

Article

The Wood Quality of Small-Leaved Lime (*Tilia cordata* Mill.) Trees in an Urban Area: A Pilot Study

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Abstract: This study performed a pilot evaluation of the wood quality—defined by a single parameter: dynamic modulus of elasticity (MOEdyn, N mm⁻²)—of small-leaved lime (*Tilia cordata* Mill.) trees in urban areas. A search of the literature revealed few studies which examined the specifics of tree wood development in urban areas. Little is known about the potential of wood from urban trees wood of their suitability for the timber industry. In this study, an acoustic velocity measuring system was used for wood quality assessment of small-leaved lime trees. The MOEdyn parameter was evaluated for small-leaved lime trees growing in two urban locations (along the streets, and in an urban park), with an additional sample of forest sites taken as the control. MOEdyn was also assessed for small-leaved lime trees visually assigned to different health classes. The obtained mean values of MOEdyn of 90–120-year old small-leaved lime trees in urban areas ranged between 2492.2 and 2715.8 N mm⁻². For younger trees, the values of MOEdyn were lower in the urban areas than in the forest site. Otherwise, the results of the study showed that the small-leaved lime wood samples were of relatively good quality, even if the tree was classified as moderately damaged (which could cause a potential risk to the community). Two alternatives for urban tree management can be envisaged: (1) old trees could be left to grow to maintain the sustainability of an urban area until their natural death, or (2) the wood from selected moderately damaged trees could be used to create wood products, ensuring long-term carbon retention.

Keywords: *Tilia cordata*; urban trees; acoustic velocity method; dynamic modulus of elasticity



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1. Introduction

The small-leaved lime (*Tilia cordata* Mill.) is a common unevenly distributed tree species found in the temperate forest zones of Europe [1–4]. This tree species is more common in mixed than in pure forest stands. In Western Europe, the small-leaved lime is found in forests dominated by *Quercus robur* L., *Fraxinus excelsior* L., *Acer pseudoplatanus* L., *Betula pendula* Roth, *Padus avium* Mill., and *Sorbus* sp. [5]. In Eastern Europe, small-leaved lime prevails in stands and grows together with *Quercus* sp. and *Carpinus betulus* L. [4]. The small-leaved lime is an important species for urban and recreational forestry and open landscapes [5–8]. These trees are often planted individually or in groups along roadsides and in urban parks. Up until now, too little attention has been paid to the growth of small-leaved lime under different environmental conditions, possibly because of its low economic value in the wood market. However, due to its wide ecological tolerance, this species could become more important in forestry under changing climate conditions [9].

In Lithuania, the small-leaved lime, as the dominant tree species in forest stands, occupies about 0.5 percent of total forest cover [10]. This tree species is the most common species in urban areas of the country and comprises about 45 percent of the total urban tree population [11,12]. Similarly, small-leaved lime trees account for about 24 percent of the total urban tree population in Nordic countries, with a maximum cover of 46.3 percent in Gothenburg [7].

Urban trees are related to several site factors, including soil moisture, porosity, fertility, and climatic factors [13,14]. The effects of limited root space, air pollution, water stress, poor drainage, soil compaction and contamination on urban tree growth has been documented [15,16]. In the northern regions, melting snow—containing salts used for de-icing roads—has a negative impact on water quality, and can significantly damage urban vegetation, including trees [17–19]. Overall, trees in urban areas are exposed to relatively high stress, which often leads to shorter average lifespan [15,20–22]. The small-leaved lime, among other deciduous species, is considered a relatively resistant native tree species, and is adaptable to changing climatic conditions (e.g., higher temperature, drought periods, etc.) [23,24]. Therefore, based on ecological and biogeographical principles, the small-leaved lime is often selected for growing in the urban areas of Lithuania.

Previous research has reported that small-leaved lime wood has good technical qualities; it is a strong and flexible wood with fine structure and uniform, straight-grained texture, making it suitable for veneer [3,25]. The colors of the small-leaved lime's sapwood and heartwood are similar. Additionally, the dried wood remains stable and easily workable, which makes it easy to use for hand carving, turning, and the manufacture of musical instruments, furniture, crates, and boxes [26]. However, the wood lacks durability and is therefore unsuitable for most outdoor construction. The wood of the small-leaved lime responds well to densification treatment, which improves dimensional wood stability but reduces thermal stability [27]. The study by De Jaegere et al. [9] reported that the small-leaved lime grows in a wide range of environmental conditions; among other ecological and silvicultural features, this species shows potential for wood production in Europe.

The environmental conditions in urban area—including enhanced air, soil and water pollution, among other disturbances—alter the wood structure of trees, reduce their growth and vitality, and can cause higher tree mortality [28]. Up until now, too little attention has been paid to the wood formation and quality of urban trees [29]. Only a few studies have investigated the growth and phenology of small-leaved lime trees in urban environments [30].

An acoustic method has often been used for determining the wood quality of standing trees and logs; it could also be used for standing urban trees [31–33]. Moreover, earlier studies [34] showed a good correlation ($R^2 = 0.63$ to 0.91) between stress wave speed and the dynamic modulus of elasticity (MOE) of standing trees. This method could allow researchers to obtain data such as the MOE (an important wood parameter) and use them to develop appropriate management methods for urban trees.

This study aimed to perform a pilot evaluation of a basic wood quality parameter (dynamic modulus of elasticity) of standing small-leaved lime (*Tilia cordata* Mill.) trees in urban areas. The data obtained from urban areas was compared with forested areas.

2. Materials and Methods

2.1. Site Characteristics

The study was carried out in western (Klaipėda city, $55^{\circ}43'01''$ N, $21^{\circ}07'02''$ E) Lithuania. The mean annual temperature was 6.9°C and the mean annual precipitation was 695 mm [35].

In Klaipėda city, the air quality (the parameters SO_2 , NO_2 , CO, and PM_{10}) in the living environment is mostly affected by the activities of Klaipėda State Seaport, Klaipėda Stevedoring Company (KLASCO) and road transport [36]. Overall, the air pollution is described as low to moderate.

For this study, 90–120-year old small-leaved lime trees (grown in four streets and in City Park in Klaipėda city) were selected, after identifying that all selected trees had similar growth conditions. Tree age was fixed from historical data provided by the institutions of Klaipėda city. For control, two sites with 90–120-year old small-leaved lime trees were selected in pure small-leaved lime stands in nonurban areas. In total, 292 small-leaved lime trees were assessed in the summer and autumn of 2019–2020.

2.2. Tree Health Assessment

The health condition of the selected urban trees was assessed visually according to requirements approved by order of the Minister of Environment of the Republic of Lithuania in 2008 and updated in 2020 [37]. All assessed trees were assigned to one of the following classes: (1) healthy trees, e.g., trees which were normally developed, with dense, evenly distributed foliage, leaves of normal size and color, and no signs of disease, pests, wounds, stem or branch damage, or tree hollows; (2) slightly damaged trees, e.g., trees which are healthy, but exhibited small shoot growth, less foliage, unevenly developed crowns, signs of minor mechanical/pest damage, or small tree hollows; (3) moderately damaged trees, e.g., trees that were obviously weakened, overshadowed by other trees, severely damaged by diseases or pests, or exhibited weakly developed crowns, drying or dried branches, little to no shoot growth, dry tops, damaged stems, large hollows, or raised tree roots; (4) severely damaged trees, e.g., trees in which the crown was more than 50% leafless or the stem was more than 40% rotten (including invisible rot noted upon cutting down of the tree). Examples of healthy and damaged small-leaved lime trees are given in Figures 1 and 2.

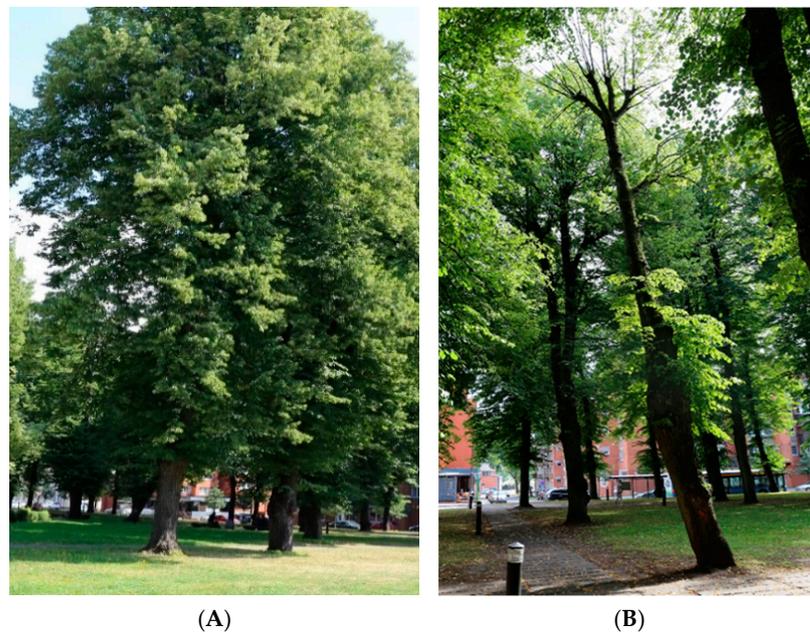


Figure 1. Examples of healthy and damaged trees in Donelaicio Park. (A) Healthy tree, Donelaicio Park. (B) Damaged tree, Donelaicio Park. (Photos: Aistė Povilaitienė).

2.3. Wood Quality Assessment

For wood quality assessment of small-leaved lime trees in urban areas, the acoustic velocity measuring system was used. The approach of time-of-flight (TOF) of a single pulse wave was taken for this study. The TOF measures the time for the stress wave to travel from the transmit probes to the receiver probes. Data on longitudinal acoustic waves were obtained. The acoustic tool ARBOTOM 3D (Rinntech), which was specifically designed for standing trees, was used for this study.

For each analysis, the standing tree stem was divided into two sections: 0–1 m section, and 1–2 m section (from the ground) (Figure 3). In each standing tree stem, three levels were marked: ground-level, one meter from the ground, and two meters from the ground. The diameter of each section's top-end (at 1 and 2 m above the ground) was measured before calculating distances between nails. Then, five nails were inserted at equal distances from each other into the stem bark at each level of the stem. Probes were fixed on the nails. To measure acoustic velocity waves, the start probe was connected with the second probe, and the second to the third, and so on until each probe was connected in order. A

total of 15 sensor probes (transmit and receiver probes) were inserted a few centimeters into the sapwood of each tree in a vertical plane. Acoustic energy was introduced into the tree through hammer impact. In order to achieve best results, each probe was hit not less than five times. In each section, 50 measurements were made. The acoustic velocity was calculated from the distance between the two sensor probes and the TOF data for each section.

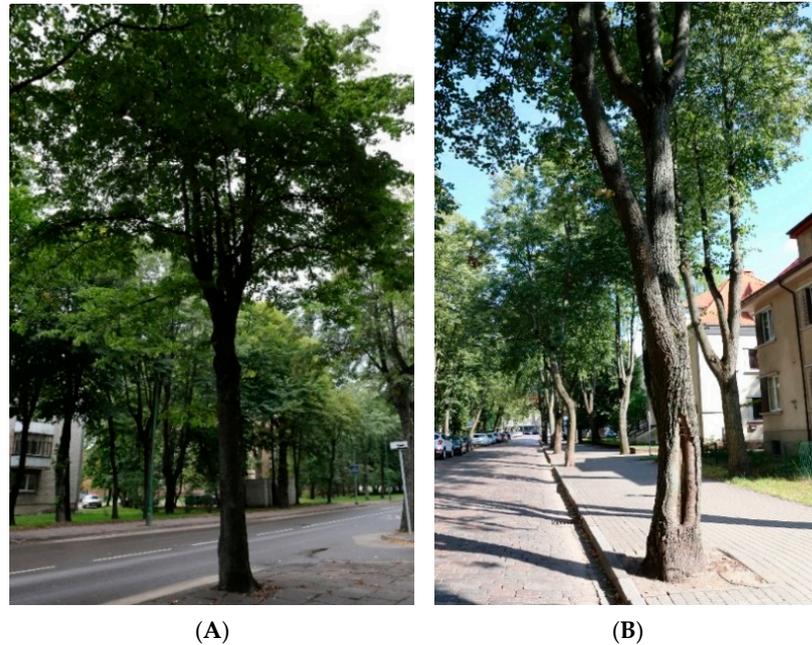


Figure 2. Examples of healthy and damaged trees in city streets. (A) Healthy tree, Sportininku Street. (B) Damaged tree, Neris Street. (Photos: Aistė Povilaitienė).



Figure 3. The use of acoustic tool ARBOTOM 3D on standing small-leaved lime trees (Photo: Aistė Povilaitienė).

The modulus of elasticity was taken as the most important parameter for the assessment of wood quality. Following the methodology applied in previous studies [38–42], the dynamic modulus of elasticity (MOEdyn) was estimated from the velocity of acoustic waves passing through the wood, according to the Formula (1):

$$MOEdyn = \rho V^2 \quad (1)$$

Here, *MOEdyn* is dynamic modulus of elasticity; ρ is wood density; and *V* is velocity of acoustic waves.

To ensure nondestructive testing, wood density of 1000 kg m^{-3} was taken as a fixed parameter [43]. The dynamic modulus of elasticity was calculated for two sections per each standing tree, totaling 584 sections.

2.4. Statistical Analyses

The obtained data were analyzed using the statistical package SAS 9.4 (SAS Institute Inc., Cary, NC, USA). To determine significant differences between the sites, ANOVA was performed, followed by the Student–Newman–Keuls multiple range test. Different letters next to mean values show statistically significant differences at $p < 0.05$ between the sites.

3. Results

3.1. Wood Quality Measurements

The mean values of the top-end diameter ($D_{\text{top-end}}$, cm) and the dynamic modulus of elasticity (MOEdyn, N mm^{-2}) of the small-leaved lime trees at each site are summarized in Table 1.

Table 1. Mean top-end diameter ($D_{\text{top-end}}$, cm) and the dynamic modulus of elasticity (MOEdyn, N mm^{-2}) of small-leaved lime trees from different sites. The std. error of the mean is given next to the mean. Different letters indicate statistically significant differences between the sites at $p < 0.05$ levels.

Sites	<i>n</i> *	Tree Age (Years)	$D_{\text{top-end}}$ (cm)	MOEdyn (N mm^{-2})
Neries Street	82	120	39.9 ± 0.7 c	2636.6 ± 77.4 b
Vilties Street	74	120	37.0 ± 0.8 d	2867.8 ± 96.6 b
Sportininku Street	82	90	33.7 ± 0.7 e	2776.9 ± 66.2 b
Tilzes Street	144	90	34.6 ± 0.5 e	2654.6 ± 46.7 b
Donelaicio Park	120	120	57.2 ± 0.8 a	1972.3 ± 56.6 c
Forest Site 1	40	120	42.9 ± 1.6 b	1838.0 ± 63.2 c
Forest Site 2	42	90	33.4 ± 0.9 e	4604.7 ± 138.3 a

* *n* shows the number of observations made for two sections of each selected standing tree.

For the urban small-leaved lime trees, the $D_{\text{top-end}}$ varied in a range from 33.7 ± 0.7 cm to 57.2 ± 0.8 cm. For the forest trees, variance fell within a range of 33.4–42.9 cm. The parameter $D_{\text{top-end}}$ at all sites was 1.2–1.3 times higher for 120-year old trees than for younger trees. The highest mean values of $D_{\text{top-end}}$ were obtained for trees in the urban park; the $D_{\text{top-end}}$ was 1.5 times higher than the values for the trees in the street sites and the forest site.

The mean values of the MOEdyn parameter showed larger variability between forest trees of different ages than between trees grown in urban and forest sites (Table 1). Tree age was not shown to have an effect on the mean MOEdyn in any of the urban sites. The lowest mean values of MOEdyn were obtained for the trees at the urban park.

To eliminate the influence of tree age on the evaluated parameters, trees of similar age were analyzed separately (Figure 4). The variation of the values of $D_{\text{top-end}}$ of 90-year old trees across all sites was insignificant. In the sites with 120-year old trees, significantly higher values of $D_{\text{top-end}}$ were obtained in the urban park and forest site (compared to the urban streets). The highest values of the parameter MOEdyn were found in 90-year old small-leaved lime trees in the forest sites, rather than in the urban areas. For older trees,

higher values of MOEdyn were obtained in urban streets. No significant differences were found between the values of MOEdyn for trees in the urban park and the forest site.

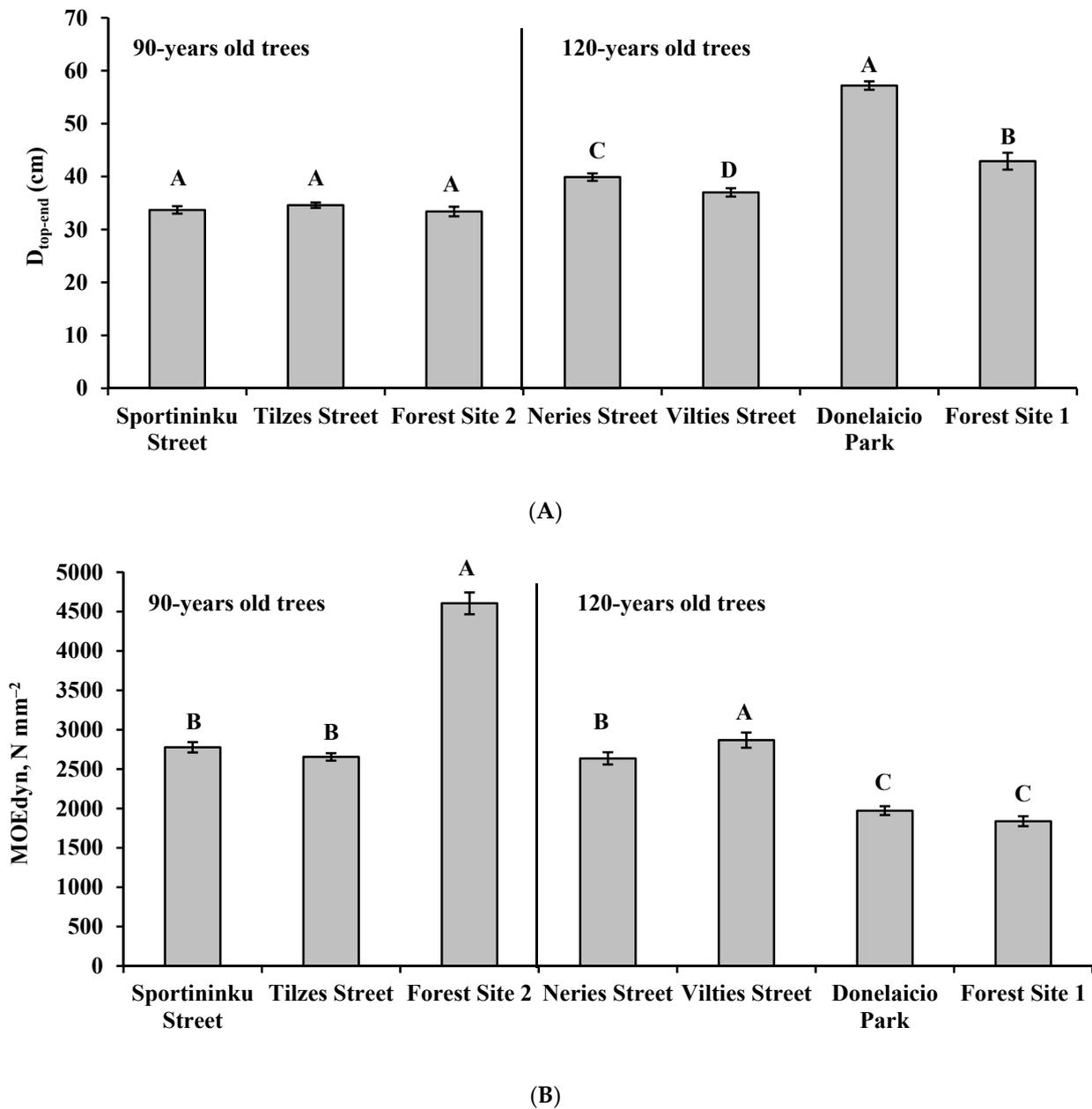


Figure 4. Mean values of top-end diameter ($D_{\text{top-end}}$, cm) (A), and dynamic modulus of elasticity (MOEdyn, N mm^{-2}) (B) of small-leaved lime trees from different sites. Bars show the standard error of the mean. Different capital letters at the top of the columns show statistically significant differences between the sites within each tree age group (separately for 90- and 120-year old trees) at $p < 0.05$.

The health of selected small-leaved lime trees in urban areas was assessed, and they were assigned to different health classes. Health classes 1, 2, 3 and 4 consisted of 25%, 30%, 24%, and 21% of all measured urban trees, respectively. The obtained MOEdyn values of the small-leaved lime trees were similar for trees assigned to health classes 1–3 (Figure 5). However, significantly lower values of MOEdyn were obtained for trees in the 4th health class, representing severely damaged trees.

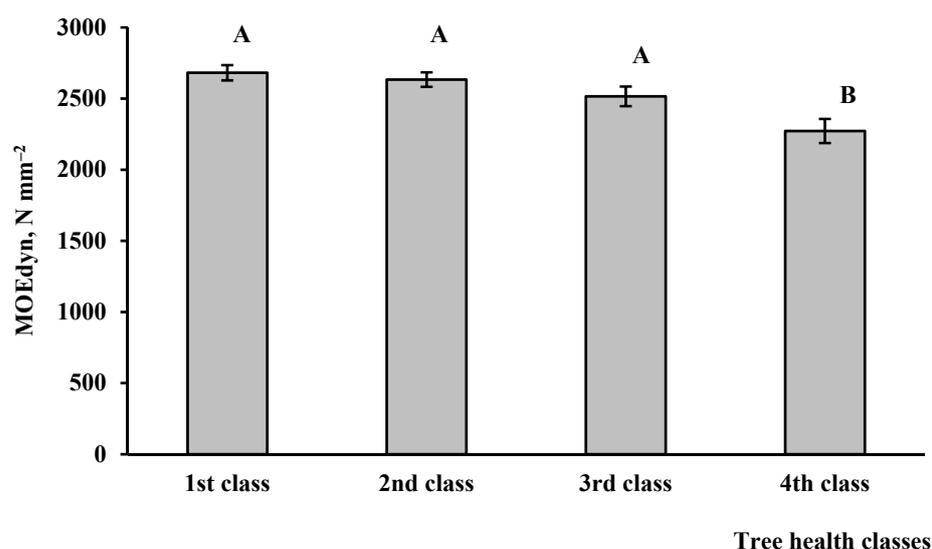


Figure 5. Mean values of the dynamic modulus of elasticity (MOEdyn , N mm^{-2}) of urban small-leaved lime trees, corresponding to different health classes. Bars show the standard error of the mean. Different capital letters at the top of the columns show statistically significant differences between the different health classes at $p < 0.05$.

3.2. Relations between Wood Quality Parameters

The correlation analysis between the top-end diameter ($D_{\text{top-end}}$, cm) and the dynamic modulus of elasticity (MOEdyn , N mm^{-2}) of the small-leaved lime trees showed moderate negative correlation ($r = 0.495$) (Figure 6). Overall, the increase in $D_{\text{top-end}}$ resulted in the decrease of MOEdyn .

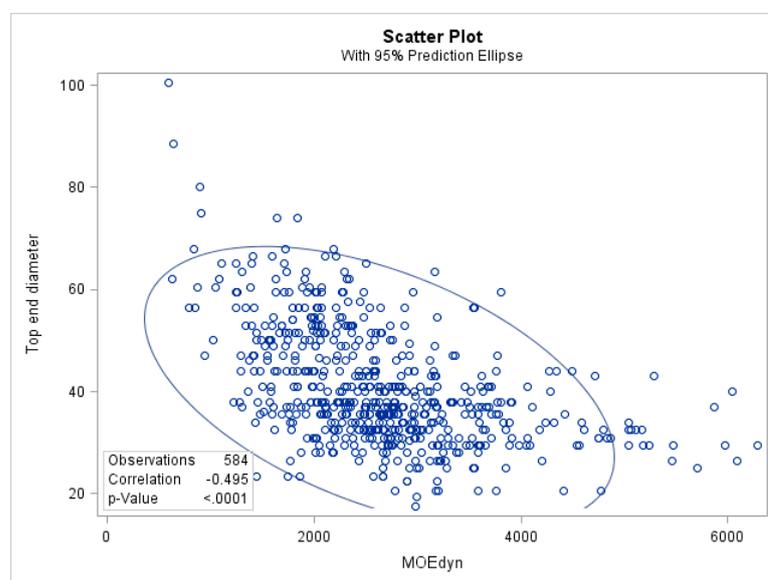
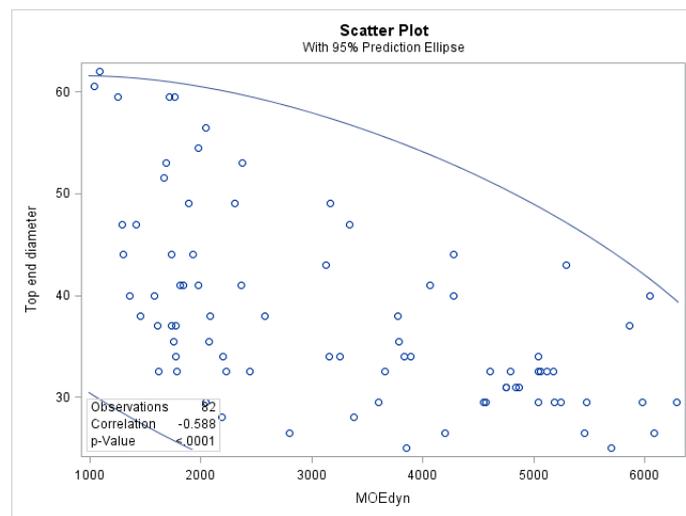
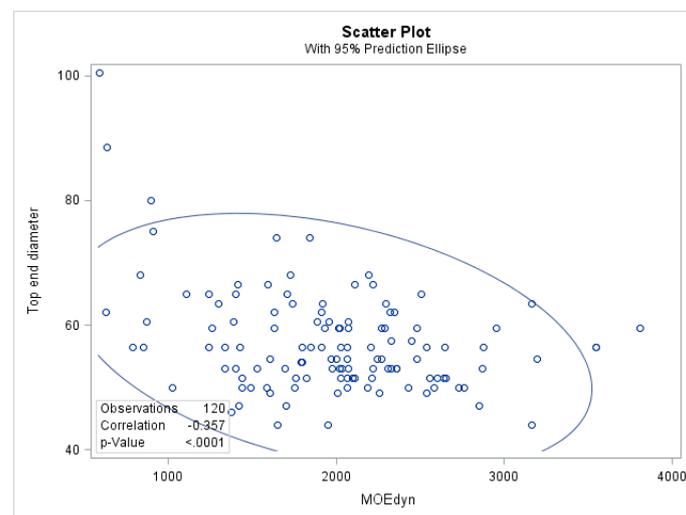


Figure 6. Correlation between top-end diameter ($D_{\text{top-end}}$, cm), and the dynamic modulus of elasticity (MOEdyn , N mm^{-2}) of small-leaved lime trees in urban sites (analysis included all data, $n = 584$).

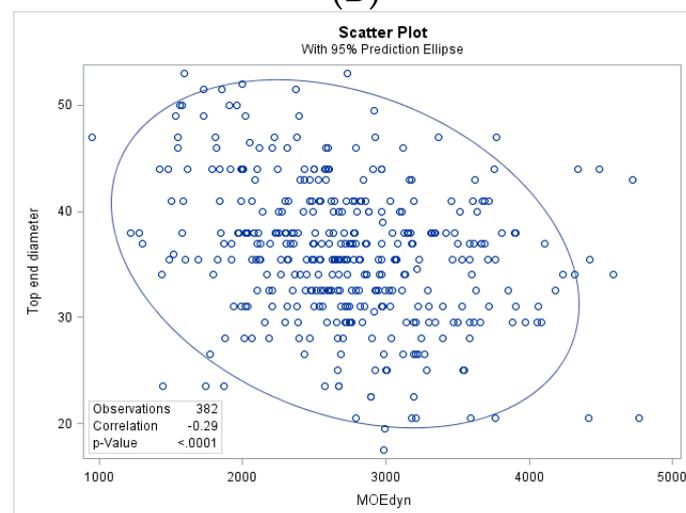
To identify differences between the sites, the data were analyzed separately for trees growing along urban streets, in the urban park, and in the forest (Figure 7). The best correlation ($r = 0.588$) between the $D_{\text{top-end}}$ and the MOEdyn of the small-leaved lime trees was obtained for trees in the forest sites. For the trees in the urban park, this correlation was relatively weak ($r = 0.357$). The weakest correlation ($r = 0.290$) was obtained for the small-leaved lime trees growing along the urban streets.



(A)



(B)



(C)

Figure 7. Correlation between top-end diameter ($D_{\text{top-end}}$, cm) and dynamic modulus of elasticity (MOEdyn, N mm^{-2}) of small-leaved lime trees in different sites: (A) forest sites; (B) urban park; (C) along streets.

4. Discussion

The present study found large variations of the dynamic modulus of elasticity (MOEdyn, N mm^{-2}) of small-leaved lime trees in different sites (i.e., urban areas and forest sites). However, the MOEdyn parameter was related to different growing conditions and basic tree characteristics. The older urban trees had lower MOEdyn values, which could be related to specific environmental conditions of the urban area [15,16]. During a relatively long period of tree growth, environmental stressors in an urbanized territory could negatively impact tree growth and wood quality. Limited availability of soil, water, and nutrients in an urban environment can also affect tree root infrastructure. On the other hand, in some places, roots grow in areas under sidewalks and roads that provide sufficient water and nutrients for tree survival and growth [44]. In urban areas, mechanical loads of constructions, vehicles and pedestrians cause soil compaction; soil macropores necessary for ventilation and irrigation are lost [18,45]. Current management strategies aim at increasing tree hydration in urban areas, which may reduce the effects of key stressors [46]. De-icing salt often causes direct damage to trees and other urban vegetation, inducing plant necrosis, followed by chemical drought (decreased availability of water to plant roots) [17–19,47]. Problems related to the use of salt in ice prevention on streets and pavements are quite common in the Nordic and Baltic countries [48,49]. The trend of higher mean annual temperatures and longer vegetation periods in urban areas (compared to forests) induces specific growth responses in urban vegetation [6,50]. Species with lower frost resistance can be successfully planted in urban areas [51]. However, unusually higher temperatures, lower humidity, drought, and increased air pollution during the growing season can negatively affect the growth and viability of many species [6,19,52,53].

Despite the specifics of growing conditions in urban areas, the evaluated small-leaved lime trees showed relatively good wood quality. Even those small-leaved lime trees that were visually evaluated as slightly or moderately damaged (assigned to 2nd and 3rd health classes, according to the Ref. [37]) showed relatively high values of the MOEdyn parameter for urban areas. This means that a more accurate determination of the health status of urban trees should be preferred over a visual assessment. Our results showed that even if a small-leaved lime tree was classified as moderately damaged (assigned to the 3rd health class), its wood showed quality parameters suitable for the timber industry. We considered that the trees assigned to the 3rd and 4th health classes could become potential risks to public health and safety; their management should be discussed. Only healthy trees contribute to the overall value of urban green areas. The timber industry is unlikely to benefit significantly from such amounts, and it is important to keep the trees with higher quality wood in the urban environment if possible. Therefore, we could cautiously assume that wood from (removed) moderately damaged urban trees could be used for wood products while maintaining further carbon storage in the wood.

Urban trees provide various ecosystem services (air cleaning, aesthetic value, etc.). To ensure the long-term sustainability of urban plantations and avoid the removal of lots of old trees all at once, it is important to address continuous renewal and permanent arboreal management in urban areas. The removal of moderately and severely damaged urban lime trees—in order to replace them gradually with new ones—could serve as a tool for more intensive carbon sequestration in urban areas. This should be especially emphasized for small-leaved lime trees, which are noted for their rapid height growth while at young ages (15–25 years) [9]. At the same time, a fairly large proportion of old, stable, and high-quality trees could be maintained. In this study, we also found a correlation between the top-end diameter ($D_{\text{top-end}}$) of urban small-leaved lime trees and their wood quality (defined by MOEdyn). The obtained results showed lower values of MOEdyn for older small-leaved lime trees, and for trees with higher $D_{\text{top-end}}$ values. For urban trees along the streets, which were pruned in the past, the parameters $D_{\text{top-end}}$ and MOEdyn did not correlate. Most likely, pruning affected the growth and development of the 1–2-m stem section. These data must be interpreted with caution because this pilot study did not include detailed historical data and environmental conditions for the whole growth period of 90–120 years.

In this city, the urban environment is quite dynamic, and has changed significantly in recent decades.

The growing of urban trees is more often related to principles of urban sustainability. In this study, we highlighted a potential way to improve the durability of urban trees via more intensive monitoring of their health status, i.e., assessing the tree wood quality using nondestructive methods. A full view of the wood properties of urban trees could be obtained if more parameters of wood quality were included. It would be possible if a combination of nondestructive and destructive methods were used. Some of the issues emerging from this study relate specifically to small-leaved lime trees. Further studies on the current topic will need to be undertaken.

5. Conclusions

This pilot study was designed to evaluate the wood quality of small-leaved lime (*Tilia cordata* Mill.) trees in an urban area, using dynamic modulus of elasticity as the main parameter. The results of this study showed that 90–120-year old small-leaved lime trees growing in the studied urban area still had the potential to be used in the timber industry. The data analysis revealed lower dynamic modulus of elasticity (MOEdyn, N mm⁻²) of small-leaved lime trees in the urban area, when compared with the control group forest sites. However, tree age was indicated as an important factor for wood quality assessment in urban areas, as 90-year old trees exhibited higher mean values of MOEdyn than for 120-years old small-leaved lime trees. Another finding of this pilot study was that the top-end diameter ($D_{\text{top-end}}$) of urban trees moderately correlated with the MOEdyn parameter, which meant that the wood of larger diameter trees was of poorer quality.

Overall, the empirical findings of this study provide two insights into urban tree management: (1) the health of old urban trees should be sustained until it poses a risk for the community, at which point the wood waste could be used as biomass for fuel or compost; (2) moderately damaged urban trees with high-quality wood could be removed and used for wood products, (i.e., continued carbon retention). Replanting politics should be applied quickly, as replanting also contributes to continuous carbon sequestration in urban areas.

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

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