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LIVE CROWN RATIO AND SLENDERNESS COEFFICIENT AS INDICATORS OF BEECH TREE STABILITY

Miloš RAČIĆ[1], Nenad PETROVIĆ[2], Nikola MARTAĆ[1], Jovan DOBROSAVLJEVIĆ[2], Janko LJUBIČIĆ[2], Ivana RAČIĆ[1], Branko KANJEVAC[2]*

Abstract: *This study investigates the applicability of the live crown ratio (LCR) and the slenderness coefficient (SC) as indicators of tree and stand stability of European beech (Fagus sylvatica L.). The research was conducted within the Forest Management Unit (FMU) "Lomnička Reka", managed by the Public Enterprise "Srbijašume". Data were obtained from the stand inventory of the analyzed FMU, conducted on a network of permanent sample plots. The analysis focused on five structurally uneven-aged stands, encompassing 103 beech trees belonging to the middle-aged silvicultural group across eight sample plots. For each measured tree, both the live crown ratio and the slenderness coefficient were determined. Logistic regression and Conditional Inference Tree (CIT) analyses were used to identify critical LCR thresholds distinguishing slender from non-slender trees, with bootstrap procedures employed to assess the stability of the results. The findings revealed a significant negative relationship between LCR and SC ($p < 0.001$), with a critical LCR threshold of approximately 0.36–0.40 identified as necessary to maintain tree stability. Both statistical approaches yielded consistent results, supporting the robustness of LCR as a reliable predictor of slenderness. The obtained results emphasize the importance of analyzing these parameters during the process of planning silvicultural measures, particularly thinning, aiming to enhance tree stability, and improve the overall resilience of beech stands.*

Keywords: beech, live crown ratio, slenderness coefficient, stand stability.

RELATIVNA DUŽINA ŽIVE KRUNE I KOEFICIJENT VITKOSTI KAO INDIKATORI STABILNOSTI STABALA BUKVE

Sažetak: *Ova studija istražuje primenljivost relativne dužine žive krune (LCR) i koeficijenta vitkosti (SC) kao pokazatelja stabilnosti stabala i sastojina evropske bukve (Fagus sylvatica L.). Istraživanje je sprovedeno u okviru gazdinske jedinice (FMU) „Lomnička Reka“, kojom upravlja Javno preduzeće „Srbijašume“. Podaci korišćeni u ovoj studiji dobijeni su iz sastojinske inventure analizirane gazdinske jedinice, sprovedene na mreži permanentnih primernih površina. Analiza je obuhvatila pet sastojina, strukturno raznodobnih, sa ukupno 103 stabla bukve na 8 primernih površina koje pripadaju*

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srednjedobnoj uzgojnoj grupi. Za svako izmereno stablo određeni su relativna dužina žive krune i koeficijent vitkosti. Za identifikaciju kritičnih vrednosti LCR koje razdvajaju vitka od nevitkih stabala korišćene su logistička regresija i analiza uslovnog stabla zaključivanja (CIT), dok su bootstrap postupci primenjeni za procenu stabilnosti dobijenih rezultata. Rezultati ukazuju na značajnu negativnu vezu između LCR i SC ($p < 0.001$), pri čemu je utvrđen kritični prag LCR od približno 0.36–0.40 kao neophodan za održavanje stabilnosti stabala. Obe statističke metode dale su konzistentne rezultate, potvrđujući pouzdanost LCR kao prediktora vitkosti. Dobijeni rezultati ukazuju na potrebu da se ovi parametri analiziraju u postupku planiranja uzgojnih mera, posebno proreda, sa ciljem povećanja stabilnosti stabala i poboljšanja ukupne otpornosti sastojina bukve.

Ključne reči: bukva, relativna dužina žive krune, koefiicijent vitkosti, stabilnost sastojine.

1. INTRODUCTION

Climate change has been identified as one of the greatest global challenges (Psistaki et al, 2024). Forest ecosystems, which cover an area of 4.06 billion hectares globally (FAO, 2020), are recognized as a fundamental component of the Earth`s climate system (Brack, 2019) while being significantly affected by climate change impacts (Kirilenko et al, 2007; Aaheim et al, 2011; Tian et al, 2016; Marković et al, 2019). These impacts are manifested through the generation of various biotic and abiotic risks (Venäläinen et al, 2020). Due to climate change, the frequency of extreme events is expected to rise (Lidskog and Sjödin, 2016; Campbell et al, 2020). The resilience of forest ecosystems, defined as their capacity to recover from such adverse effects (Ibáñez et al, 2019), has declined in tropical, arid, and temperate forests (Forzieri et al, 2022). Adequate forest management can enhance the resilience of forest stands, thereby ensuring the preservation of ecosystem services and biodiversity (Triviño et al, 2023).

Tree crowns represent a fundamental structural feature of both individual trees and entire forest stands, owing to the multitude of ecological and functional roles they fulfill (Zhu et al, 2021; Jucker et al, 2025). A significant role of tree crowns is reflected in biomass production and the process of photosynthesis (He et al, 2023). By hosting nearly 50% of terrestrial biodiversity (Lowman, 2021), tree crowns constitute a key structural component essential for sustaining and protecting biological diversity within forest ecosystems (Matsumoto et al, 2017). Proper crown formation, achieved through adequate and timely implementation of silvicultural treatments, greatly enhances the stability of individual trees and forest stands (Kaźmierczak and Jędraszak, 2014; Pretzsch, 2014). In the context of climate change, tree crowns may play a critical role in the adaptation and response of forest ecosystems (McNeil et al, 2023).

The study of crown structural elements is of great practical importance for the forestry profession (Stajić et al, 2017). One of the key indicators of crown structure is the live crown ratio (LCR), defined as the proportion of the total tree height that has live foliage (Zarnoch et al, 2004). LCR is used as an indicator of tree vigor, as higher values of LCR generally indicate greater vitality and favorable physiological condition (Schomaker et al, 2007). Trees with low LCR are generally less structurally stable and more susceptible to mechanical damage, which underscores the significance of LCR as an indicator of both tree vitality and stand stability (Karamzadeh et al, 2023). In addition to being an indicator of tree vigor and stand stability, LCR also serves as an indicator of tree and stand growth, with research showing that trees with higher LCR values generally exhibit greater growth rates (Patton et al, 2019), which is of considerable practical importance for forestry, particularly in the implementation of silvicultural treatments.

Besides crown characteristics, several other parameters have been identified as important indicators of tree stability, among which the slenderness coefficient (SC) is particularly significant. Defined as the ratio of total tree height to diameter at breast height, SC has been widely acknowledged in silvicultural research as a robust and practical measure of tree resistance to mechanical stresses caused by external factors such as wind, snow, and ice (Wang et al, 1998; Kanjevac et al, 2023). Previous studies have shown that SC is negatively correlated with diameter at breast height, basal area, and tree volume, while exhibiting a positive relationship with total tree height (Shamaki, 2022).

European beech (*Fagus sylvatica*) forests are the most widespread forest type in Serbia, covering 660,400 ha (29.3% of the total forested area) and occurring across altitudes from 100 to 1,700 m (Banković et al, 2009). Given their ecological significance, economic value, and role in maintaining biodiversity and forest stability, the study of beech forests is of paramount importance for sustainable forest management.

Based on the ecological and silvicultural importance of beech forests and the critical role of crown structure, this study aims to evaluate the applicability of the live crown ratio as a tool for guiding tending interventions to promote and maintain vigorous European beech stands.

2. MATERIAL AND METHODS

The research was conducted within the Forest Management Unit (FMU) "Lomnička Reka", which is managed by the Public Enterprise "Srbijašume" (Figure 1). The FMU is located in the municipality of Kruševac, Central Serbia (between 18°59′ and 19°05′ E, and 43°24′ and 43°28′ N), at elevations ranging from 300 to 1394 m above sea level. The total area of the management unit is 3,399.96 ha. The mean annual temperature is 12.5 °C, while the total annual precipitation amounts to 1025.7 mm. The predominant forest management type is mixed beech high forest, covering an area of 2,300.48 ha, of which 432.11 ha (18.8%) belong to the middle-aged silvicultural group that constitute the primary focus of this research (Forest Management Plan "Lomnička Reka" 2026 – 2035).

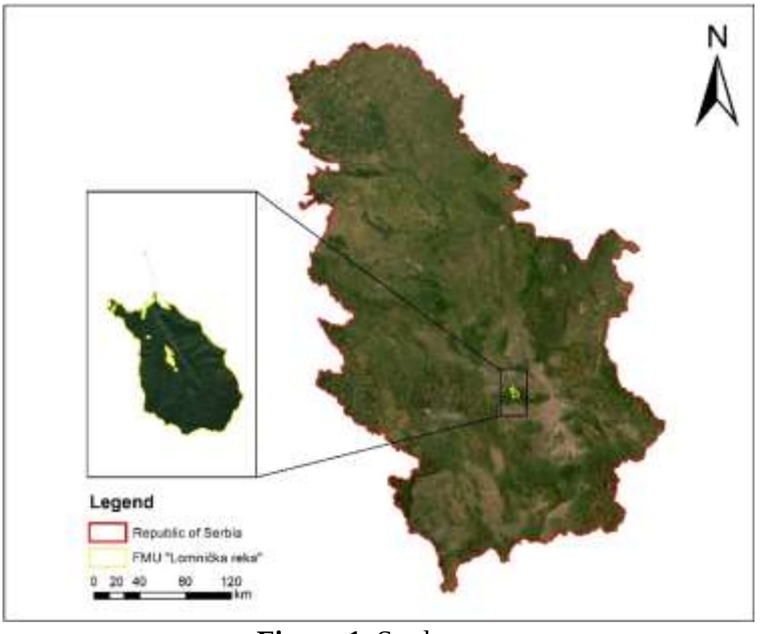


Figure 1. Study area

The data used in this study were obtained from the stand inventory of the analyzed FMU, conducted on a network of permanent sample plots spaced 200 × 200 m apart. Sampling was performed using a system of concentric circular plots with areas of 0.02 and 0.05 ha, followed by field verification to ensure data accuracy. The analysis focused on five structurally uneven-aged stands, encompassing 103 beech trees across eight sample plots belonging to the middle-aged silvicultural group.

For each measured tree, both the live crown ratio and the slenderness coefficient were determined. The live crown ratio (LCR) is defined as the ratio of the length of the live crown to the total tree height:

$$LCR=CL/H$$

where CL represents the crown length (m) and H is the total tree height (m).

The slenderness coefficient (SC) is defined as the ratio of the total tree height to the diameter at breast height, with both measurements expressed in centimeters:

$$SC=H/DBH$$

where H is the total tree height and DBH is the diameter at breast height measured at 1.3 m above ground. Based on SC values, trees were classified into two categories: slender (above 80) and non-slender (below 80) (Pach et al, 2022; Wonn and O`hara, 2001; Skrzyszewski and Pach, 2020).

To identify the critical LCR threshold distinguishing slender from non-slender trees, two statistical approaches were applied. The first was logistic regression, in which the probability of a tree being slender was estimated as a function of LCR. The threshold was defined as the inflection point of the model, corresponding to a 50% probability of slenderness. Logistic regression was used to analyze the effect of the LCR on the probability of a tree being slender. The model is defined by the formula:

$$\ln(P/(1-P)) = \beta 0 + \beta 1 x LCR$$

P represents the probability that a tree is slender, β0 is the intercept, and β1is the coefficient for LCR.

The stability of this threshold was assessed using a bootstrap procedure with confidence interval estimation. The predictive performance of the model was evaluated using the Receiver Operating Characteristic (ROC) curve and the Area Under the Curve (AUC). The ROC illustrates the relationship between sensitivity and the false positive rate, and the AUC quantifies the overall ability of the model to discriminate between slender and non-slender trees.

The second approach applied was the Conditional Inference Tree (CIT), which partitions trees into groups based on LCR and assesses the statistical significance of the splits. Bootstrap analysis was also employed to the CIT threshold to evaluate the reliability of the obtained values.

This combined approach allows both statistical and visual assessment of the relationship between LCR and tree slenderness, with identification of critical thresholds relevant for silvicultural practice. A similar methodological approach has been used for determining the LCR threshold for stability in Turkey oak (*Quercus cerris*) stands (Stancioiu et al, 2021) and to establish habitat thresholds for deadwood, which serve as a basis for management recommendations in European forests (Müller and Bütler, 2010). All data processing and statistical analyses were conducted using R (R core Team, 2025).

3. RESULTS AND DISCUSSION

The descriptive statistics (Table 1) revealed that the mean slenderness coefficient (SC) was 77.81, with values ranging from 34.74 to 143.64. The relatively high standard deviation (24.40) indicates notable variability in tree slenderness within the stand. The average LCR was 0.397, with a range from 0.125 to 0.812, showing a moderate variation among trees (SD = 0.131).

Table 1. *Descriptive statistics of SC and LCR*

Variable	N	Mean	SD	SE	Min	Max
SC	103	77.81	24.40	2.40	34.74	143.64
LCR	103	0.397	0.131	0.013	0.125	0.812

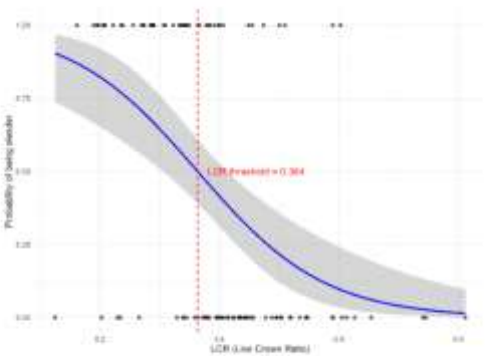
Trees with a high SC are more vulnerable (Šēnhofa et al, 2020), as their stems are not adapted to withstand high mechanical disturbances (Valinger and Fridman, 1997). Studies conducted in beech stands indicate that thinning regimes have a significant effect on the slenderness coefficient, with the lowest values observed in stands managed using the crown thinning method (Stefančík et al., 2018). Research conducted in stands of other tree species likewise underscores the significance of timely and appropriately implemented silvicultural interventions in enhancing stand stability and resilience. The study of the effects of stocking and thinning on wind damage in *Pinus radiata* plantations indicated that the SC is a significant indicator of tree stability. Lower stocking density and appropriate thinning reduce slenderness, increase stem diameter, and promote the development of crowns and roots, which significantly reduce the risk of stem breakage and wind damage (Cremer et al, 1982). Similar results were obtained in the studies of Douglas-fir plantations, where the importance of timely thinning was highlighted, and early interventions were shown to reduce SC and increase tree stability (Wilson and Oliver, 2000). Therefore, the SC can be used as a practical indicator in the planning of silvicultural management measures.

The estimated coefficients show that the intercept was 3.4218, while the coefficient for LCR was -9.4111, which was statistically significant ($p < 0.001$). The positive intercept indicates that when LCR = 0, the probability of a tree being slender is high, whereas the negative LCR coefficient indicates increasing LCR decreases the probability of slenderness (Table 2).

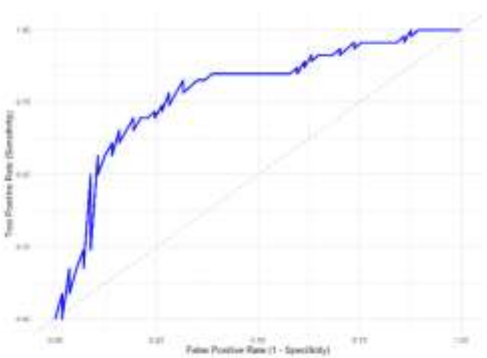
Table 2. *Results of Logistic regression*

Predictor	Estimate	Std. Error	Z value	p value	Inflection point (LCR)	AUC
Intercept	3.4218	0.8903	3.843	0.0001	0.364	0.785
LCR	-9.4111	2.2792	-4.129	0.000036		

This result confirms the inverse relationship between LCR and tree slenderness, which is consistent with expectations and previous studies. Based on the estimated coefficients, the model's inflection point– the LCR threshold at which the probability of slenderness is 50%– was calculated as 0.364 (Graph 1). This threshold represents a practical boundary for distinguishing between slender and non-slender trees and may serve as a guideline in silvicultural practice, for instance, in planning thinning treatments or selecting trees for removal. The predictive performance of the model was evaluated using the ROC curve (Graph 2), with an AUC of 0.785 (Table 2), indicating a good ability of the model to discriminate between slender and non-slender trees and confirming that LCR can be a reliable predictor of tree slenderness in the analyzed sample.

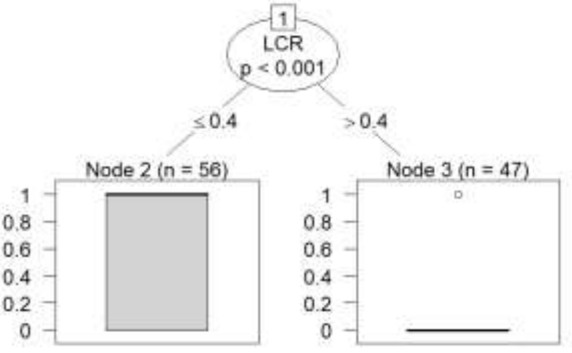


Graph 1. *Logistic regression: Slenderness ~ LCR*



Graph 2. *ROC curve*

The analysis using the CIT model divided the trees into two statistically significant groups based on LCR values: trees with LCR ≤ 0.4 were predominantly slender, whereas trees with LCR > 0.4 largely belonged to the non-slender category (Graph 3). Similar results from previous studies, based on the regression model, indicate that in order for European beech trees (*Fagus sylvatica* L.) to maintain a SC below 100, the LCR should be at least 0.4 (Turtoi et al., 2019).



Graph 3. *Conditional Inference Tree (CIT)*

Table 3. *Bootstrap estimation of the LCR threshold derived from logistic regression and CIT models*

Method	Mean LCR Threshold	95% Confidence Interval
Logistic Regression	0.3637	0.3113 – 0.4095
CIT	0.3688	0.3227 – 0.4062

Bootstrap analysis was applied to assess the stability of the LCR threshold estimated from both the logistic regression and the CIT models (Table 3). For the logistic regression, the mean LCR threshold was 0.3637, with a 95% confidence interval ranging from 0.3113 to 0.4095. This value represents the inflection point at which the probability of a tree being slender equals 50%, thus providing a practical boundary between slender and non-slender trees. For the CIT model, the mean bootstrap threshold was 0.3688 (95% CI: 0.3227–0.4062), clearly separating trees into two groups according to LCR, where lower LCR values indicate predominantly slender trees and higher values correspond to non-slender trees. The close agreement between the thresholds obtained from both statistical approaches indicates the robustness of the estimated critical LCR value and supports the reliability of LCR as a predictor of tree slenderness within the studied stand. Results from previous studies indicate similar LCR threshold values, around 0.36–0.39, highlighting their importance for ensuring tree stability and suggesting that this range can serve as a practical guideline for determining the optimal timing of thinning interventions in young Turkey oak stands (Stancioiu et al, 2021).

4. CONCLUSION

The analysis revealed a clear negative relationship between the live crown ratio (LCR) and the slenderness coefficient (SC), confirming that trees with a higher LCR—i.e., longer live crowns—are less likely to be slender and therefore more stable. The identified LCR threshold range of 0.36–0.40 provides a practical criterion for distinguishing slender and stable trees and can guide the timing and intensity of thinning and other silvicultural interventions. Both species-specific traits and stand and site conditions influence LCR and SC, indicating that thresholds may vary under different ecological circumstances. Future research should explore additional factors such as soil conditions, slope, exposure, and competition dynamics, particularly in the context of climate change, to refine these thresholds.

Due to the limited spatial coverage and specific site conditions, the identified live crown ratio (LCR) threshold should be regarded as an indicative value applicable to the studied stands. Nevertheless, these results can serve as a basis for future research that, through a larger and more diverse sample, could verify and confirm this threshold, as well as explore its potential applicability in a broader ecological context. Incorporating LCR assessments into forest inventories allows for more informed management decisions, helping to reduce the risk of mechanical damage, promote proper stem and crown development, and enhance the structural stability of beech stands.

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REFERENCES

Aaheim, A., Chaturvedi, R. K.,Sagadevan, A.A. (2011). Integrated modelling approaches to analysis of climate change impacts on forests and forest management. *Mitig Adapt Strateg Glob Change* 16, 247–266. https://doi.org/10.1007/s11027-010-9254-x

Banković, S., Medarević, M., Pantić, D., Petrović, N. (2009). Nacionalna inventura šuma Republike Srbije - Šumski fond Republike Srbije, *Ministarstvo poljoprivrede šumarstva i vodoprivrede Republike Srbije -Uprava za šume*, Beograd, 1-244.

Brack, D. (2019). Forests and climate change. *Proceedings of background study prepared for the fourteenth session of the United Nations forum on forests*. New York, NY, USA: United Nations Forum on Forests.

Campbell, J.L., Rustad, L.E., Driscoll, C.T., Halm, I., Fahey, T.J., Fakhraei, H., Groffman, P.M., Hawley, G.J., Leuenberger, W., Schaberg, P.G. (2020). Simulating Impacts of Ice Storms on Forest Ecosystems. *J. Vis. Exp*. (160), e61492, doi:10.3791/61492

Cremer, K.W., Borough, C.J., McKinnel, F.H., Carter, P.R. (1982). Effects of stocking and thinning on wind damage in plantations. *NZ J For Sci* 12, 244–268.

FAO. (2020). Global forest resources assessment 2020—Key findings. Rome.

Forzieri, G., Dakos, V., McDowell, N.G. et al. (2022). Emerging signals of declining forest resilience under climate change. *Nature* 608, 534–539. https://doi.org/10.1038/s41586-022-04959-9

Forest management plan for Forest Management Unit "Lomnička Reka" (2026–2035). *Public Enterprise "Srbijašume"*, 170.

He, L., Zhang, X., Wang, X., Ullah, H., Liu, Y., & Duan, J. (2023). Tree crown affects biomass allocation and its response to site conditions and the density of *Platycladus orientalis* Linnaeus plantation. *Forests*, 14(12), 2433. https://doi.org/10.3390/f14122433

Ibáñez, I., Acharya, K., Juno, E., Karounos, C., Lee, B.R., McCollum, C., et al. (2019). Forest resilience under global environmental change: Do we have the information we need? A systematic review. *PLoS ONE* 14(9): e0222207. https://doi.org/10.1371/journal.pone.0222207

Jucker, T., Fischer, F.J., Chave, J. et al. (2025). The global spectrum of tree crown architecture. *Nat Commun* 16, 4876. https://doi.org/10.1038/s41467-025-60262-x

Kanjevac, B., Račić, M., Dobrosavljević, J., Martać, N. (2023). Responses at the stand and tree level to ice storm injuries in beech forests in Eastern Serbia. *Reforesta* 16:16-26. https://dx.doi.org/10.21750/REFOR.16.02.107

Karamzadeh, S., Nikooy, M., Abkenari, K. T., Tavankar, F., Lo Monaco, A., & Picchio, R. (2023). The Relationship between Stand Structure and Tree Growth Form—Investigating the Effects of Selection Cuttings in Mountainous Mixed Beech Forests. *Forests*, 14(9), 1861. https://doi.org/10.3390/f14091861

Kaźmierczak, K., Jędraszak, A. (2014). The influence of crown length on tree stability. *Žmogaus Ir Gamt. Sauga*, 42-44.

Kirilenko, A. P., Sedjo, R. A. (2007). Climate change impacts on forestry. *Proceedings of the National Academy of Sciences*, 104(50), 19697-19702.

Lidskog, L., Sjödin, D. (2016). Extreme events and climate change: the post-disaster dynamics of forest fires and forest storms in Sweden. *Scandinavian Journal of Forest Research*, 31:2, 148-155, https://doi.org/10.1080/02827581.2015.1113308

Lowman, M. (2021). Life in the Treetops—An Overview of Forest Canopy Science and Its Future Directions. *Plants, People, Planet* 3:16–21.

Marković, M., Rajković, S., Marković, N. (2019). The crown condition of beech trees after the disastrous ice storm on Mt. Crni Vrh. *Sustainable Forestry: Collection*, 78-79, 65-78.

Matsumoto, H., Ohtani, M., Washitani, I. (2017). Tree Crown Size Estimated Using Image Processing: A Biodiversity Index for Sloping Subtropical Broad-Leaved Forests. *Tropical Conservation Science*. 10. https://doi.org/10.1177/1940082917721787

McNeil, B.E., Fahey, R.T., King, C.J., Erazo, D.A., Heimerl, T.Z., Elmore, A.J. (2023). Tree crown economics. *Front. Ecol. Environ*., 21, 40–48.

Müller, J., Bütler, R. (2010). A review of habitat thresholds for dead wood: A baseline for management recommendations in European forests. *Eur. J. For. Res*., 129, 981–992.

Pach, M., et al. (2022). Climate-Smart Silviculture in Mountain Regions. In: Tognetti, R., Smith, M., Panzacchi, P. (eds) Climate-Smart Forestry in Mountain Regions. Managing Forest Ecosystems, vol 40. *Springer, Cham*. https://doi.org/10.1007/978-3-030-80767-2_8

Patton, S.R., Russell, M.B., Windmuller-Campione, M.A., Edgar, C.B. (2019). Modeled diameter growth response to intermediate treatments of planted white spruce (Picea glauca) affected by eastern spruce budworm (*Choristoneura fumiferana*) in Minnesota, USA. *Can. J. For. Res*., 49, 1633–1637.

Pretzsch, H. (2014). Canopy space filling and tree crown morphology in mixed-species stands compared with monocultures, *Forest Ecology and Management*, Volume 327, 251-264, ISSN 0378-1127, https://doi.org/10.1016/j.foreco.2014.04.027

Psistaki, K., Tsantopoulos, G., & Paschalidou, A. K. (2024). An overview of the role of forests in climate change mitigation. *Sustainability*, 16(14), 6089.

R Core Team. (2025). R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria.

Schomaker, M. E., S. J. Zarnoch, W. A. Bechtold, D. J. Latelle, W. G. Burkman, and S. M. Cox. (2007). Crown-classification: A guide to data collection and analysis. USDA Forest Service General Technical Report SRS-102. USDA Forest Service, Southern Research Station, Raleigh, North Carolina.

Shamaki, S. (2022). Relationships between tree slenderness coefficients and stand characteristics for major plantation-grown species in North-western Nigeria. *Journal of Agriculture and Environment*, 18(2), 125-134.

Skrzyszewski, J., Pach, M. (2020). The use of the slenderness coefficient in diagnosing wind damage risks. *Acta Silvestria*, 57, 7-24.

Stajić, B., Vukić, K., Janjatović, Ž., Kazimirović, M. (2017). Efikasnost korišćenja prostora za rast belog jasena (Fraxinus excelsior L.) sa područja Majdanpečke domene. *Glasnik Šumarskog fakulteta*, 115, 99-126. https://doi.org/10.2298/GSF1715099S

Stancioiu, P.T., Serbescu,A.A., Dutcˇa, I. (2021). Live Crown Ratio as an Indicator for Tree Vigor and Stability of Turkey Oak (*Quercus cerris* L.): A Case Study. *Forests*, 12, 1763. https://doi.org/10.3390/f12121763

Stefančík, I., Vacek, Z., Sharma, R.P., Vacek, S., Rösslová, M. (2018). Effect of thinning regimes ongrowth and development of crop trees in Fagus sylvatica stands of Central Europe over fifty years. *Dendrobiology*, 79, 141-155.
http://dx.doi.org/10.12657/denbio.079.013

Šēnhofa, S., Katrevičs, J., Adamovičs, A., Bičkovskis, K., Bāders, E., Donis, J., Jansons, Ā. (2020). Tree Damage by Ice Accumulation in Norway Spruce (Picea abies (L.) Karst.) Stands Regarding Stand Characteristics. *Forests*, 11(6), 679.
https://doi.org/10.3390/f11060679

Tian, X., Sohngen, B., Kim, J. B., Ohrel, S., & Cole, J. (2016). Global climate change impacts on forests and markets. *Environmental Research Letters*, 11(3), 035011.

Triviño, M., Potterf, M., Tijerín, J. et al. (2023). Enhancing Resilience of Boreal Forests Through Management Under Global Change: a Review. Curr Landscape Ecol Rep 8, 103–118. https://doi.org/10.1007/s40823-023-00088-9

Turtoi, A. V., Stancioiu, P. T., Dutcă, I. (2019). The live crown ratio-an indicator for growth vigor of European beech trees (Fagus sylvatica L.). *Romania Revista Padurilor*, Vol. 134, No. 4, 29-40.

Valinger, E., Fridman, J. (1997). Modelling probability of snow and wind damage in Scots pine stands using tree characteristics. *For. Ecol. Manag*., 97, 215–222.

Venäläinen, A., Lehtonen, I., Laapas, M., Ruosteenoja, K., Tikkanen, O. P., Viiri, H., ... & Peltola, H. (2020). Climate change induces multiple risks to boreal forests and forestry in Finland: A literature review. Global Change Biology, 26(8), 4178-4196.

Wang, Y., Titus, S.J., LeMay, V.M. (1998). Relationships between tree slenderness coefficients and tree or stand characteristics for major species in boreal mixedwood forests. *Canadian Journal of Forest Research*. 28(8): 1171-1183. https://doi.org/10.1139/x98-092

Wilson, J. S., Oliver, C. D. (2000). Stability and density management in Douglas-fir plantations. *Canadian Journal of Forest Research*, 30(6), 910-920.

Wonn, H.T., O'Hara, K.L. (2001). Height: Diameter ratios and stability relationships for four northern Rocky Mountain tree species. *Western Journal of Applied Forestry*, Volume 16, Issue 2, 87–94. https://doi.org/10.1093/wjaf/16.2.87

Zarnoch, S.J., Bechtold, W.A.; Stolte, K.W. (2004). Using crown condition variables as indicators of forest health. *Can. J. For. Res*. 34: 1057-1070.

Zhu, Z., Kleinn, K., Nölke, N. (2021). Assessing tree crown volume—a review, Forestry: An International Journal of Forest Research, Volume 94, Issue 1, 18–35.
https://doi.org/10.1093/forestry/cpaa037

LIVE CROWN RATIO AND SLENDERNESS COEFFICIENT AS INDICATORS OF BEECH TREE STABILITY

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Summary

Forest stability is increasingly challenged by the effects of climate change, which can exacerbate the occurrence of extreme events such as storms, ice accumulation, and droughts, posing significant risks to both individual trees and forest ecosystems. Understanding the factors that influence tree and stand stability is therefore essential for sustainable forest management. The live crown ratio (LCR) and slenderness coefficient (SC) have been widely recognized as practical measures of tree stability and vigor. The LCR is defined as the ratio of the length of the live crown to the total tree height, while SC is calculated as the ratio of tree height to diameter at breast height. This study aimed to evaluate the applicability of LCR and SC as indicators of European beech tree stability and to determine critical LCR thresholds that could guide silvicultural interventions.

Research was conducted in the Forest Management Unit (FMU) "Lomnička Reka" in Central Serbia, managed by the Public Enterprise "Srbijašume". The area covers 3,399.96 ha, with elevations ranging from 300 to 1,394 m. The analysis focused on five structurally

uneven-aged stands, encompassing 103 beech trees across eight sample plots belonging to the middle-aged silvicultural group. Data were collected through stand inventories conducted on a network of permanent sample plots (200 × 200 m), using concentric circular plots with areas of 0.02 and 0.05 ha. Field verification ensured the accuracy and reliability of recorded measurements.

For each tree, LCR and SC were determined. Trees were classified as slender or non-slender based on an SC threshold of 80. Two complementary statistical approaches were applied to identify critical LCR thresholds associated with tree slenderness. Logistic regression modeled the probability of a tree being slender as a function of LCR, with the inflection point representing the LCR value at which the probability of slenderness equals 50%. The Conditional Inference Tree (CIT) method partitioned trees into statistically significant groups based on LCR values. Bootstrap procedures were employed for both methods to assess the stability and reliability of estimated thresholds.

Descriptive statistics revealed a mean SC of 77.81, with values ranging from 34.74 to 143.64. The average LCR was 0.397, ranging from 0.125 to 0.812. Logistic regression analysis identified a statistically significant inverse relationship between LCR and SC ($p < 0.001$), with an estimated LCR threshold (inflection point) of 0.364. CIT analysis indicated a similar threshold, with trees having LCR ≤ 0.4 predominantly classified as slender, and those with LCR > 0.4 as non-slender. Bootstrap analysis confirmed the robustness of these thresholds.

The findings highlight the practical importance of crown structure for forest management. Trees with higher LCR values show lower slenderness and greater stability. Maintaining optimal LCR through timely thinning and other interventions can reduce slenderness, support stem and crown development, and lower susceptibility to wind or snow damage. LCR and SC are influenced by species traits, stand density, site conditions, and ecological factors, suggesting that future research should explore additional drivers such as soil, slope, exposure, and competition, especially under climate change.

RELATIVNA DUŽINA ŽIVE KRUNE I KOEFICIJENT VITKOSTI KAO INDIKATORI STABILNOSTI STABALA BUKVE

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Rezime

Stabilnost šuma je sve više ugrožena posledicama klimatskih promena, koje mogu pojačati učestalost ekstremnih događaja kao što su oluje, nakupljanje leda i suše, predstavljajući značajne rizike kako za pojedinačna stabla, tako i za šumske ekosisteme. Razumevanje faktora koji utiču na stabilnost stabala i sastojina stoga je od suštinskog značaja za održivo upravljanje šumama. Relativna dužina žive krune (LCR) i koeficijent vitkosti (SC) su široko prepoznati kao praktične mere stabilnosti i vitalnosti stabala. LCR se definiše kao odnos dužine žive krune I ukupne visine stabla, dok je SC izračunat kao odnos visine stabla i prečnika stabla na prsnoj visini. Ova studija je imala za cilj da proceni primenljivost LCR i SC kao indikatora stabilnosti stabala evropske bukve i da odredi kritične LCR pragove koji bi mogli da usmere šumarsko-uzgojne intervencije.

Istraživanje je sprovedeno u gazdinskoj jedinici (FMU) „Lomnička Reka“ u Centralnoj Srbiji, kojom upravlja Javno preduzeće „Srbijašume“, a koja pokriva ukupnu površinu od 3.399,96 ha i nadmorske visine u rasponu od 300 do 1.394 m. Analiza je bila fokusirana na pet strukturno raznodobnih sastojina, obuhvatajući 103 stabla bukve na 8

primernih površina u srednjedobnoj uzgojnoj grupi. Podaci su prikupljeni putem sastojinske inventure sprovedene na mreži permanentnih primernih povrsina (200 × 200 m), koristeći koncentrične kružne uzorke površine 0,02 i 0,05 ha. Terenska verifikacija je obezbedila tačnost i pouzdanost zabeleženih merenja.

Za svako stablo određeni su LCR i SC. Stabla su klasifikovana kao vitka ili ne-vitka na osnovu SC praga od 80. Primijenjene su dve komplementarne statističke metode kako bi se identifikovali kritični LCR pragovi povezani sa vitkošću stabala. Logistička regresija je modelirala verovatnoću da je stablo vitko u zavisnosti od LCR-a, pri čemu infleksiona tačka predstavlja LCR vrednost pri kojoj je verovatnoća vitkosti 50%. Metoda uslovnog stabla zaključivanja (CIT) je podelila stabla u statistički značajne grupe na osnovu LCR vrednosti. Bootstrap procedure su primenjene za obe metode radi procene stabilnosti i pouzdanosti procenjenih pragova.

Deskriptivna statistika je pokazala prosečan SC od 77,81, sa vrednostima u rasponu od 34,74 do 143,64. Prosečan LCR iznosio je 0,397, sa rasponom od 0,125 do 0,812. Analiza logističke regresije pokazala je statistički značajnu obrnutu vezu između LCR i SC ($p <$ 0,001), sa procenjenim LCR pragom (infleksionom tačkom) od 0,364. CIT analiza je pokazala sličan prag, pri čemu su stabla sa LCR ≤ 0,4 uglavnom klasifikovana kao vitka, dok su stabla sa LCR > 0,4 pripadala ne-vitkoj kategoriji. Bootstrap analiza je potvrdila pouzdanost ovih pragova.

Rezultati ističu praktičnu važnost strukture krune za gazdovanje šumama. Stabla sa većim LCR vrednostima pokazuju manju vitkost i veću stabilnost. Održavanje optimalnog LCR kroz pravovremeno proređivanje i druge mere može smanjiti vitkost, podržati razvoj stabla i krune, i smanjiti podložnost oštećenjima od vetra ili snega. LCR i SC zavise od svojstava vrste, gustine sastojine, uslova staništa i ekoloških faktora, što sugeriše da bi buduća istraživanja trebalo da ispituju dodatne faktore kao što su zemljište, nagib, izloženost i konkurencija, posebno u kontekstu klimatskih promena.