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ORIGINAL PAPER

Economic value production of trees as a criterion of their maturity in an uneven-aged forest

Rudolf Petráš, Julian Mecko, Ladislav Kulla*

National Forest Centre, Forest Research Institute Zvolen, T. G. Masaryka 2175/22, SK – 960 92 Zvolen, Slovak Republic

Abstract

Tree maturity of the four main tree species that are most frequent in the uneven-aged forests of the Western Carpathians was analysed. The maturity was determined on the base of the economic value production in relation to tree diameter. We derived mean timber values of spruce, fir, pine, and beech trees (€ m^{-3}) depending on their diameters, quality and stem damage, and in the case of beech also depending on tree age. The assortment structure was calculated using the models of tree assortment tables that account for the stated tree parameters. The assortment prices were taken from the price list of logs in assortment and diameter classes of the Forests of the Slovak Republic, state enterprise, for the year 2016. Trees are mature when their mean timber monetary value is at maximum. Results show, that the highest mean value production of the majority of beech trees of average and above-average stem quality is 70 – 80 € m^{-3} for trees with diameters between 45 and 55 cm. Monetary values of spruce and fir trees with diameters above 60 to 90 cm are 80 – 95 € m^{-3}, while the monetary values of pine trees with the same diameters are approximately 70 – 115 € m^{-3}. The value production of trees is reduced if the stems are of worse quality or damaged, but in the case of beech it also decreases with greater diameter or tree age.

Key words: target diameters; stem quality; stem damage; assortment structure; selection management system

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1. Introduction

Tree and stand maturity are one of the most important indicators of efficient management in forest stands and are primarily based on their lifelong production. Forest stands are mature when the requirements on their target production are optimally fulfilled. In even-aged forests maturity is determined by the stand age, when the mean annual production is the highest, i.e. when the total mean stand increment culminates (Halaj et al. 1990). Target stand production can be represented by the highest volume production, high production of the most demanded or best-quality assortments, but above all by the highest economic value production quantified by the gross or net income expressed in monetary terms. Halaj et al. (1990) derived maturity ages for even-aged stands of spruce, fir, pine, oak and beech based on the culmination of the total average value increment. As a basis they used the models of yield tables (Halaj et al. 1981; Halaj & Petráš 1998) and assortment yield tables (Petráš et al. 1996). The ages were later updated using new timber prices and models of modal stocking of real stands (Petráš & Mecko 2013). Similarly, the maturity ages of poplar clone stands of Robusta a I–214 were derived (Petráš et al. 2008a, b, 2015a).

In uneven-aged close-to-nature forests, and particularly in selection forests, which represent their ideal form, it is inefficient and practically impossible to determine a single maturity age for the whole stand or for each tree species. Maturity in selection forests must be related to individual trees, which shall optimally meet the requirements on the target production. The criteria of tree maturity should be as simple as possible, but at the same time they should integrate more factors. The physical age of trees cannot be used in these cases due to the varying dynamics of tree growth under the conditions of uneven-aged stands and particularly due to the difficulties in its assessment for this purpose. The physical age of a tree is usually replaced by the target diameter. Its application is practical because unlike other tree parameters, diameters can be determined easily and unambiguously. Maximum stem diameter retained after a selective cut is frequently used as an additional decision parameter in the optimisation of typical "inverse J" shaped diameter distributions of selection forests in European conditions (Pukkala et al. 2012). On the other hand, most yield regulation systems

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**Corresponding author. Ladislav Kulla, e-mail: kulla@nlcsk.org* applied in uneven-aged tropical forests define trees to be harvested by minimum harvestable diameter, although other maturity condition criteria are also important and might be regarded (Seydack 1995).

Under the conditions of Central Europe, several authors have dealt with the economic value production and the target diameter, also called a dimension of the rotation type (Hanewinkel 2002; Hanewinkel et al. 2014; Doležal et al. 1969; Priesol & Polák 1991; Poleno 1999 and others). Saniga & Vencurik (2007) derived target diameters for mountainous fir-spruce forests of the Western Carpathians from the optimal curves of diameter frequencies for 3 groups of stands regardless of tree species. Reininger (1992, 1997) also presents only particular target diameters and their modification if stems are damaged by rot or are of worse quality. Due to this, he suggests that trees to-be-harvested should be selected not only on the base of the target diameter but also with regard to their quality. We can say that in the majority of national works the method of quantification of the impact of individual factors on the target diameter of trees is missing.

The aim of the presented paper is to analyse the value production of spruce, fir, beech, and pine trees, and to determine their target diameters as indicators of their optimal maturity. Tree species were selected on the base of their economic importance in the production of mixed and selection forests in the region.

2. Material and methods

The models of tree assortment tables (Petráš & Nociar 1990, 1991a, b) and the prices of raw timber assortments were taken as the basis for the calculation of tree value production. The models of assortment tables were derived from a large empirical material, which was collected during sorting of felled trees of the examined tree species in the main growth regions of Slovakia. The models produce the percentual proportions of assortments from the volume of the timber with the diameter greater than 7 cm inside bark assigned as $S\%$. The proportions were calculated using relationship (1) depending on tree diameter d, stem quality q, stem damage dmg, and tree age t.

$$S\% = f(d, q, dmg, t) \qquad [1]$$

All tree parameters are significant only in the case of beech. In the case of fir and spruce, diameter, quality, and stem damage are significant, while in the case of pine, assortment structure is significantly affected only by tree diameter and stem quality. The models are non-linear for all tree species, and non-linearity is significant not only in relation to the single variables, but also for their combination. Generally can be stated, that trees with thicker stem with above-average quality and without significant stem damage have higher proportion of valuable assortments than thinner trees with bellow average stem quality and stem damage. In the case of beech, the proportion of valuable assortments decreases significantly at the age higher than 120 years.

Assortments are represented by quality and diameter classes of logs. Assortment quality classes of logs I – VI are characterised as follows:

Class	Purpose of utilisation
I	Cross-cut veneer, special sport and technical equipment, with minimal diameter 40 cm for spruce, fir and beech, and 30 cm for pine.
II	Rotary-cut veneer, matches, sport equipment, with minimal diameter same as I.
III (A, B)	Saw timber (IIIA of higher quality, IIIB of lesser quality) and construction timber, with minimal diameter 16 cm.
V	Pulpwood, chemical and mechanical processing for the production of cellulose and agglomerated boards.
VI	Fuelwood.

In the model of tree assortment tables, the classes from I to IIIB are further divided into diameter classes 1 to 6+:

Class	Diameter [cm]	Class	Diameter [cm]
1	16 – 19	2	20 – 29
3	30 – 39	4	40 – 49
5	50 – 59	6+	60 and more.

It is natural that the proportion of higher diameter classes increases with increasing tree diameters.

Stem quality is evaluated according to the properties of its lower third as follows:

Class	Stem characteristics
A	Stems of the highest quality, straight, untwisted, centric, without shape distortions and knots, which can be used for veneer production.
B	Stems of average quality with minor technical defects, with sound and decayed knots not larger than 4 cm, which can be used as saw timber of better quality.
C	Stems of below-average quality with major technical defects, greater curvature, twisted growth up to 4%, sound knots without limitations, decayed knots in the conifers up to 6 cm and in deciduous tree species up to 8 cm, which can be used as saw timber of lesser quality or as pulpwood.
D	Stems of lower quality than in C class, with extensive rot, which can be used as fuelwood.

Percentual proportions of assortments were calculated using formula (1) separately for each tree species, for every stem quality A, B, C, and D in the case of beech, and for undamaged and damaged stems. The extent and the intensity of stem damage is not quantified, only its presence or absence is evaluated. The information about stem damage is important because it is related to the future or already existing presence of fungal infection and rots in stems. Its presence is evaluated not only in stems, but also on stumps, root swellings and surface roots. Tree age is included only in the assortment models for beech, because adverse forms of false heart are frequent in older trees of this species. This was lately confirmed by Račko & Čunderlík (2011) and Trenčiansky et al. (2017). Due to this, the assortment structure of beech was calculated separately for the trees aged 100 and 140 years. These particular ages were selected as an example of the age influence on assortments structure and consequently on timber value in the case of beech. For the calculation of the assortment structure using relationship (1), we applied the mathematical form of the models of assortment tables (Petráš 1992).

The economic value production was quantified as an mean timber value of each tree *value [€ m⁻³]* calculated as a multiplication of the proportion of assortments (quality and diameter classes) *S%* and their *prices*:

$$value[€\ m^{-3}] = \frac{S\%}{100} \cdot prices \qquad [2]$$

The assortment prices were taken from the price list of logs in assortment and diameter classes for the first quarter of the year 2016 published by the Forests of the Slovak Republic, state enterprise.

3. Results

The economic value of trees was calculated using formula (2) and represents as an mean economic timber value of each tree. It depends on the structure of the assortments that can be potentially produced from every tree and their prices. Tree maturity was assessed on the base of the development of the mean value of the produced timber (€ m^{-3}) in relation to its diameter (Fig. 1 – 5). A tree is mature when it reaches the diameter when this value culminates. Timber values of all tree species grow faster when tree diameters exceed 16 cm, i.e. when better quality assortments I – III start to be more abundant in the assortment structure. The highest timber values are obtained for the best stems of A class regardless of tree species. In the case of spruce and fir (Fig. 1 and 2), the values continuously grow and reach 95 € m^{-3} at 90 cm tree diameter. The values of damaged stems are by about 5 € m^{-3} lower. In the case of average-quality stems (B class), the values of spruce timber culminate at tree diameters of 60 to 70 cm, when they reach the maximum of approximately 81 € m^{-3} or 75 € m^{-3} if a stem is damaged. The values of fir stems are by about 1 – 2 € m^{-3} higher. The timber values of spruce undamaged or damaged stems of below-average quality C culminate at diameters of 90 cm at a level of 78 – 70 € m^{-3}, while in the case of fir, the maximum values of 76 – 67 € m^{-3} are obtained at diameter from 50 to 70 cm.

Pine timber values (Fig. 3) are significantly different from spruce and fir. Timber values of best-quality pine stems of class A continuously grow, and reach maximum of 114 € m^{-3} at diameters of 90 cm. This is caused by the fact that the best-quality part of the stem becomes longer and goes up to the tree crown which is shorter than in the case of spruce or fir. In the case of pine, the pruned part of a stem makes approximately 2/3 of stem volume, while in the case of spruce and fir it is only about 1/3. The timber values of pine stems of average quality B culminate at diameters between 60 and 75 cm at a level of 72 € m^{-3}. The timber values of stems of below-average quality C grow up to 60 € m^{-3} at tree diameters around 90 cm. The impact of stem damage on timber quality and value is very small in the case of pine, and thus, it is not taken into account.

The mean values of beech timber (Fig. 4 and 5) are significantly different from coniferous tree species, particularly in relation to tree diameters and stem damage. The timber values of stems of A and B classes culminate at diameters from 45 to 55 cm. As tree diameters grow, the timber values of such stems markedly decrease. For example, in the case of undamaged stems of class A, the timber value is reduced from 82 € m^{-3} to 72 € m^{-3}. This trend is visible also in the case of stem damage, which is a much more significant factor in the case of beech than for spruce or fir. In addition, it is necessary to point out that in the case of beech the greatest stepwise increase of timber value is around tree diameters of 42 and 43 cm. This is caused by the fact that minimum top diameter of best-quality logs of class I is set to 40 cm. These logs have significantly highest price when compared with others beech cutouts. Due to the occurrence of false heartwood, the effect of tree age cannot be neglected. The frequency of adverse forms of false heartwood increases with tree age (Račko & Čunderlík 2011; Trenčiansky et al. 2017). Due to this, we calculated the model timber values for 100 and 140-year-old trees separately. At the culmination point of the timber values, the values of older trees are lower only by 2 – 4 € m^{-3}. The lowest timber values are in the case of stems of below-average quality of class C or D, and vary approximately in the range from 51 to 46 € m^{-3}. Their culmination is not obviously related to tree diameters, as it occurs within a wide span between 40 and 70 cm.

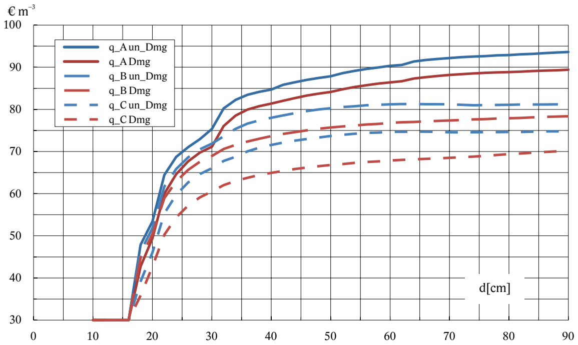

Fig. 1. Mean spruce timber value (€ m^{-3}) in relation to diameter *d*, quality *q* and stem damage (*Dmg* – damaged, *un_Dmg* – undamaged).

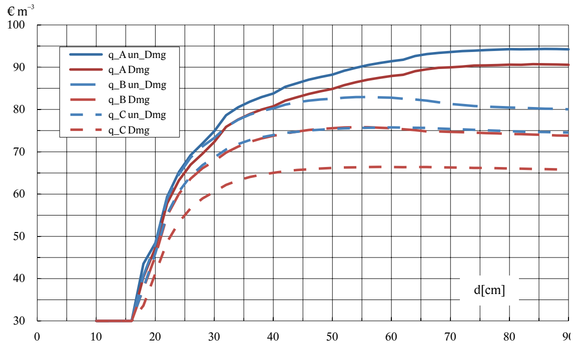

Fig. 2. Mean fir timber value (€ m^{-3}) in relation to diameter *d*, quality *q* and stem damage (*Dmg* – damaged, *un_Dmg* – undamaged).

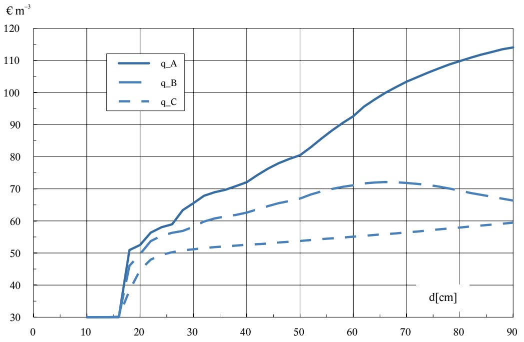

Fig. 3. Mean pine timber value (€ m^{-3}) in relation to diameter *d* and stem quality *q*.

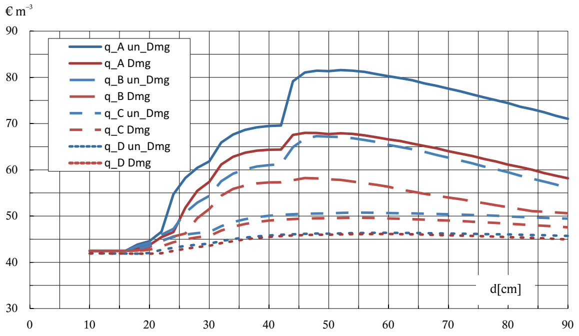

Fig. 4. Mean beech timber value (€ m^{-3}) in relation to diameter *d*, quality *q* and stem damage (*Dmg* – damaged, *un_Dmg* – undamaged) at the age of 100 years.

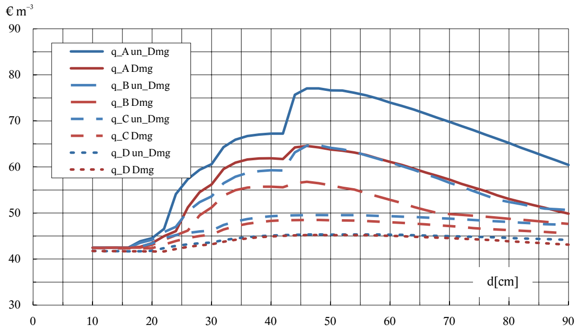

Fig. 5. Mean beech timber value (€ m^{-3}) in relation to diameter *d*, quality *q* and stem damage (*Dmg* – damaged, *un_Dmg* – undamaged) at the age of 140 years.

From the derived mean value production of timber we can unambiguously conclude that tree maturity depends not only on tree diameter, but also on stem quality and stem damage, and in the case of beech also on tree age. When summarising the obtained knowledge we can state that the timber values of best-quality stems of all three coniferous tree species culminate at a diameter around or above 90 cm. In the case of stems of average quality, the culmination shifts to lower diameters: 50 – 60 cm in the case of fir, 60 – 70 cm for spruce, and 60 – 75 cm in the case of pine. Timber values of stems of below-average quality slightly increase up to the largest diameters. The values of fir culminate at diameters of 50 – 70 cm. Timber values of spruce and fir culminate at the same tree diameter regardless of the stem damage. Only the value in € m^{-3} is significant. The values of damaged stems are lower by 5 € m^{-3}, 6 – 7 € m^{-3} and 8 – 9 € m^{-3} in the case of qualities A, B, and C, respectively.

Beech is significantly different from coniferous tree species. Its timber values culminate in the interval of diameters from 45 to 60 cm for all qualities and also in the case of stem damage. The culmination of trees with B stem quality and of older trees with A stem quality occurs within the smallest range of diameters from 45 to 50 cm. Younger trees reach their maturity at diameters by 5 cm greater than older trees. In addition, the timber values of younger trees with the same diameters are higher by 3 – 5 € m^{-3} than of older trees. Stem damage has a similar, though a more pronounced effect on beech maturity than in the case of spruce and fir. Tree diameter at which timber values culminate does not change with the damage. Only the timber values of damaged stems are reduced by 8 – 14 € m^{-3}. Beech timber values are generally lower than the values of coniferous tree species. This is also valid for diameters at which their timber values culminate.

4. Discussion

Tree maturity depends on tree value production, which integrates volume, quality and economic importance (price) of the produced timber. It is determined by tree diameter, at which the mean monetary timber value per 1 m^3 is the highest. This diameter can be considered as a target diameter for tree harvesting in a selection forest. According to our results, in the case of coniferous tree species it is mainly affected by stem quality. In the case of beech, damage and tree age also have significant effects apart from quality.

The presented results showed a different influence of tree parameters on the value of the produced timber. The influence is similar only in the case of spruce and fir. This results mainly from a similar stem shape and quality including the impact of stem damage on rot. As Petráš & Nociar (1991a) state, small differences between them are caused only by larger knots, and lower susceptibility of fir to wood root than of spruce. The great similarity of the use properties of both tree species causes that the prices of their assortments have been the same for a long time (Petráš et al. 2002). In the case of the slight differences in their prices, the value production has not changed significantly. It would become more pronounced if the price relations between the assortments changed more distinctively as stated by Poleno (1968) and Halaj et al. (1990). In such cases, the culmination of the mean timber values would change. The value production of spruce and fir is similar to the one of pine. The similarity is given by the stem shape. However, pine crown is situated higher than crowns of spruce and fir, and in the case of best-quality stems can the zone without knots reach the crown. The big advantage of pine is the low susceptibility of its timber to rot. A special feature of beech is its well-known great susceptibility to the formation of false heartwood. The frequency of its occurrence increases with higher age and greater diameter of trees, as well as with stem damage. Stem damage causes not only false heartwood but also rots. They are the main factors why beech values do not reach the values of the three coniferous tree species. This was also accounted for by Halaj et al. (1990) when deriving the economic maturity of beech stands. Similar causes of lower value production of beech in mixed stands with spruce and fir were mentioned by Petráš et al. (2015b).

When comparing our results with target diameters of trees published by other authors it is necessary to account for the methodology of their derivation. Saniga & Vencurik (2007) derived target diameters of trees from optimum curves of diameter frequencies without analysing the production value. They present target diameters for three groups of selection stands equal to 50, 70, and 74 cm regardless of tree species, but considering site production potential. Our results are derived from the assortment models for mean conditions in productive (management) forests of Slovakia, and are not comparable with the target diameter equal to 50 cm for the exposed sites of the protective character. The values of 70 – 74 cm correspond with our results for spruce and fir stems of average up to above-average quality, but underestimate pine and slightly overestimate beech.

Reininger (1992, 1997) states a lower target diameter of only 50 cm for undamaged stems of saw quality. When stems are damaged by rot are of worse quality, target diameter is significantly reduced. The author suggests the target diameter of approximately 60 cm for stems of best quality A. The given values of diameters are regardless of tree species.

Sterba (2004) applied a maximum dbh of 60 cm for spruce, fir, beech, pine and larch within the optimised treatment of mixed uneven-aged forests on productive sites in Austria targeted at a de Liocourt-equilibrium diameter distribution curve with a residual basal area of 40 m^2 ha^{-1}.

Poleno et al. (2009) attempted to apply a time criterion in the assessment of target diameters of trees on the base of their real diameters and annual diameter increments. At the same time they also indicated some doubts about their practical implementation. They stated that the culmination of the mean value increment of trees shifts to a higher age in comparison to diameter increment, particularly in the case of best-quality trees.

Recently, economic criteria based on the net present value regarding time factor through interest rate have been applied to address financial tree maturity, which depend mainly on tree value increment related to growing vigour, and on the stumpage value already achieved closely correlated to tree diameter (Knoke 2012). Vauhkonen & Pukkala (2016) simulated harvesting of trees with a value increment lower than the pre-defined threshold reflecting the interest rate (3, 5%). They proved that mainly large sized dominant trees were subjects to harvest, although in dense stands with high competition also thin trees were harvested. For the steady state economically optimised harvesting in a spruce continuous cover forest in Finland, Rämö & Tahvonen (2016) derived target harvest diameters from 20 cm in the case of 5% interest rate to 30 cm in the case of 1% interest rate.

The most complex approaches of harvesting optimisation in uneven-aged forests consider simultaneously both ecological and economic criteria. Roessiger et al. (2016) developed a matrix transition model that is density-dependent and sensitive to individual growth dynamics, which schedules optimal harvesting to maximise the net present value of cuttings and the remaining stand simultaneously to the long-term stand dynamics projection. Based on this model, the economic maturity of individual trees ranged from diameter 12 to 72 cm.

5. Conclusion

Our results indicate that the value production of trees culminates in a wide interval of diameters, hence it is not appropriate to define a single target diameter for a stand or a tree species. The level of value production depends not only on tree diameters but also on stem quality and is reduced by stem damage. In contrast to coniferous tree species, beech value decreases with increasing diameter and tree age.

At productive sites of the Western Carpathians, the highest mean value production of the majority of beech trees of average and above-average stem quality is 70 – 80 € m^{-3} for trees with diameters between 45 and 55 cm. The highest mean monetary values of spruce and fir trees with diameters from 60 to 90 cm are 80 – 95 € m^{-3}, while the monetary values of pine with the same diameters are approximately 70 – 115 € m^{-3}. The given ranges of diameters can be considered as target values when managing uneven-aged forests under given conditions.

The culmination of the value production of coniferous tree species in relation to tree diameters is not distinct. In the case of best-quality stems the culmination does not occur because the values gradually increase with the growing diameter. This allows to apply other criteria of maturity apart from the target diameter, for example, to modify stand density, structure, and tree species composition without significant impact on the value production of trees. As for beech, the situation differs, and from the point of the production value it is not appropriate to leave trees with diameters above 60 cm in a stand.

In general, the value production of a mixed uneven-aged forest in the Western Carpathians increases as the proportions of coniferous tree species and the proportion of high-quality, undamaged and well-growing trees increase.

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