Mechanical resistance of *Quercus robur* L. at the environmental boundary of the species distribution in the steppe

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Abstract. The paper studies the mechanical resistance of old-age pedunculate oak trees which grow at the environmental boundary of the species distribution in the steppe. The trees of the studied species growing in the south of the East European Plain (Donetsk Ridge) can be about 200 years old and still be viable (good condition) and have a high mechanical resistance (critical mass \( m_{cr} \)=10⁵ kg, and flexural stiffness=9.8·10⁷ N·m²) even under unfavourable environmental conditions. A strong dependence of the morphometric parameter of the ratio was established between the tree trunk diameter and its height on the parameters of the trunk bending stiffness, its critical mass, and the relative resistance to bending. The obtained results of statistical analysis can be used to monitor oak forests and scattered trees of *Quercus robur* L. in order to single out plants with low mechanical resistance with the help of the d/l parameter which serves as a morphometric marker of the tree resistance.

1. Introduction
At the boundaries of Donetsk, a large industrial centre in Eastern Europe, there is a unique natural forest, which is a remnant of an ancient forest that belongs to a network of ravine forests in the basin of the river Kalmius. According to cartographic materials (general topographic maps (dated 1700s) and maps by Friedrich Theodor von Schubert (dated 1800s)), the Putylivsky forest (48°03'53" N, 37°47'34" E) had existed and had been used for timber harvesting long before the city of Donetsk was founded (1869). With the start of industrialisation the region was mainly deforested due to a high demand for timber used for construction and charcoal production (figure 1). Forest guards who worked in the forest before the revolution of 1917 and the transformation of a part of the forest into a Soviet period.
Figure 1. The Putylivsky forest on the maps by Schubert (a) and on the contemporary map of Donetsk (b). The green corridors that were found in 1878 (the red line). Notes: OziExplorer V 3.95.6d and Google Earth V 7.1.5 were used to link the modern map with the map by Schubert.

In 2013-2014, when the data regarding the morphology and allometry of pedunculate oak were collected, the total area of the forest was about 80 ha, including the ravines and streams flowing into the river Kalmius [1]. Pedunculate oak (Quercus robur L.) is one of the most common and long-living tree species in the European temperate forests. Its natural habitat extends over a large part of Europe [2,3]. The pedunculate oak plays an important role in the structure and the functioning of forest ecosystems [4,5]. It is a dominant species in the Putylivsky forest and it is found at the environmental boundary of the species distribution in the steppe.

The oaks selected from the remnants of the old-age forest in Donetsk are generally between 150 and 250 years old [1]. They grow both on the slopes and tops of ravines. The average age of trees growing on the slopes is $143 \pm 31$ years and on the tops it is $183 \pm 35$ years [1]. The mean values of the ratio between the age and the diameter (years/cm) of the trees on the slopes ($1.828 \pm 0.336$ years/cm) and on the tops ($2.735 \pm 0.394$ years/cm) showed a significant difference ($P<0.05$).

Ontogenetic changes of the trunk and parent branches of the tree include the changes in their geometry and morphology [6]. The trunk resistance to static and dynamic loads, i.e. its mechanical resistance, depends on its morphometric parameters (diameter ($d^4$) and length ($1/l^2$)). Therefore, the ratio between the tree trunk diameter and the length of the trunk or its parent branches can be used as a morphological marker of the mechanical resistance in studies monitoring the state of oak forests [6]. As the tree ages, its mechanical resistance grows, however, a number of environmental factors (anthropogenic pollution, cyclic temperature variations, windfalls, snow and ice storms, etc.) reduce its parameters.

In our research, we evaluated all the studied old-age pedunculate oak trees using L.S. Savelieva’s scale (1975) and gave them 6 points (good state). It looks like this: ‘excellent’ vital condition of the tree – the habitus is completely preserved, there are no visible damage to the crown and trunk (8 points (b.)); ‘good’ – close to the assessment of ‘excellent’, but with weaker foliage, there are dry branches in the crown (6 b.); ‘satisfactory’ – most of the skeletal branches of the tree are alive, but there are significant violations (4 b.); ‘unsatisfactory’ – a smaller part of the skeletal branches of the tree is alive, and critical violations are also observed (2 b.); ‘dry’ – the tree completely dies (0 b.). That is why all the processes described above will not contribute to the evaluation of the mechanical resistance of trees.
2. Methodology

The mechanical resistance of trees was determined using the following parameters (math equation (1)-(4)). Resistance of the tree trunk or its parent branches to bending under dynamic or static loads [7,8].

\[
\text{Resistance to bending} = EI
\]

Relative resistance to bending [9]:

\[
RRB = \frac{r^2 \cdot MOE}{4\rho}
\]

where, \( r \) is the radius of the base of the trunk, \( MOE \) is the modulus of elasticity, and \( \rho \) is the density of wood. Critical mass (\( m_{cr} \)) and the maximum load (\( P_{cr} \)) [8].

\[
P_{cr} = \frac{\pi^2 \cdot MOE \cdot I}{2l^2}
\]

\[
m_{cr} = \frac{P_{cr}}{g}
\]

where \( I \) is the second area moment, \( l \) is the trunk length, and \( g \) is gravity acceleration.

Statistical data processing was performed using ‘Statistica 8’ and ‘Excel 2010’ programs (Microsoft Corporation). Regression analysis methods were used to describe the dependencies of the parameters of the mechanical resistance (\( P_{cr} \) (maximum load), \( m_{cr} \) (critical mass), \( RRB \) (relative resistance to bending), \( EI \) (resistance to bending)) on the morphological marker of mechanical resistance (\( d/l \)). Pearson coefficient of correlation (\( r \)) was used to determine the strength of the relationship between the parameters of mechanical resistance and \( d/l \).

3. Results and discussion

The field data were used to evaluate the mechanical resistance of the old-age trees of Quercus robur L. in the Putylivsky ravine oak forest.

It was established that the value of the ratio between the trunk diameter and its height \( d/l \) was on average \( 0.05\pm0.01 \) for all the studied specimens. The regression analysis was used to reveal a reliable correlation between \( d/l \) and the critical load and the mass (\( R^2>0.99 \)) which a tree can withstand under seasonal temperature variations (figure 2).

**Figure 2.** The dependence of critical load on the ratio between \( d/l \) as a morphometric marker of mechanical resistance. Designations: Freeze is the value in winter with a temperature below zero, Thawing is the value during thawing; Summer is the value in summer with a temperature above zero.

**Figure 3.** The dependence of critical mass on the ratio between \( d/l \) as a morphometric marker of mechanical resistance. Designations: Freeze is the value in winter with a temperature below zero, Thawing is the value during thawing; Summer is the value in summer with a temperature above zero.
For example, in winter, when the temperature is below zero the values of $P_{cr}$ and $m_{cr}$ for trees over 100 years old were high ($10^5$ kg), which are beyond what is achievable even under the wind forces characteristic of the region (on average the reduction of $m_{cr}$ is expected to be by $\sim$20% [10]), and under conditions of snow and ice storms (figure 3).

The relative resistance to bending directly depends on the physical and mechanical characteristics of the wood (MOE). As a result, the research showed that with a growing diameter of the tree trunk the RRB of the pedunculate oak grows in the power-law relation ($R^2=0.98; x^{1.86}$), that is why the temperature factor should not influence the resistance of old-age trees with a sufficient ratio between $d/l$ and the trunk strength margin (figure 4).

**Figure 4.** The dependence of relative resistance to bending on the ratio between $d/l$ as a morphometric marker of mechanical resistance. Designations: Freeze is the value in winter with a temperature below zero, Thawing is the value during thawing; Summer is the value in summer with a temperature above zero.

The regression analysis showed a reliable correlation between the bending stiffness and $d/l$ ($R^2=0.98$). The slope of the logarithmic dependence under temperature variations was 3.7 and the value of the power-law relation changed depending on the air temperature (figure 5).

On average, when freezing, the bending stiffness of the trunks of old-age trees was $9.8 \times 10^7$ N·m², and when thawing it was $5.9 \times 10^7$ N·m². Such a reduction in stiffness (EI) is insignificant for pedunculate oaks older than 100 years old and the seasonal temperature changes do not lead to a reduction in the mechanical resistance of the plant as a whole.

The analysis of the strength of relationship ($r_{xy}$) between the parameters of the mechanical resistance ($P_{cr}$, $m_{cr}$, RRB, EI) and the ratio between the diameter of the tree trunk and its height ($d/l$) with due consideration of the age of the plants revealed a strong relationship for the old-age trees of *Quercus robur* L. growing in the Putylivsky ravine oak forest (table 1). The obtained results of statistical analysis can be used to monitor oak forests in order to single out plants with low mechanical resistance with the help of the $d/l$ parameter, which serves as a morphometric marker of tree resistance.

**Figure 5.** The dependence of the bending stiffness on the ratio between $d/l$ as a morphometric marker of mechanical resistance. Designations: Freeze is the value in the winter under temperature below zero, Thawing is the value during thawing; Summer is the value in the summer under the temperature above zero.

**Table 1.** The strength of relationship ($r_{xy}$) between the parameters of the mechanical resistance and $d/l$ considering the age of the pedunculate oak trees.

| Age     | $P_{cr}$ | $m_{cr}$ | RRB | EI  |
|---------|----------|----------|-----|-----|
| 105-150 | 0.97     | 0.97     | 0.97| 0.96|
| 151-200 | 0.96     | 0.96     | 1.00| 0.96|
| 201-254 | 1.00     | 1.00     | 1.00| 1.00|
| Total (105-254) | 0.95 | 0.95 | 0.98 | 0.96 |
4. Conclusion

On the eastern boundaries of the habitat of the species, the oldest pedunculated oak forests grow as a part of rare natural forests and forests planted by Skryazhinsky in 1819, von Graff in 1843, and Leman in 1875. Thus, the oldest of the trees are 140-200 years old. There might be older oak specimens in the steppe region which grow under adequate local conditions. These facts and the age of Quercus robur L. trees in Putylivsky forest allow us to suppose that the pedunculate oak trees growing in the south of the East European Plain (Donetsk Ridge) can be about 200 years old and still be viable (6 points) and have a high mechanical resistance (\( m_c = 10^5 \text{ kg} \), \( E = 9.8 \times 10^7 \text{ N m}^{-2} \)) even under unfavourable environmental conditions. This shows the benefit of planning and planting perennial tree plantations in mixed urban and steppe landscapes.

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