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Crown volume in forest stands of pedunculate oak and common hornbeam

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Abstract

Background and Purpose: *The structure of the crown volume in a forest stand is one of the main factors that drive the growth and development of trees. It changes dynamically with the age of the forest stand and according to the management activities and natural disturbances that remove trees from the stand. The aim of this article is to analyse crown volume structure in relation to the stand age and diameter at breast height (DBH) of pedunculate oak and common hornbeam trees in one of the most important forest types in Croatia.*

Materials and Methods: *Data for the research were collected from a set of 47 permanent sample plots established as a chronosequence over the distribution range of pedunculate oak and common hornbeam forests in Croatia. The combined area of all the plots amounted to 33.45 ha. Trees were measured for DBH, total height and height to crown base, and a detailed map of crown projection areas was made for each plot. In total, the crowns of 1,609 pedunculate oak trees and 1,979 common hornbeam trees were measured. Crown volumes were calculated for each tree, the trees were pooled into age classes of 20 years, and analyses were carried out per tree species, per age class. A nonlinear regression with an exponential function of crown volume was performed to establish the relationship between the crown volume and DBH in each age class.*

Results and Discussion: *Up to a stand age of 40 years, crowns of pedunculate oak dominate in the canopy layer (66%), after which crowns of common hornbeam trees assume dominance. Coefficients of determination for the regression lines for pedunculate oak crowns are higher than the coefficients for common hornbeam. In all age classes, they are higher than 0.50, except for the first age class for common hornbeam and the seventh age class for pedunculate oak. The shape of the regression lines of pedunculate oak crown volume shift more to the right side of the diameter range as the stand matures, while those of common hornbeam are more static and form a bundle of lines.*

Conclusions: *Results indicate that the relationship between the crown volume of pedunculate oak and common hornbeam trees and DBH can be described by a nonlinear regression model with an exponential function. Further research is needed to assess the possibilities of integrating the obtained regression models into simulators of forest growth and development.*

INTRODUCTION

The structure of the forest stand in its widest sense is composed of all the elements that distribute live biomass within its space. One of the most important aspects of the stand structure for its development is the structure of the tree crowns in the canopy layer, where essential living processes like photosynthesis take place. Crown volume, combined with other elements of the crown structure (diameter, length, crown surface area, ratio of total tree height and crown length, etc) is an important factor in the research of forest stand structure. This is especially true in the case of the upper, sunlit part of the crown which contributes greatly to the reception of sunlight and its use in the process of photosynthesis *(1)*. The crown projection area, together with crown volume, also determines the amount of intercepted precipitation, and regulates the amount of precipitation that reaches the forest floor *(2, 3)*. With the help of the crown projection area and crown volume, it is easy to calculate canopy cover and canopy closure *(4)*. Canopy closure regulates important microclimatic conditions within the forest stand, such as the amount of diffuse light, air and soil temperature, and air and soil humidity, all of which are very important factors in the processes of tree growth and stand regeneration.

The crown structure of a forest stand is defined trough the size, shape, growth and development of tree crowns, their distribution in time and space, and the proportions of the crown compared to other parts of the tree. The crown size and shape of a particular tree is the result of an intricate interplay of its internal genetic composition and the influence of the surrounding biotic and abiotic factors. The range of variations in crown size and shape depends on tree species, site quality, age, position of the tree in the canopy, immediate environment, degree of shading by competing trees, spatial distribution (number of trees per hectare and clumping of trees), and management interventions throughout the life of the forest stand *(5)*.

The importance of the crown for the development of single trees and the forest stand as a whole has been the research focus for many studies. Some of the essential works are those of Burger and Badoux *(6, 7),* as well as Assman's study on forest yield *(8)*. In Croatia, the role of the crown in the development of the stand structure has been the research interest of Šafar *(9),* Krejči *(10),* Križanec *(11),* and recently Dubravac *(5, 12, 13, 14),* who focuses on the relationship between crown structure development, tree size (diameter at breast height) and age.

Because of the great variation in the size and shape of the crowns of forest tree species, it is almost impossible to accurately calculate crown volume. Therefore, crown volumes are usually approximated with a geometrical shape like a cone or paraboloid. The area of the horizontal crown projection is usually calculated as the area of a circle with a radius that represents the average radius of 2, 4 or 8 measured radii *(8),* or as the sum of sections of different sized circles *(15)*. Crown volume can also be calculated from an ellipsoid equation *(16, 17)* with the measured values of the horizontal crown projection and crown length. Recently, there has been an ongoing effort to develop a methodology for automatic measurement of crown size, mostly with the aid of photography *(18, 19)*. These photographic methods have their disadvantages in closed canopies of forest stands with lots of undergrowth. On the other hand, aerial photography can only assess the crowns of the dominant trees visible in the aerophoto pictures.

The importance of the distribution of crown sizes over a range of tree sizes and the ability to correctly assess their variability has gained in importance since the development of computer simulations of forest stand growth and development *(20, 21, 22)*. For example, determining the best options for the preservation of remnants of old-growth pedunculate oak forest *(23, 24)* would be greatly enhanced with the aid of computer simulation. Crown structure is also very important when the results of computer simulations are being visualised in modern software packages *(25, 26)*.

Therefore the aim of this article is to present the results of research on crown volume as an important structural feature in forest stands of pedunculate oak and common hornbeam with regard to stand age. Regression models are developed to facilitate the integration of acquired knowledge in some of the computer simulators for forest growth and development.

MATERIALS AND METHODS

Mixed forests of pedunculate oak (*Quercus robur* L.) and common hornbeam (*Carpinus betulus* L.) are one of the most important forest types in Croatia, but are also widely distributed throughout Europe. From the perspective of stand structure, the most prominent feature is the vertical distribution of crowns in two layers. The dominant canopy layer is mostly composed of light-demanding pedunculate oak trees, while crowns of shade-tolerant hornbeam occupy the stand space beneath them. The silvicultural system applied to these forest stands in Croatia is even-aged stand management with shelterwood regeneration in several cuts at the end of the rotation. Stands are grouped into age classes of 20 years according to the age of the main tree species, in this case the pedunculate oak. It is important to emphasise that trees of admixed species, common hornbeam in particular, can be of different ages due to the silvicultural interventions that are applied throughout the life of the stand.

In total, 47 permanent sample plots were established based on the methodology of Dubravac and Novotny *(27)* as a chronosequence over the distribution range of pedunculate oak and common hornbeam forests in Croatia. The plots varied in size from 20 x 20 m in young stands, up to 60 x 60 m in old stands.

All trees over 7.5 cm in diameter at breast height (DBH) were permanently numbered, stem-mapped, and measured for DBH. Maps of horizontal crown projections of all numbered trees were drawn, based on the measurements of the extent (radius) of the crown from the stem axis in four cardinal directions, or more than four directions in the case of highly asymmetrical crowns (Figure 1A). Total tree height and height to crown base were measured on all oak trees and on a subset of common hornbeam trees on the respective plots. Three-di-

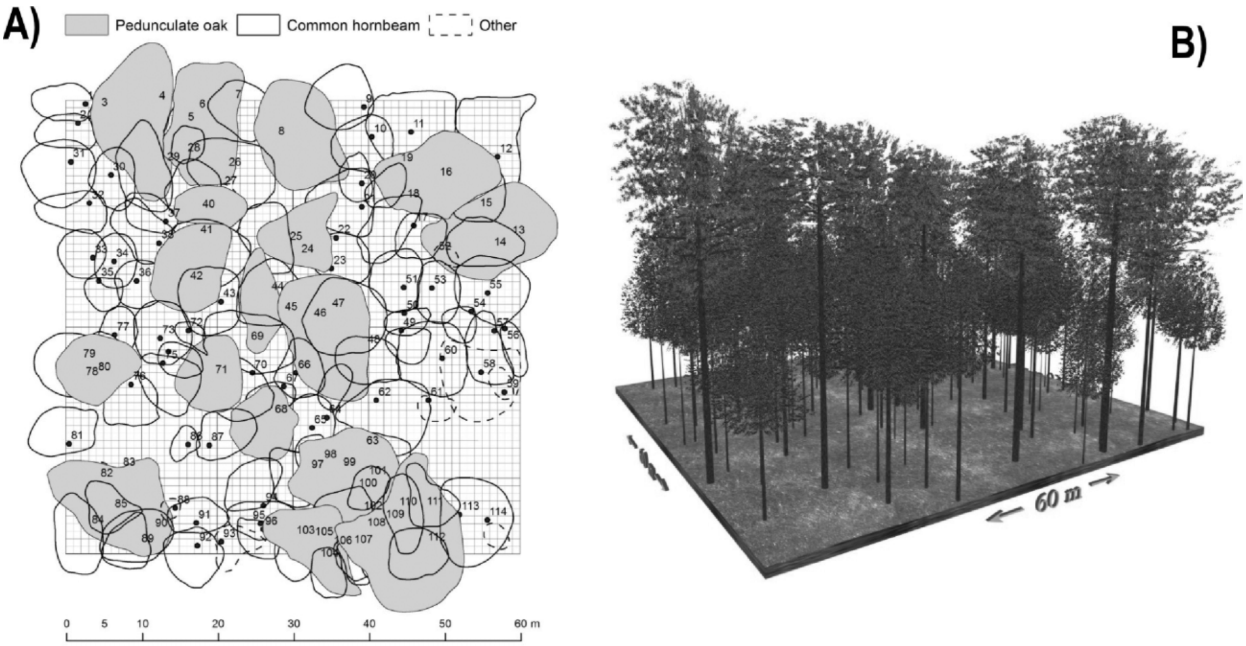

Figure 1. *Map of stem positions and horizontal crown projection areas (A), and three-dimensional visualisation of 138-year-old stand on plot No. 37 (B).*

mensional visualisation of stands on sample plots was carried out in the 3DMax software package after the crown projection area maps had been digitised (Figure 1B). Three trees of pedunculate oak were felled on each plot to establish their age by counting growth rings. Based on the age of the pedunculate oak trees, the stand age was determined and all the plots were pooled into age classes of 20 years. Basic statistics on the sampled forest stands are given per age class in Table 1. The combined area of all the permanent sample plots amounted to 33.45 ha.

The volumes of the crowns of pedunculate oak and common hornbeam trees were calculated according to the methodology of Hren and Krejči *(28)* for all oak trees and the subset of common hornbeam trees that had been measured for total tree height and height to crown base. First, the trees' average crown diameters (D_C) were calculated from the measurement of the maximum and minimum diameter of the crown projection measured on the map of the crown projection areas. Then the crown volume was computed for each tree with Equation 1:

$$V_c = \frac{D_C^2 \pi \cdot L_C}{4} f_C \qquad (1)$$

where V_C is the crown volume, D_C is the average diameter of the crown projection area, L_C is the length of the crown calculated as the difference between the total tree height and height to crown base, and f_C is the crown form factor, which assumes values of 0.56 and 0.61 for trees of pedunculate oak and common hornbeam respectively. Hren and Krejči *(28)* calculated crown form factors for pedunculate oak and common hornbeam as the ratio of the calculated crown volume based on the measurements of the height of the widest part of the crown and the volume of a cylinder with height and diameter equal to crown length and crown diameter.

TABLE 1

Mean values per age class of stem number (n ha^{-1}), basal area (BA, m^2 ha^{-1}), average DBH and total tree height (h, m) of sampled stands of pedunculate oak and common hornbeam.

Age class (years)	number of plots	Pedunculate oak				Common hornbeam			
		n ha^{-1}	BA, m^2 ha^{-1}	DBH, cm	h, m	n ha^{-1}	BA, m^2 ha^{-1}	DBH, cm	h, m
I (0–20)	1	3475	17.5	7.0	7.9	3175	7.6	4.2	7.7
II (21–40)	6	1779	20.8	14.1	17.2	1935	7.3	7.2	11.7
III (41–60)	4	263	16.4	26.8	23.6	724	9.1	13.1	16.6
IV (61–80)	8	232	17.4	31.4	26.5	590	11.4	14.7	17.4
V (81–100)	7	121	20.5	44.7	30.1	349	11.1	15.8	17.2
VI (101–120)	12	116	23.0	48.9	30.7	381	10.4	15.9	17.9
VII (121–140)	9	50	18.8	68.3	36.8	166	9.6	24.7	20.2

Crown volumes were calculated for a total of 3,588 trees, of which 1.609 were pedunculate oak trees and 1.979 were common hornbeam trees. Trees were pooled into age classes according to the stand age of the respective sample plot. A regression was made of the crown volume against DBH for each species within each age class. A nonlinear regression was performed with an exponential function with two parameters:

$$V_C = f(DBH), \quad V_C = b_0\, EXP(b_1\, DBH) \qquad (2)$$

where V_C is the crown volume, DBH is the diameter at breast height, and b_0 and b_1 are the regression parameters.

RESEARCH RESULTS AND DISCUSSION

In Table 2, the mean values for the measured and calculated crown volumes of pedunculate oak and common hornbeam are given per age class. The mean crown volume of oak trees ranges from 4.9 m^3 in the first age class up to 1,097.5 m^3 in the seventh age class, while trees of common hornbeam on average have crown volumes from 1.5 m^3 in the first age class up to 272.8 m^3 in the seventh age class. Overall, the crowns of pedunculate oak have higher volumes compared to hornbeam. In younger stands (age classes I and II), oak crown volumes are roughly two times greater compared to hornbeam, and in the last age class they are three times greater. There is a significant increase in the average crown volume of oak trees between age classes VI and VII, which can be explained by management activities linked to the preparation of the forest stand for regeneration. This activity requires the retention of oak trees with well-developed crowns, while trees with a smaller crown-to-DBH ratio are removed.

Values of standard deviation (Table 2) indicate a high variability in the crown volumes within each age class, i.e. a great variability in the sizes and shapes of tree crowns due to their displacement in the stand space as a result of competition between trees. Variation in crown volume is further enhanced by the silvicultural interventions performed in these stands from the time of their establishment.

To get a very rough estimate of the relation between the crown volumes of the two species at the stand level, we have multiplied the average crown volume of a single tree by the average number of trees per hectare in a given age class (Table 3). After an initially equal number of

TABLE 2

Mean tree crown volume for pedunculate oak and common hornbeam trees in stands of different age classes.

Age class (years)	Pedunculate oak			Common hornbeam		
	n	Mean m^3	Standard deviation m^3	n	Mean m^3	Standard deviation m^3
I (0–20)	21	4.9	4.7	19	2.8	1.5
II (21–40)	258	37.1	30.8	260	17.4	11.8
III (41–60)	78	136.0	134.1	211	67.8	70.6
IV (61–80)	346	212.1	160.1	406	149.6	142.4
V (81–100)	239	356.6	260.9	254	200.1	201.2
VI (101–120)	498	444.8	333.4	452	258.9	208.6
VII (121–140)	169	1097.5	569.8	377	384.4	272.8

TABLE 3

Estimate of crown dominance at the whole-stand level in the volume of the canopy layer in stands of different age class.

Age class (years)	Pedunculate oak			Common hornbeam		
	average crown volume per tree m^3	Average n/ha $n\ ha^{-1}$	stand crown volume $m^3\ ha^{-1}$	average crown volume m^3	Average n/ha $n\ ha^{-1}$	stand crown volume $m^3\ ha^{-1}$
I (0–20)	4.9	3475	17097.0	2.8	3175	8826.5
II (21–40)	37.1	1779	65912.0	17.4	1935	33707.7
III (41–60)	136.0	263	35754.9	67.8	724	49116.2
IV (61–80)	212.1	232	49204.9	149.6	590	88246.3
V (81–100)	356.6	121	43153.4	200.1	349	69824.4
VI (101–120)	444.8	116	51601.4	258.9	381	98644.7
VII (121–140)	1097.5	50	54875.5	384.4	166	63815.4

trees per hectare in young stands, the disproportion in oak and hornbeam abundance in the stands grows towards the last age class. Common hornbeam trees are greater in number towards the last age class, and thus compensate for the smaller crown volume of a single tree.

In the first two age classes (up to a stand age of 40 years), crowns of pedunculate oak dominate in the stand's canopy layer (Figure 2). This is in part due to intensive management activities during the regeneration phase at the end of old stands and at the beginning of young stands with the aim of helping pedunculate oak trees to overcome regeneration competition. On these sites, the fiercest competitor is common hornbeam. In the later development phases of the stand, pedunculate oak has already established its dominant position in the canopy, and crowns of shade-tolerant common hornbeam gradually fill in the additional free space of the understory.

Regression analysis of the relationship between the crown volume and DBH was performed with a nonlinear exponential function. An example is given for the sixth age class (101 to 120 years of age) in Figure 3. It is evident from Figure 3 that crown volume exponentially grows with DBH, both in pedunculate oak trees as well as in common hornbeam trees. The figure is furnished with the diameter distributions of the trees used in the regression model with a normal distribution superimposed. The diameter distribution of pedunculate oak trees is distributed normally, while the diameter distribution of common hornbeam trees exhibits displacement towards the left side of the distribution.

Basic indices on the obtained regression models (parameters, coefficient of determination and p-values) are given in Table 4. Coefficients of determination, as a measure of the proportion of variability in crown volume explained by DBH, are generally very high, indicating a high degree of relationship between the two regressed variables. However, in the first age class, the coefficient of determination for crown volume of common hornbeam trees is the lowest, probably due to the small sample size in this age class (n = 21). Overall, oak trees exhibit a higher degree of relation between the crown volume and DBH compared to hornbeam.

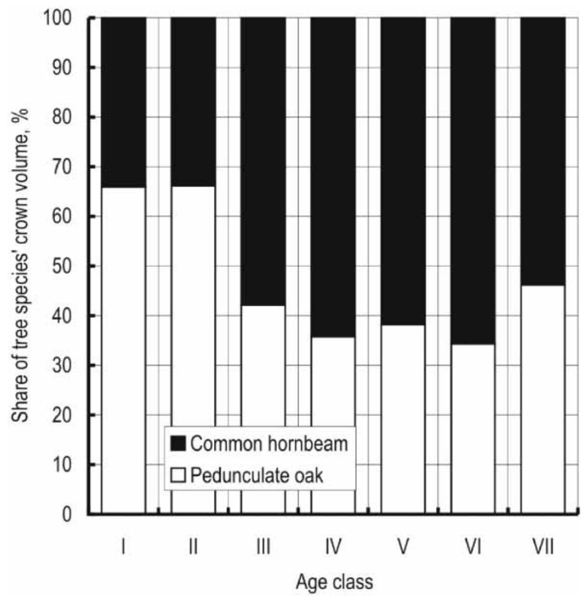

Figure 2. *Relation between the total crown volume of pedunculate oak and common hornbeam trees at the whole-stand level per age class.*

All regression lines are given in Figure 4. The shape of the regression lines of pedunculate oak crown volume shift more to the right side of the diameter range as the stand matures, while those of common hornbeam are more static. This can be explained by the fact that common hornbeam trees after the establishment of the oak's dominance in the canopy layer, always have roughly the

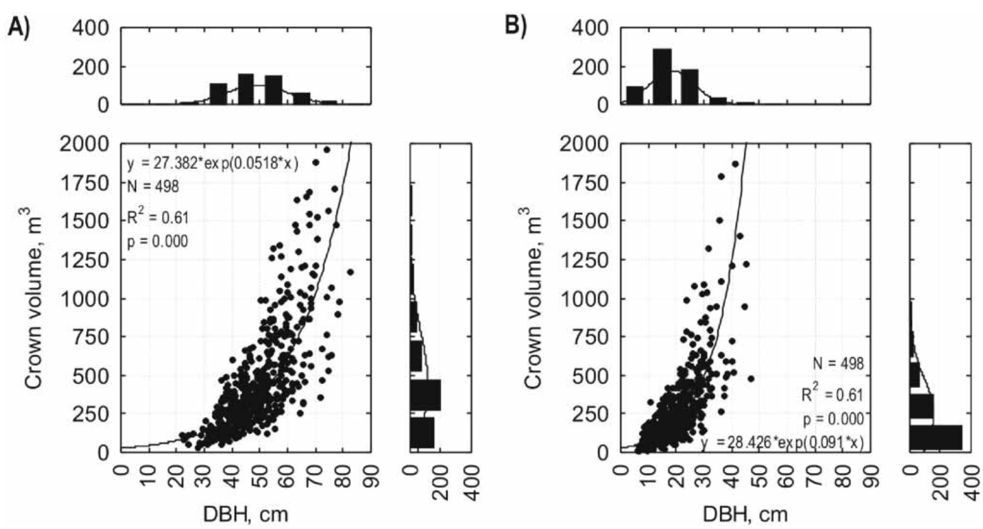

Figure 3. *Example of regression of crown volume against DBH in the sixth age class (stand age between 101 and 120 years) for trees of pedunculate oak (A) and common hornbeam (B).*

TABLE 4

Regression parameters, model R^2 and p value for non-linear models of crown volume over diameter at breast height for pedunculate oak and common hornbeam trees in stands of different age class.

Age class (years)	Pedunculate oak					Common hornbeam				
	n	parameters b_0	parameters b_1	R^2	p	n	parameters b_0	parameters b_1	R^2	p
I (0–20)	21	0.399	0.284	0.621	0.000	19	0.543	0.357	0.230	0.038
II (21–40)	258	2.548	0.140	0.652	0.000	260	2.226	0.242	0.512	0.000
III (41–60)	78	2.634	0.131	0.787	0.000	211	6.383	0.147	0.585	0.000
IV (61–80)	346	9.124	0.088	0.638	0.000	406	14.450	0.117	0.574	0.000
V (81–100)	239	18.285	0.060	0.540	0.000	254	18.389	0.102	0.520	0.000
VI (101–120)	498	27.382	0.052	0.611	0.000	452	28.426	0.094	0.654	0.000
VII (121–140)	169	122.910	48.769	0.435	0.000	377	48.769	0.068	0.554	0.000

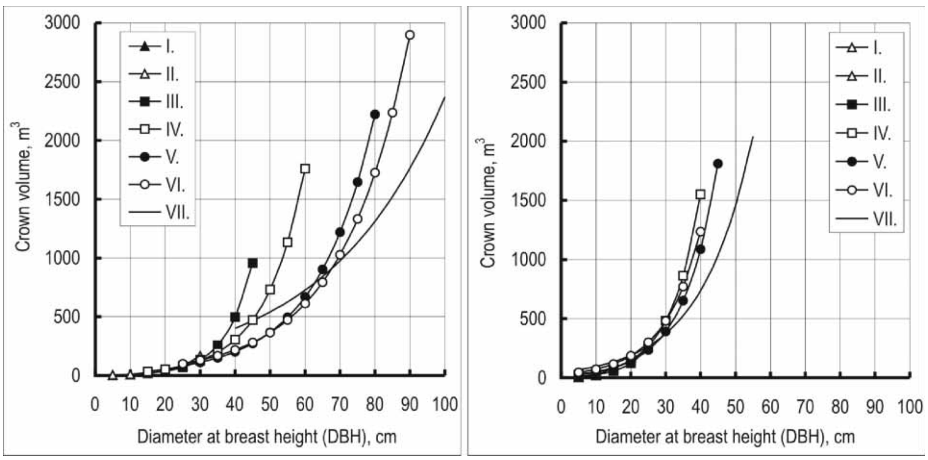

Figure 4. *Regression lines of crown volume over DBH for all age classes for pedunculate oak trees (A) and common hornbeam trees (B).*

same amount of available space in the understory. Given the dynamics of hornbeam fluctuations in the stands due to the silvicultural system applied, the diverse age of the hornbeam trees in the stands also presents an influencing factor. On the other hand, with silvicultural interventions in the form of thinnings, additional space is given to the crop trees, i.e. future trees whose growth we have to enhance over time to obtain the best economic results.

CONCLUSIONS

Pedunculate oak trees have greater average crown volumes compared to common hornbeam trees across all age classes. The difference between oak and hornbeam average crown volumes increases with stand age. In younger stands (age classes I and II), oak crown volumes are roughly two times greater compared to hornbeam, and in the last age class they are three times greater. Pedunculate oak trees at the stand level dominate in the canopy layer in the first two age classes, and in subsequent age classes, crowns of common hornbeam dominate due to the tree species' greater abundance in the stand.

Crown volume of pedunculate oak and common hornbeam is exponentially related to DBH. Obtained nonlinear regression models describe this relationship with sufficient accuracy, with coefficients of determination being generally higher than 50% across the age classes. The only exception is the first age class, due to the small sample size. Additional research is needed to shed more light on crown development in young stands of pedunculate oak and common hornbeam.

The obtained nonlinear regression models are suitable for the integration of the knowledge gained on crown structure of pedunculate oak and common hornbeam forest stands into modern computer-aided simulators of stand growth and development. Use of these contemporary tools as a decision support system in everyday forest management could greatly improve our ability to manage valuable pedunculate oak forests in a sustainable way.

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