. The results of the studies carried out showed that the non-destructive methods (NDT) applied are valid both for identifying different defects in a tree trunk, including ring shake, without affecting its biological activity, overcoming the difficulties of prediction using only the visual inspection, which to estimate some mechanical characteristics of the wood tissue such as the dynamic modulus of elasticity (MOEd) and therefore, the prediction for the static MOE in poplar wood.

These NDT techniques are adaptable for selection in all segments of the forest wood supply chain in order to facilitate and make the evaluation process more efficient. Moreover, the information obtained by acoustic techniques may be relevant in adapting cutting patterns to logs of lower stiffness and favouring the segregation of logs into batches and altering the cutting patterns for lower stiffness logs in order to produce timber that will not be rejected during the grading process. Considering the relative ease and rapidity of applying non-destructive instrumentation to both standing trees and logs, such a method could support foresters in determining whether trees from a timber sale or just some part of them might be suitable for structural products or whether they should be directed towards bioenergy, pallet stock, or other existing, lower-value markets. However, for the correct interpretation of the observed data, sufficient knowledge of the characteristics of the investigated tree species is required in order to understand which factors could influence the measurements. The development of new applications for existing technologies is ongoing, with continuous advances and refinements. In the field of NDT technologies, as well as in other fields of research, the use of these tools requires extensive experience with testing techniques due to the difficulty in interpreting data. Only with accurate interpretation can this technology assist in managing wood quality, assessing forest value, and improving the timber quality of forest stands. If correctly integrated into forest inventories, these methodologies allow a large number of measurements to be carried out in the field in a short time and with a satisfactory level of accuracy.

The results obtained in this Ph.D. can be useful for forest operators, timber industry associations and stakeholders involved in forest management, as well as for engineers and decision-makers to support the development of a specific subsidy framework. In fact, thanks also to the study of European forest contexts such as the Bulgarian, the results obtained in terms of forest mechanization can be extended to the Calabrian territory or even in all forest geographic areas (e.g. Mediterranean Basin) with similar characteristics in terms of productivity, slopes and road network.

Future investigations will focus on the use of different methods to determine environmental management using the benefits of applying “precision forestry”. In increasingly sustainable and multifunctional systems such as forestry, information and communication technologies (ICT) can play a significant role in the innovation and efficiency of management processes and the creation of new products and services to support forest owners and wood plantations, entrepreneurs, forest technicians and citizens, with important positive effects on the quality of wood production, on the reduction of production costs and on the minimization of the environmental and social impacts of the recision forestry which are still excluded. In fact, in forestry, environmental impact studies usually exclude the impact of woodworking (sawmills and furniture), which is related to forestry management, mechanization and wood quality.

From the experience gained through my Ph.D., it was possible to identify, the weaknesses and merits of the Calabrian wood supply chain, with significant potential for optimizing process and machinery innovation. In fact, from my point of view the Calabrian region, has enormous quantities of usable wood mass, but to its detriment, it has a structure of the forestry stock, in terms of public and/or private property, very fragmented: that does not emphasize the concept of supply chain. In fact, a high fragmentation of forest areas, means a difficult management of the forest patrimony and therefore a scarce interest in enhancing: both wood products and forest management and utilization techniques. Calabrian forest proprietaries as well as forest enterprises, tend to serve (with some exceptions) the local market with sales systems that reduce the financial risk and management complexity of the forest. In my research, it was pointed out that some forest utlization models from Eastern European countries are perfectly adaptable to the orography of the Calabrian terrirory. In addition, it has been observed how innovation has a fundamental role on decision-making choices, concerning: a better quality in the obtained wood products; a higher degree of security of the operators of the forest-wood supply chain. At the same time, if we add to these results the strong forestry vocation and the strategic position at the center of the Mediterranean of this region, the policy instruments (National and European) and the entrepreneurial capacity (with about 1800 forestry companies of various types), we get the potential (even in the short term) that can certainly improve and make more competitive the Calabrian Forest-Wood Supply Chain.

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