PERIODICUM BIOLOGORUM
VOL. 115, No 3, 331–338, 2013

UDC 57:61
CODEN PDBIAD
ISSN 0031-5362

Original scientific paper

Growth dynamics of crown shapes in stands of pedunculate oak and common hornbeam

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Key words: stand structure, crown structure, crown shape, pedunculate oak, common hornbeam

Received January 18, 2013.

Abstract

Background and Purpose: *Structure of crowns in forest stands is one of the main factors which determines growth and development of trees. Dynamic change occurs with the age of the stand due to silvicultural interventions or natural disturbances during which trees are removed from the stand. The aim of this article is to analyse the structure of the crown shape of pedunculate oak and common hornbean trees with regard to diameter at breast height (DBH) and the age of the stand in one of the most important forest community in Croatia.*

Materials and Methods: *The investigation is based on data collected on 47 permanent experimental plots which were established as a chronosequence in a natural range of forests of pedunculate oak and common hornbeam in Croatia. The total surface of all plots amounts to 33.45 ha. Breast height diameter, tree height and stem height were measured on the trees in the experimental plots, and a detailed ground plan was made of horizontal crown projections, from which the crown diameters were calculated. In total 1505 pedunculate oak trees and 2026 common hornbeam trees were measured. For each tree the crown shape was calculated and trees were then grouped in age classes of 20 years, and the shape of the crown analysed according to species and age classes. Correlation between crown shapes and diameter at breast height was investigated for stands of the sixth age class (101 – 120 years) for each species by means of linear regression.*

Results and Discussion: *The shape of the crown of pedunculate oak, although it shows a trend toward growth in relation to diameter at breast height, the regularity pattern of the shape indicates weak character (r=0.441), i.e. variability is explained with only 19%. Crown shapes of common hornbeam are almost constant in relation to diameter at breast height (r=114), and correlation between the examined values cannot be equated by any rational analytical term. Investigation of growth dynamics of crown shape structure was carried out according to the species of trees and age classes, and the interval in which 68% ($\bar{x} \pm 1.0\,s$) and 95% of data ($\bar{x} \pm 1.96\,s$) were included.*

Conclusions: *The results of the investigation indicate that dependence on crown shape and diameter at breast height of penduculate oak and common hornbeam cannot be described by any rational analytical term. Average values of the crown shapes according to age classes can be used as form factors for calculation of crown volume. Data are applicable in various applications, such as for example their integration in a simulator of growth and development of forest stands and examination of the effect of different silvicultural scenario.*

INTRODUCTION

Forest ecosystems are the most valuable natural sustainable resources, whose growth and development is affected by a series of factors (natural and anthropogenic). As a consequence of permanent and diverse courses of growth and development of individual trees we differentiate trees according to diameter, height and other elements. The complexity of the interactive effect of different factors leads to the formation of specific composition of stands which are called stand structure. In the widest sense stand structure includes all elements which form the volume of wood and distribute it in the area. An important element of stand structure, as an essential factor of its development and internal formation, is the crown structure, in which key processes take place for the growth and development of the stand, such as photosynthesis.

The structure of the crowns of forest stands is defined by their size and shape, growth and development, distribution in space and time, and crown proportions in relation to other parts of the trees. The size and shape of the crown of an individual tree is the result of changes of internal inherited characteristics under the influence of external factors. Regardless of whether it is the influence of natural or anthropogenic factors, or, which is most often the case, mutual effect (interaction), the range of changes depends on the tree species, site quality, age, stage of development, social position of the tree in the stand, immediate surroundings, degree of crown cover, surface arrangement, spacing between trees, forest vegetation, management activities and stand structure according to the number of trees *(1)*.

The crown is an essential part of the tree on which production all elements of tree growth depend *(2)* and which, in cooperation with the soil, represents the main factor of all existential processes in the stand. The crown is also responsible for generative reproduction, as it provides seed which is the basis of all principles of sustainable forest management. The dimensions of tree crowns are used for modelling height and/or diameter increment of individual trees and mortality *(3)*.

A significant component of the crown structure is the crown shape, represented by the relation of crown diameter and length. Together with other elements the crown structure (diameter, length, area and crown volume; relation of the total height of the tree and length of the crown, etc.) represents an important factor in investigations of stand structure, particularly in the case of the upper part of the crown exposed to the sun, which largely contributes to the reception of solar radiation and its utilisation in the process of photo-synthesis *(4)*. Horizontal projection of the crowns, shape and volume, also determine the degree of interception of precipitation and regulate the amount of precipitation which reaches the forest soil *(5, 6)*. By means of a projection of crowns and crown volumes the stand canopy and crown cover over soil can be calculated *(7)* which regulate important microclimatic conditions within the stand, such as: the amount of direct and diffuse light, air and soil temperature, air and soil humidity. All the aforementioned factors are essential in the processes of the growth of trees or regeneration of stands.

The crown shape is typical for each type of tree and for some of its relatives, and is conditioned by ecological, stand, management and existential conditions of development. They change during years of development. In early years it is usually elongated (time of maximal height growth), and later gradually becomes rounder, on average more on broadleaved species than on conifers. This relation is greater as the crown becomes rounder. The crown can be slender to broad with a series of transitional symmetric and asymmetric shapes of the following characteristics: conical, elongated, flat-topped, platelike/disk, shallow, cylindrical, paraboloidal, oval etc. The crown shape of deciduous tree species is usually paraboloidal *(8)*.

Because of the exceptionally great variability in crown diameter and length of forest tree species, it is almost impossible to precisely calculate the volume and shape of crowns. Geometry of crowns is very complex and defined by many changeable and irregular shapes *(9)*. Consequently, for example, crown volumes are usually approximated by one of the more simple geometric bodies, such as cone or paraboloid. The area of horizontal projection of the crown is usually calculated as the area of the circle whose radius includes an average of two, four or eight measured radii of a crown *(10),* or as the sum of circular segments of four or eight circles of different radii *(11)*. Crown volume can be calculated by means of ellipsoid *(12, 13)* utilizing the measured values of horizontal projections and the crown length. More recently the possibility is being investigated of automatic measurement of crown sizes primarily by photographing the stand from the ground or measuring the crown in aero-photographs *(14, 15)*. The technique of photographing the stand from the ground has so far proved to be unsuitable in the case of a stand with dense canopy and dense undergrowth. On the other hand, aero-photographs enable measurement of only crowns in the dominant layer which is visible on the photographs.

The role of the crown in the development of an individual tree and entire forest stands has been the subject of many investigations. Burger and Badoux *(16, 17)* were first to reveal the significance of the crown in the structure of the stand. However, the basis for analysis of the growing space of trees in a stand should be attributed to an excellent study of Assmann, and particularly his investigation on the development of stand volume *(10)*. Investigation of tree crowns in Croatia, which is directly concerned with the role of the crown in the development of stand structure, among others, can be found in studies *(18-20)* and more recently in many investigations on the development of crown structure of pedunculate oak and common hornbeam in relation to diameter at breast height and age of stands *(1, 8, 21–24)*. A considerable number of authors have studied the dependence fir tree crowns in selection stands on particular structure elements, for instance, dependence on diameter at breast

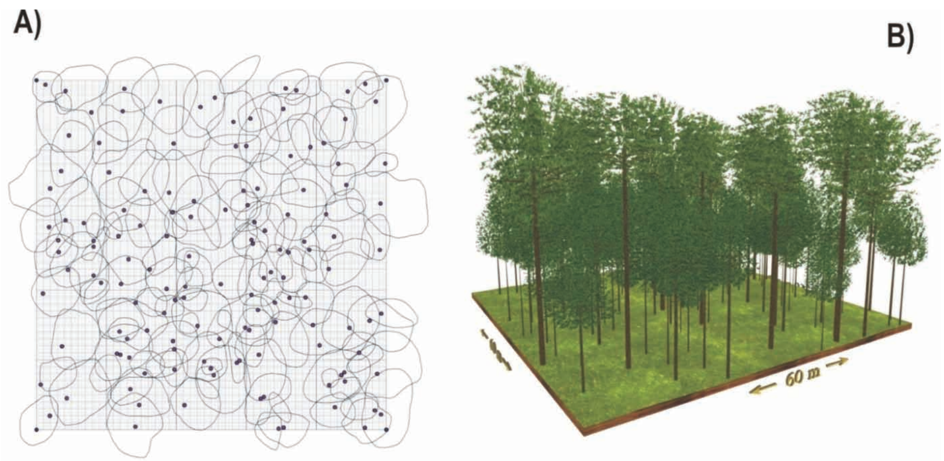


Figure 1. *Map of stem positions and horizontal crown projection areas of a 77 year- old stand on plot No. 21 (A), and 3-dimensional visualization of a 138 year-old stand on plot No. 37 (B).*

height, height, wood volume, elements of regeneration *(25–29)*.

Knowledge of the distribution of crown sizes depending on the size of the trees, and the ability to sufficiently accurately quantify the variability of the distribution gain importance with the accelerated development of computational models for simulation of growth and development of forest stands *(30–33)*. For example, decisions on the best possible silvicultural options for preservation of the remains of old forests of pedunculate oak *(34, 35)* would be much easier with the use of computational simulations. Crown structure is also very important when it is necessary to visualize the results of computational simulations in one of the modern computer programmes *(21, 36, 37)*.

The majority of investigations on crown dimensions, most often diameter (width) of tree crowns were carried out in Croatia on smaller areas (one to several stands or at the level of management units). This investigation is based on a representative sample of measured data on the whole area of distribution in stands of pedunculate oak and common hornbeam. Consequently, the aim of this study was to present the results of an investigation on the dynamics of development of the crown shape of pedunculate oak and common hornbeam depending on the age of the stand and diameter at breast height, and how these relations change with increase in the diameter at breast height and age.

MATERIALS AND METHODS

Natural stands of pedunculate oak (*Quercus robur* L.) and common hornbeam (*Carpinus betulus* L.) were investigated on elevations (spurs), formed by tree species with different requirement for light. They offer essentially different conditions for the development of tree crowns than pure oak stands on micro-depressions. With regard to characteristic complexity and differentiation of layers, in these stands greater crown cover over soil is possible. From the aspect of stand structure, the most important characteristic of this forest type is vertical distribution of crowns in two layers. The dominant upper canopy layer usually consists of crowns of heliophitic pedunculate oak, while the crowns of sciophitic common hornbeam usually cover the area below them.

The investigation was performed on 47 permanent experimental plots according to the methodology of Dubravac and Novotny *(38),* Dubravac *(8)* as a chronosequence in the whole area of distribution of a forest of pedunculate oak and common hornbeam in Croatia. The total area of all experimental plots amounted to 33.45 ha. The plots were of various sizes, from 20 x 20 m in young stands up to 60 x 60 m in old stands. For biological surveillance the plots belong to the developmental stage of young growth (older), young stands, middle-aged stands, older and old stands. All the trees over diameter at breast height of 7.5 cm were permanently numbered, their position determined and diameter at breast height, tree height and stem length measured. For each plot a layout of horizontal crown projections was produced for of all numbered trees, based on the measured radius of crowns in four directions, or more directions in the case of markedly asymmetric crowns (Figure 1A) on the basis of which crown diameters were calculated. After digitalization of the layout of horizontal crown projections 3-dimensional visualization of stands on the experimental plots was performed in programme packet 3Dmax (Figure 1B). On the basis of the age of stands all the experimental plots were grouped in age classes of 20 years. Basic indicators of the measured stands are presented in age classes in Table 1.

Schematic presentation of the measured characteristics of trees on plots is shown in Figure 2. Diameter of the crowns (D) were measured in photographs of horizontal crown projections (mapped) and drawn on graph paper for each plot. Crown diameter was calculated as the arithmetic mean of the largest and smallest diameter through the centre of the tree. Crown lengths (l_k) were

TABLE 1

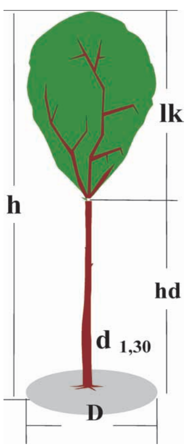
Mean values per age class of stem number (n ha^{-1}), basal area (BA, m^2 ha^{-1}), average DBH and total tree height (h, cm) of the sampled stands of pedunculate oak and common hornbeam.

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

calculated as the difference between total tree height (h) and length of the stem (h_d). Crown shape was calculated as the quotient between the diameter (D) and crown length (l_k) according to the formula:

$$O_k = \frac{D}{l_k} \quad (1)$$

Crown shapes were calculated for a total number of 3531 trees (1505 pedunculate oak and 2026 common hornbeam). Trees were grouped in age classes of 20 years according to the age of the experimental plots and stand age. For the example of regression analysis (12 experimental plots, 397 measured crown shapes pedunculate oak and 500 measured crown shapes common hornbeam), dependence of crown shape on diameter at breast height of the trees was examined for stands of the sixth age class (101 to 120 years).



Explanation:

$d_{1.30}$ (cm) – diameter breast height
h (m) – tree height
h_d (m) – stem length
l_k (m) – crown length
D (m) – crown diameter

Figure 2. *Schematic presentation of the measured sizes of trees on plots.*

RESEARCH RESULTS AND DISCUSSION

Current research on the dynamics of growth diameter and crown length of pedunculate oak and common hornbeam indicates great variability, which is indirectly reflected in the crown shape *(22, 39)*. The 6th age class (101-120 years) was taken as an example of the dependence of the crown shape on DBH. The crown shape of pedunculate oak increases with greater diameter at breast height and trees with greater diameter at breast height consequently have larger crown shape. Trees with greater diameter at breast height, dominant trees, have more space for the development of their crowns, which is then reflected in the size of the crown (diameter and length). The crown shape, although it shows a trend to increase in relation to diameter at breast height, shows a pattern of weak character (r=0.441), i.e. variability is explained by only 19% (Figure 3). The crown shapes of common hornbeam are almost constant in relation to DBH, r=114 (Figure 4), where the measured data are distributed randomly over the whole graph, and the relationship between the observed values cannot be explained by any rational analytic term. Thus in the further course of the investigation the development of crown shape per age class will utilize average values. The figures are supplemented by a histogramic presentation of a breakdown of frequency of diameter at breast height and crown shape with corresponding normal distribution (Gauss distribution) which shows regular share of the above

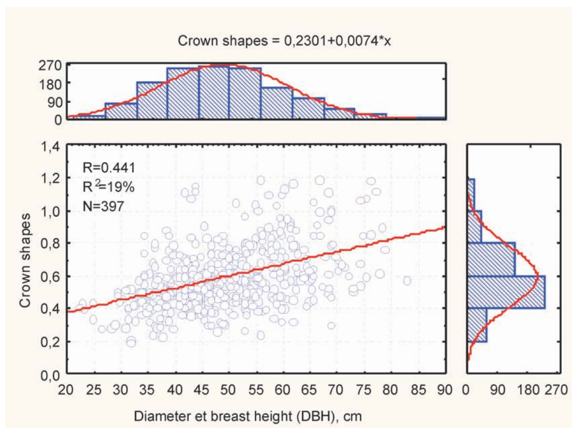


Figure 3. *Example of regression data on crown shape of pedunculate oak with division of the variables of the 6th age class (101–120 years).*

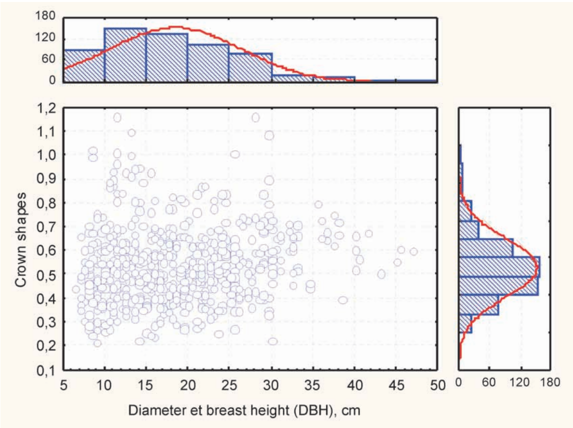


Figure 4. *Cloud data on crown shape of common hornbeam with division of the variables of the 6th age class (101–120 years), r=0.114; N=500*

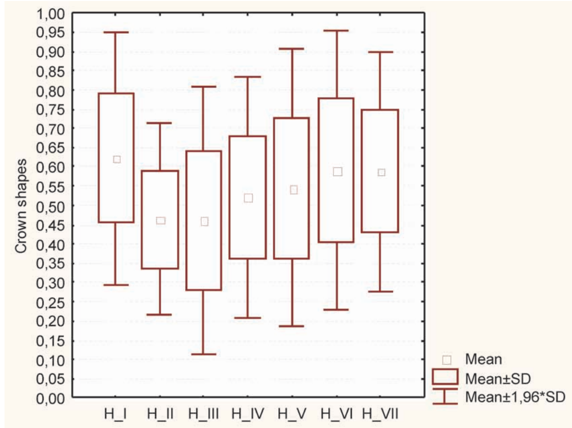


Figure 5. *Variability of crown shapes of pedunculate oak according to age classes.*

variables. In other words, diameter at breast height and crown shape is grouped around the arithmetic mean of the observed variables.

Table 2 shows the average values and standard deviations of the crown shape of pedunculate oak and common hornbeam according to age classes, and their average values and the interval which includes 68% (± 1.0 s) and 95% of data (± 1.96 s), which are clearly shown in Figures 5 and 6. The average crown shape of pedunculate oak (Figure 5) is greatest in the youngest stands of the first age class, where it amounts to 0.62. This value should be taken with some reserve because of the small sample of one experimental plot and only 20 measured trees. Furthermore, that value is significantly reduced in the stands of the second and third age class, where it amounts to 0.47, and 0.46, and in the older stands there was a slight trend toward growth in the crown shape with increased age of the stand (0.52–0.59). Thus, with infiltration of the trees into a co-dominant position in the stand the shape of the crown changes and as a result trees develop more in width than length and the quocient D/l_k changes. In conclusion oak trees with a markedly dominant position develop crowns freely in width and length. In the case of common hornbeam (Figure 6), in contrast to pedunculate oak, crown shapes are smallest in the youngest stands of the first age class (0.41) and later show a trend toward growth with the age of stands up to the sixth age class, with average values of 0.48 to 0.61. In stands of the sixth age class there was a significant decrease in values of crown shapes (0.54) but in the oldest stands of the seventh age class this value again increased to 0.60. A decrease in the average crown shape of common hornbeam in the sixth age class can be explained by the commencement of work on reforestation, during which regeneration cut in the stand only leave trees with well developed crowns, while trees with less relation between the crown and diameter at breast heightare removed from the stand. On the basis of data from a large number of specimen plots on the length and widths of crowns and their own observations, Hren and Krejči *(19)* calculated average form factors of crowns which were previously used for calculating crown volume. The aforementioned authors thus obtained average crown shape of pedunculate oak of 0.56 and of common hornbeam of 0.61, disregarding the age of the stand. The present investigation

TABLE 2

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

Age class (years)	Pedunculate oak			Common hornbeam		
	n	Mean	Standard deviation	n	Mean	Standard deviation
I (0–20)	20	0.62	0.17	18	0.41	0.17
II (21–40)	258	0.47	0.13	262	0.48	0.16
III (41–60)	78	0.46	0.18	211	0.50	0.15
IV (61–80)	345	0.52	0.16	406	0.54	0.17
V (81–100)	238	0.54	0.18	257	0.61	0.24
VI (101–120)	397	0.59	0.19	500	0.54	0.16
VII (121–140)	169	0.59	0.16	377	0.60	0.18

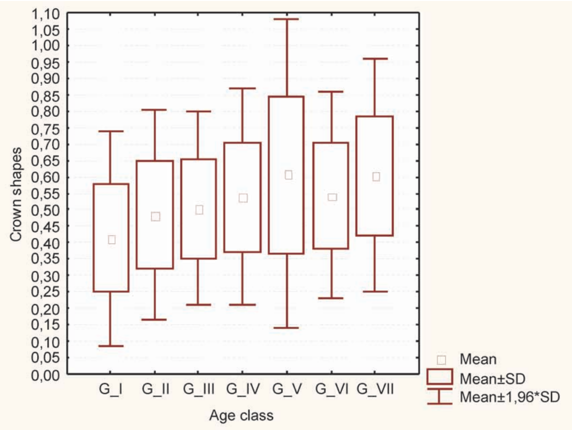


Figure 6. *Variability of crown shapes of common hornbeam according to age classes.*

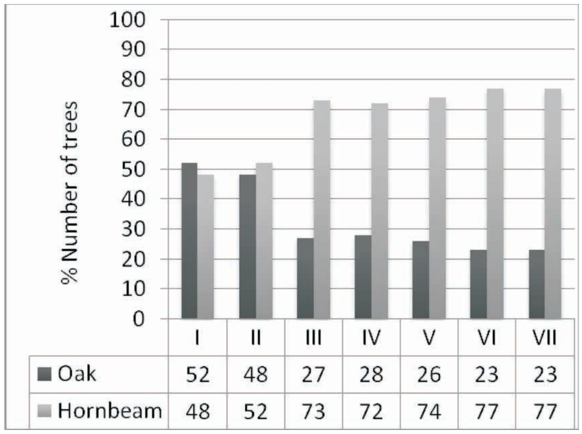


Figure 7. *Percental share of trees of oak and hornbeam according to age classes.*

gives more dimension as it provides quantative values of crown shape according to age classes, thus offering more realistic calculations of the crown volume.

The values of standard deviations (Table 2, Figures 5, 6) show great variability of the crown shapes within each age class (particularly hornbeam in the fifth age class) which occurs as a result of different competing relations between the trees in the stand.

The number of trees in the stand has a significant affect on stand structure and also crown structure *(40)*. After approximately the same initial number of trees per hectare in the first two age classes (up to stand age of 40 years) difference in the numbers between pedunculate oak and common hornbeam increased with the growth of the stand (Table 1). Figure 7 shows that in the first two age classes the percental relation of the number of trees of oak and hornbeam was approximately the same. From the third age class (41–60 years) the percental share of common hornbeam was greater, up to three times more than pedunculate oak. This is partially a reflection of intensive silvicultural interventions during the phase of natural reforestation of the stands at the end of the rotation of old stands and at the commencement of silvicultural interventions of tending young stands, the object of which is to help young pedunculate (plants) to withstand the pressure of competitive species of trees. In stands of this type of forest common hornbeam is the greatest competitor of young pedunculate trees. In later development stages, when pedunculate oak assumes its place in the dominant layer of the stand, crowns of skiophitic common hornbeam slowly fill up the space in the existing layer. This can partially be explained by the fact that trees of common hornbeam, after establishment of the domination of pedunculate oak in the upper layer of the stand, always have use of the same area in the understory layer. On the otherhand, during the whole lifetime of the stand, silvicultural interventions by thinning and seed felling of the best trees of pedunculate oak attemptto free additional space for growth and development of crowns andachievement of the best possible economic result and ultimately to ensure natural reforestation.

During the investigation we found various crown shapes, from very long and narrow to very wide and short. The relation itself between diameters and lengths of the crowns of oak and hornbeam primarily indicate their difference, which then is reflected in the variability of crown shape *(8, 22, 39)*. Shapes of the crown of pedunculate oak and common hornbeam show diversity due to the position of the maximal crown width. In oak this place is situated in the upper half of the crown height, measured from the top, which was demonstrated in previous investigations *(41),* and in hornbeam in the lower half of the crown. The above is explained by their biological position in the stand. Pedunculate oak occupies the upper layer, a dominant position in the stand, and the oak crown is relatively shorter and wider. On the contrary in common hornbeam the shape of the crown in the investigated stands has somewhat greater value of crown shape. In older stands of hornbeam there is more space for its development, due to incomplete density of the upper storey layer, when the effect of direct sunlight is complete and the trees form very strong tree crowns.

After several years of investigation of these stands, particularly the crowns, with the use of photographs it can be concluded that the average morphological stand crown shapes (model) of oak and hornbeam "appear like this" (Figure 8). This is confirmed by other studies *(9, 10)*. The crown of pedunculate oak has the shape of a paraboloid. From the top towards the bottom the radius of the crown grows to maximal values which reach approximately between 1/3 and 1/2 of the crown height measured from the top. Part of the crown which lies above the greatest crown diameter is defined as the crown of light, and the part under the greatest crown diameter is the crown of shade. The base of the crown has a pointed, conical shape due to dieback of the lower branches, and the influence of the understorey layer of the stand of hornbeam. Consequently, in pedunculate oak the part of

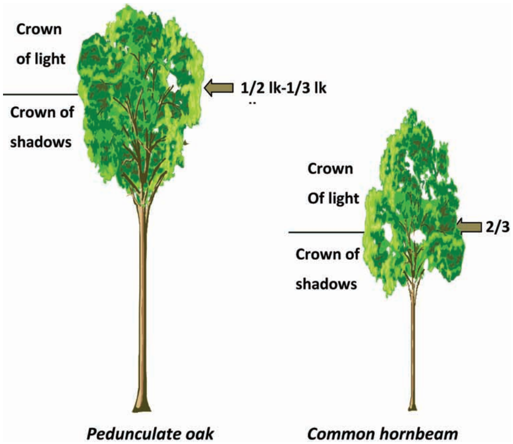


Figure 8. *Typical morphological crown shape (model) in a stand of pedunculate oak and common hornbeam.*

the crown exposed to light is always less than 0.5 of the crown length. When the crown is more open towards the sky, because of its position in the stand as a result of thinning, or in later phases because of commenced reforestation activity, during which only trees of well developed crowns remain, the greatest crown width is lower and clearly becomes the relative length of part of the crown which is exposed to light. In the case of common hornbeam, because of its biological position in the stand, the greatest crown width is lower and is situated approximately 2/3 of the crown length measured from the top, and thus such a part of the crown which is exposed to light is always greater than 0.5 of the crown length.

CONCLUSIONS

The structure of the investigated stands of pedunculate oak and common hornbeam is complicated by great variability, which is mainly a reflection of silvicultural interventions during the rotation of these stands. The result of which is variability expressed in the crown structure, and consequently also the crown shape.

The crown shape of pedunculate oak, expressed in the relation of the diameter and length of the crown (D/l_k), although it shows a trend toward growth in relation to diameter at breast height, has shape pattern of weak character ($r=0.441$) with variability explained by only 19%. In common hornbeam crown shapes are always constant in relation to diameter at breast height and the relationship between the observed sizes cannot be equated by any rational analytic term. The average crown shape of pedunculate oak is greatest in the youngest stands of the first age class, where it amounts to 0.62, thereafter the value significantly decreases in stands of the second and third age class to 0.47, and 0.46, and in the older and old stands a slow trend towards growth occurs with increased age of the stand from 0.52 to 0.59. In common hornbeam crown shapes show a trend towards growth with the age of the stand up to the fifth age class, where it amounts to 0.41 to 0.61. In stands of the sixth age class significant decrease in the values of crown shapes occurs (0.54), and in the oldest stands of the seventh age class this value amounts to 0.60. Average crown shapes, according to age classes can be used as form factors for calculating the crown volume of the above tree species.

Quantified results and models of crown shapes, obtained on a representative sample of 47 experimental plots and 3531 measured trees in the field, according to tree species and age classes, are suitable for future integration of the results of this investigation in modern computer simulators of growth and development of forest stands. The application of such modern tools in the daily management of forest ecosystems would revitalize to a great extent approach to discovery of the best possible objective comprehension of the complexity of the development of stand structure. The knowledge obtained from the present investigation is a contribution to improvement in the management of valuable pedunculateoak forests, with the aim of preserving basic forestry postulates: natural reforestation, biodiversity and sustainable income.

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