DOI: 10.2478/frp-2018-0008
Available online: www.lesne-prace-badawcze.pl

Leśne Prace Badawcze / *Forest Research Papers*
Marzec / March 2018, Vol. 79 (1): 69–76

ORIGINAL RESEARCH ARTICLE

e-ISSN 2082-8926

Determining the conversion factors for selected lengths of medium-sized pine and spruce wood in the S2 group

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Abstract. The aim of the study was to verify the commonly used conversion factors, their realignment and adaptation to current requirements for wood group S2. Our re-evaluation was based on medium-sized pine and spruce wood between 1 m and 3 m long, with an upper diameter of 5 cm to 24 cm without bark. Measurements were carried out on individual raw material pieces (rollers) as well as entire stacks. In total, 1092.026 steres of pine wood and 482.430 steres of spruce wood from five different forest districts were measured. The conversion factors for both pine and spruce were observed to be generally lower than those currently used in PN-D-95000-2002 and the directives of the General Director of State Forests regarding technical requirements on medium-sized round wood. We also confirmed the dependence between the value of the conversion factor and the average diameter of the roller in the stack, although this was not consistently statistically significant due to the influence of a multitude of factors that potentially cancel each other out. The differences of conversion factors obtained for the S2A and S2B groups suggest that more extensive research for pine and spruce wood as well as the development of separate conversion factors is necessary. However, developing appropriate conversion factors for wood of the S2A group (S2AC and S2AP), especially pine wood, will be challenging due to the large range of diameters and curvature permitted by the regulations.

Keywords: conversion factor, medium-sized wood, measurement of wood in stacks

1. Introduction

The volume of harvested wood raw material can be measured or calculated in various ways and at different stages:

- during harvesting – using the measuring equipment of a harvester,
- after skidding – measuring the stacks (manually or using photo-optical methods), with the use of conversion factors,
- on transport vehicles – manually or using optical methods (industrial cameras or scanning),
- at a wood processing plant – using stationary equipment – scales referenced to the medium-sized timber, and in the case of logs and long wood – 2D scanners, 3D scanners and sometimes even computerised tomography.

The last of these measurement methods is the most accurate, but not all wood processing plants have such modern measuring devices. Moreover, in order for the results of these measurements to be used in trade, the devices should be certified by authorised institutions. Harvester measurements are most often treated as estimates used for initial settlements with the logging contractor (verification of the quantity of harvested timber takes place after measurements are performed at the recipient's site), whereas measurements on transport vehicles are rarely used. The versions using cameras or scanners require additional equipment, such as a frame. However, manual stack measurement is still used to a greater or lesser extent in many countries. The scope of its use depends on the sophistication of logging technologies and the level of development of the wood-processing industry.

In Poland, the medium-sized wood raw material of the S2 group is prepared for transport in regular and irregular stacks (PN-D-95000: 2002). To calculate the volume of the stacked wood, conversion factors are used to determine the ratio of the volume of wood raw material under bark (m^3) to the stack volume (m[p]).

Received: 28.08.2017, reviewed: 26.11.2017, accepted: 13.02.2018

Research on the conversion factor for medium-sized logs has been conducted many times at the Forest Research Institute, starting from the 1950s (Cichowski 1955; Grodzki 1961). The studies were only on pine and spruce wood, about 1 m long or close to that length. Most research on this topic was conducted in the 1970s. At that time, the scope of earlier research was expanded to include medium-sized pine wood of 2.40, 7.0, 6.0 and 5.0 m in length (Cichowski and Makowski 1972, 1973; Cichowski 1978).

Along with changes in the technologies of harvesting, loading and processing wood, a need arose to include conversion factors in the PN-D-95000:1993 standard (amendment of the PN-88-D-95000 standard) for medium-sized timber with lengths longer than 2.40 m, very infrequently applied up to now because of the lack of using forwarders with trailers.

Studies (Cichowski and Makowski 1973; Cichowski 1978; Camp 2012) show that the value of the conversion factors for a given timber assortment depends on a number of elements, namely, diameter and length, care taken during logging practices (mainly the quality of branch removal), the care with which the wood is stacked, curvature, share of bark, taper, size of measured stacks, origin of the timber (mature stand/pre-mature stand, log with a stump/top). Some authors also point to the dependence of the conversion factor on the moisture content of the wood (Ljubojević et al. 2011), which is noticeable the longer it remains in the stack. However, the diameter and length of the wood have a the greatest influence on this value. The higher the diameter of the logs is, the higher is the conversion factor, whereas when the logs are longer, the factor is lower.

In 2011, the Forest Research Institute assessed the conversion factors included in a draft regulation of the Director General of State Forests (Witkowska 2011). The assessment revealed deficiencies in the studies used as the basis for determining the needed factors (Table 1). The deficiencies mostly concerned the conversion factors for certain tree species and the length of assortments included in the PN-D-95000:2002 standard.

The impact of the obsolescence of the conversion factors included in the regulation and developed based on the previously collected data also affected the changes made in the past 25 years and the frequent modifications of the technical conditions required of wood raw material. Therefore, the conversion factors used should be verified, updated and adapted to the current technical requirements.

2. Materials and methods

The research material consists of measurement data from five forest districts: Gidle (Regional Directorate of State Forests [RDSF] in Katowice), Lądek (RDSF in Wrocław), Maskulińskie (RDSF in Białystok), Pińczów (RDSF in Radom) and Przytok (RDSF in Zielona Góra). The study covered medium-sized pine and spruce wood with lengths of 1–3 m and with an upper diameter under bark of 5–24 cm. The study was conducted in 2014–2015 in the field as a part of the work of measuring individual pieces (logs) and long wood of wood raw material. The measurement of the volume of wood stacks was performed as shown in Figure 1.

Table 1. Conversion factors for pine and spruce medium-sized wood, under bark

Wood species	Length [m]	According to the standard PN-D-95000:2002	According to a study
Pine	1.0; 1.2	0.65	0.65–0.70 (Cichowski, Makowski 1973)
	2.0; 2.4	0.62	0.62 (Cichowski 1978)
	3.0	-	-
	4.0	-	-
	5.0	0.60	0.60 (Cichowski 1978)
	6.0	0.60	0.59 (Cichowski 1978)
	7.0	0.60	0.58 (Cichowski 1978)
Spruce	1.0; 1.1; 1.2	0.70	0.70 (Cichowski, Makowski 1973)
	2.0; 2.4	0.67	0.63 mechanical piling 0.67 manual piling (Moskała 1982)
	3.0	0.65	-
	4.0	0.65	-
	5.0	0.65	-
	6.0	-	-
	7.0	-	-

Figure 1. Elements of irregular stack measurement (h_0–h_n – height, *l* – stack length, *s* – stack width)

The wood harvesting method (chain saw or harvester) was not recorded, but in most cases, the wood was extracted and stacked mechanically using forwarders or forest tractors with trailers. Only part of the spruce and pine (1.2 m) logs were stacked by hand.

Measurements of the length (*l*), width (*s*) and height (*h*) were made using a tape and measuring rod with an accuracy of 1 cm. The nominal length of the wood was assumed to be the length of the stack. Height measurements of the stacks were made every 1 m on each side.

The so-called 'zero method measurement' of stack height has been used in fieldwork since 2008 to measure the front and back stack sides of medium-sized logs. Taking this measurement into account is required when the wood stacks are irregular. It allows a more accurate calculation of the average stack height to be made. The previous method of calculating stack height, based on starting the height measurements at a distance of 1 or 2 m from the beginning of the stack, was correct only in the case of regular stacks. In irregular stacks, this method inflated their average height, which in turn led to an increase in volume. During the measurements, care was taken to ensure that the height at the 'zero meter' (*h*0) contained at least two logs. The height of the sleepers was not included in the height measurement. Stack width was measured along the bottom edge on both sides of the stack.

The surface area was calculated for the front and back sides of each stack using the arithmetic mean of the height and the width of the stack. The arithmetic mean of the surface areas of both sides multiplied by the length of the stack was its volume. It was expressed using the following formula:

$$V = l \times [(h_0' + h_1' + \ldots + h_n') \times s' / (n'+1) + \\ + (h_0'' + h_1'' + \ldots + h_n'') \times s''/(n'' + 1)] / 2$$

where
V is the stack volume (m[p]),
l is the stack length (log) (m),
s is the stack width (m),
h is the stack height (m),
$n + 1$ is the number of measurements.

The volume of individual logs was calculated based on the mid-diameter under bark. For this purpose, the diameter of each log was measured from both ends, crosswise. The measurements were performed with an accuracy of 1 mm, and then the arithmetic means were calculated. The results of the measurements were used to calculate the average tree taper of the stack, which was the basis for calculating the mid-diameters of individual pieces. Their volume was calculated based on the mid-diameters, rounded mathematically. The simplified formula for log volume (m^3) was

$$V = \pi \times l \times \frac{[2d_g + (l \times z)^2]}{160000}$$

where
l is the log length (m),
dg is the diameter of the thinner (top) end under bark (cm),
z is the tree taper (cm/m).

In order to characterise and compare the conversion factors for individual log lengths, weighed averages, standard deviations (SDs), standard error (SE) means and coefficients of variation (CVs) were calculated. The normality of the distribution of conversion factors was tested using the Shapiro–Wilk test. Owing to the fact that, in the past, a dependence of the conversion factor on various parameters of the wood making up the stack was observed, we decided to examine its dependence on the average diameter of a log in the stack as the parameter most associated with the value of this factor. To this end, we used Spearman's rank correlation. For the analysis of the conversion factors for individual wood lengths, the cluster analysis was used (hierarchical methods and k-means grouping). The calculations were performed using the Statistica 8 statistical package (Statsoft 2008).

If field conditions permitted, the front and back sides of individual wood stacks were photographed.

3. Results and discussion

Medium-sized pine wood

Measurements of the wood raw material were made in Gidle, Maskulińskie, Pińczów and Przytok. The research material consisted of medium-sized pine logs with a total volume of 1092.026 m(p), that is, 682.919 m^3. Wood with a length of 1.2 m totalled 180.951 m(p); a 1.8 m length – 289.597 m(p) and a 2.5 m length – 621.478 m(p), respectively 12, 5 and 18 stacks for a total of 35 analysed stacks.

The wood raw material was classified and recorded to the S2AP and S2BG groups during the measurements (the S2BC group was not measured). The parameters distinguishing the studied groups are the size of the upper diameter under bark and simple or multiple sweep (Table 2).

Both groups, that is, S2AP and S2BG, were measured only in the case of 1.2-m long pine logs. A detailed list of the research results for medium-sized pine logs of the analysed lengths is presented in Table 3.

The weighted average conversion factor for the S2A group timber with a length of 1.2 m was lower than the factor obtained for the S2B group. In the case of one stack of S2A material, the conversion factor was 0.660 (Figure 2) and significantly exceeded the factor values for both groups. This might have been due to the extremely careful arrangement of this stack and very little curvature of the individual pieces. The average conversion factor for the entire S2 group with a length of 1.2 m was 0.622. However, the analysis of variance did not show a significant difference between the average conversion factors for the S2A and S2B groups at the probability level of $p = 0.09$.

In the case of wood with lengths of 1.8 and 2.5 m, only timber in the S2B group was recorded. The weighted average conversion factors for this wood did not differ significantly and amounted to 0.625 and 0.626, respectively.

The results obtained for the S2B group with a length of 1.2 m were slightly lower than those obtained by Cichowski and Makowski (1973) and Cichowski (1978); however, these results are similar to those obtained in the case of longer lengths. The result of the conversion factor for S2A differed significantly from the values obtained earlier, but this is the consequence of the lower technical requirements for this group.

The calculated weighted averages of the conversion factors for particular lengths of wood were characterised by very low variability. The value of the coefficient of variation ranged from 1.9% to 3.5%.

An increase in the average diameter was usually accompanied by an increase in the conversion factor, although the dispersion of this value was sometimes quite significant (Figs. 2–4). In the case of longer medium-sized wood (2.5 m), this may result from the varied care with which the wood raw material was stacked, but not only. A higher bark thickness was visually noted in a wood stack from the Gidle Forest District (volume of 30.276 m^3, average diameter of 17.9 cm) than in the case of other stacks. This distinctly influenced the value of the conversion factor, which amounted to

Table 2. Selected wood parameters of the group S2AP and S2BG

Parameter	S2AP[1]	S2BC[2]	S2BG[2]
Minimum upper diameter without bark	5 cm	Od 5 do 12 cm	≥ 13 cm
Maximal bottom diameter without bark	not limited	not defined	not defined
Simple sweep	acceptable to 12 cm/m	acceptable to 1.5 cm/m (for softwood)	acceptable to 1.5 cm/m (for softwood)
Multiple sweep	permissible amounting to half the amount of simple sweep	permissible amounting to half the amount of simple sweep	permissible amounting to half the amount of simple sweep

1)Zarządzenie nr 33 Dyrektora Generalnego Lasów Państwowych z 17 kwietnia 2012 r.(Zarządzenie 2012a)
2)Zarządzenie nr 34 Dyrektora Generalnego Lasów Państwowych z 17 kwietnia 2012 r. (Zarządzenie 2012b)

Table 3. Research results for medium-sized pine wood

Length [m]	S2AP			S2BG		
	Wighted mean conversion factor (mean ± SE)	Standard deviation SD	Coefficient of variation CV [%]	Wighted mean conversion factor (mean ± SE)	Standard deviation SD	Coefficient of variation CV [%]
1.2	0.617±0.009	0.02768	4.5	0.634±0.006	0.012390	1.9
1.8				0.625±0.005	0.011229	1.8
2.5				0.626±0.005	0.021827	3.5

0.596. This value proved to be significantly lower than that in the case of the conversion factor for a stack with a similar average diameter (17.7 cm) of logs (volume of 41.204 m^3), whose conversion factor was 0.641.

Figures 3 and 4 show distinct groups of points displaying the conversion factors for individual stacks – two clusters in each of the figures. The use of cluster analysis confirmed the existence of these groups, although the differences between them, in relation to the conversion factors, did not turn out to be statistically significant at the probability level of *p* equals to 0.10 and 0.52, respectively. The value of the conversion factors for these groups, determined as a result of the analysis, was 0.612 and 0.628, respectively, for 1.8-m long wood and 0.619 and 0.635, respectively, for 2.5-m long wood. The occurrence of the clusters may suggest the existence of assortment groups for which separate conversion factors should be calculated.

The relationship between the average diameter of a log in the stack and the conversion factor turned out to be very high and statistically significant only for the 1.8-m long wood raw material (Table 4).

Medium-sized spruce wood

The study was conducted on 482.430 m(p), a total of 317.283 m^3 of wood raw material, consisting of 152.692 m(p) with a length of 1.2 m, 110.095 m(p) with a length of 1.5 m, 152.040 m(p) with a length of 2.4 m and 67.603 m(p) with a length of 2.5 m, numbered as 30, 34, 16 and 6 stacks, respectively, for a total of 86 stacks.

The research material was collected from the Lądek Forest District. The limited availability of the wood raw material only allowed us to measure stacks of logs with lengths of 1.2 and 1.5 m in the S2BG group. Timber of the remaining lengths, that is, 2.4 and 2.5 m, consisted only wood raw material in the S2AP group. There was not enough collected data for 2.5-m long wood stacks because of the small amount of this material available during the research period. Detailed results of the research are presented in Table 5.

Table 4. Spearman correlation coefficients for the relation 'diameter – conversion factor' for medium-sized pine wood

Length [m]	N	R	t(N-2)	*p*
1.2 S2A	8	0.43	1.16	0.29
1.2 S2B	4	-0.40	-0.62	0.60
1.8	5	0.90	3.58	0.04
2.5	17	0.47	2.08	0.05

The CV of the conversion factors for individual wood stacks with a log length of 1.2 m (S2B) was 4.8%. Its dependence on the average diameter of the wood was clear

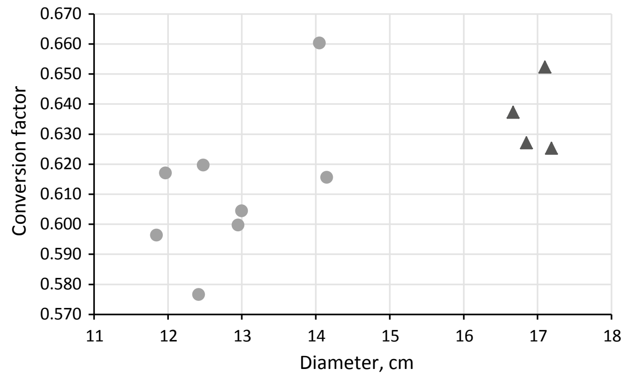

Figure 2. Dependency of the conversion factor on the mean pine roller diameter with the length of 1.2 m: ● − S2A group, ▲ – S2B group

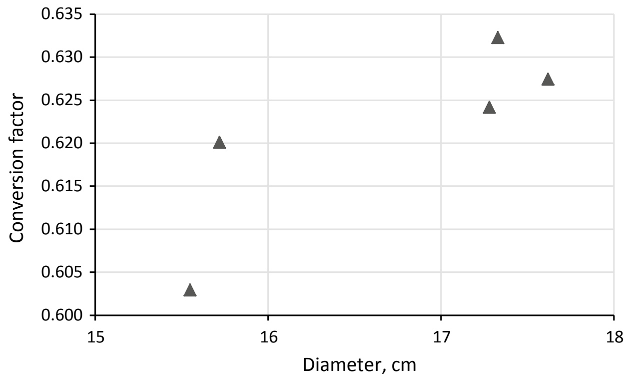

Figure 3. Dependency of the conversion factor on the mean pine roller diameter with the length of 1.8 m

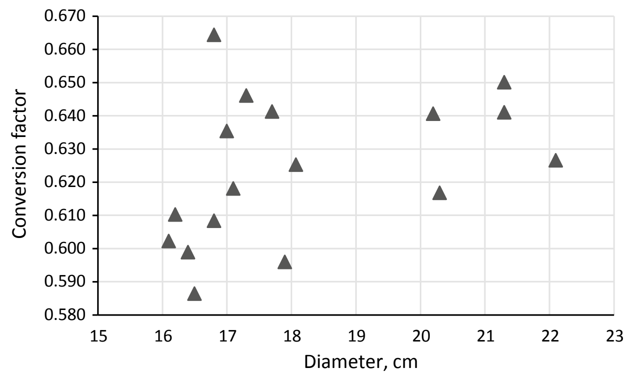

Figure 4. Dependency of the conversion factor on the mean pine roller diameter with the length of 2.5 m

(Figure 5). An increase in the average diameter was accompanied by an increase in the conversion factor. The conversion factor for wood with a diameter of more than 17 cm was higher by approximately 0.050 than the factor for thinner raw material. The applied cluster analysis showed that the difference between these groups was statistically significant at the probability level of $p < 0.001$. The determined average conversion factors for these groups were 0.656 and 0.701, respectively. The average weighted value of the conversion factor for 1.2-m long wood was 0.691 and is close to the result obtained by Cichowski and Makowski (1973).

The coefficient of variation of the conversion factor for 1.5-m long wood (S2B) was 6.2%, even though the average diameter for individual stacks was not highly variable. The conversion factor for the studied wood raw material ranged from 0.643 to 0.798. As a result of the applied cluster analysis (hierarchical method), four groups of conversion factors were distinguished. The analysis of variance showed the existence of significant differences between them at the probability level of $p = 0.01$. The average values of weighted conversion factors for these groups were 0.669, 0.675, 0.681 and 0.747. The average weighted value of the conversion factor for all wood stacks with a length of 1.5 m was 0.683.

Similarly, the relatively high variation of the conversion factor (8.2%) was found for stacks with a length of 2.4 m. In this case, it is more justified. All measured stacks of this length contained wood raw material from theS2A group. The share of logs with a diameter of 5−12.9 cm in individual stacks ranged from 15.0% to 74.0%. The obtained conversion factor for the stack increased as the share of thinner logs decreased. Generally, stacks with an average diameter of 14 cm and higher had a greater conversion factor by about 0.06 in relation to stacks with a smaller average diameter, which was the result obtained from the cluster analysis. The weighted average conversion factors for these groups (Figure 7), which differed significantly, were 0.590 and 0.653, respectively. The average weighted value of the conversion factor for wood with a length of 2.4 m was 0.609. The obtained value is lower by 0.021 than the value obtained by Moskała (1982) for mechanically stacked spruce logs.

The variation in the conversion factor for wood with a length of 2.5 m was low (1.9%). Despite the fact that the wood raw material was not homogeneous in terms of dimensions (from 19.2% to 58.2% of logs with a thickness of 5–12.9 cm), the weighted average conversion factors for the thinner and thicker wood raw material were similar, amounting to 0.646 and 0.654. The value of the weighted average conversion factor for wood with a length of 2.5 m (S2A) was 0.651.

The distribution of the conversion factor depending on the average diameter of a spruce log is illustrated in Figures 5–8. As in the case of pine, a decrease (in general) in the conversion factor is noticeable with an increase in the length of the assortment. The statistical analysis (Table 5) shows a strong significant correlation between the conversion factor and the average diameter for wood with a log length of 2.4 m, and a slightly weaker correlation, although still statistically significant, for wood with a length of 1.2 m. For other lengths, the correlation is poor and not statistically significant.

The research material used to calculate the conversion factors for spruce wood was sufficient only for timber with a length of 1.2 and 1.5 m in the S2B group and 2.4 m in the S2A group. In the case of wood with a length of 2.5 m, the research should be expanded to include material from both groups.

4. Summary

The conversion factors for medium-sized pine and spruce wood included in the PN-D-95000:2002 standard as well as in the General Directorate of State Forests on technical framework conditions are generally higher than those obtained in this research, which indicates the need to correct the factors currently used.

Table 5. Research results for medium-sized spruce wood

Length [m]	S2AP			S2BG		
	Weighted mean conversion factor (mean ± SE)	Standard deviation SD	Coefficient of variation CV [%]	Weighted mean conversion factor (mean ± SE)	Standard deviation SD	Coefficient of variation CV [%]
1.2				0.691±0.006	0.032383	4.8
1.5				0.683±0.007	0.043092	6.2
2.4	0.609±0.012	0.050004	8.2			
2.5	0.651±0.005	0.012687	1.9			

The existence of a dependence between the value of the conversion factor and the average diameter of a log in the stack was confirmed, although this was not always statistically significant. Differences in the strength of the dependence of the conversion factor and the average diameter of the pine and spruce wood raw material may be the result of the influence of many elements sometimes cancelling each other out.

A difference between the conversion factors for the S2AP and S2BG groups of 1.2-m long pine wood was observed. Therefore, research should be expanded to develop different conversion factors for various lengths of medium-sized wood in the S2A and S2B groups (the S2B group includes the S2BC and S2BG groups, which differ by the minimal top diameter value), to eventually take into consideration various categories of cuts, forest habitat types or harvesting methods (harvester/chain saw).

This need is also confirmed by the existence of clusters of conversion factors observed during the analysis of the measurements performed for both pine and spruce wood.

Developing the correct conversion factor for wood in the S2A group (S2AC and S2AP), especially for pine, may be difficult because of the large range of diameters and curvature allowed in the technical requirements for this assortment.

Conflicts of interest

The authors declare no potential conflicts of interest.

Table 5. Spearman correlation coefficients for the relation mean diameter-conversion factor for medium-sized spruce wood

Length [m]	N	R	t(N-2)	p
1.2	30	0.53	3.28	0.00
1.5	34	0.32	1.94	0.06
2.4	16	0.89	7.23	0.00
2.5	6	0.37	0.80	0.47

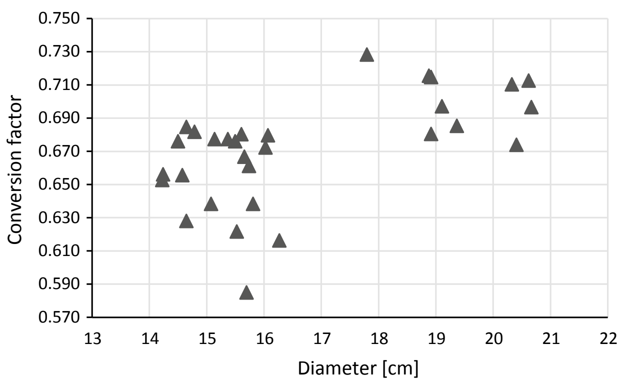

Figure 5. Dependency of the conversion factor on the mean spruce roller diameter with the length of 1.2 m

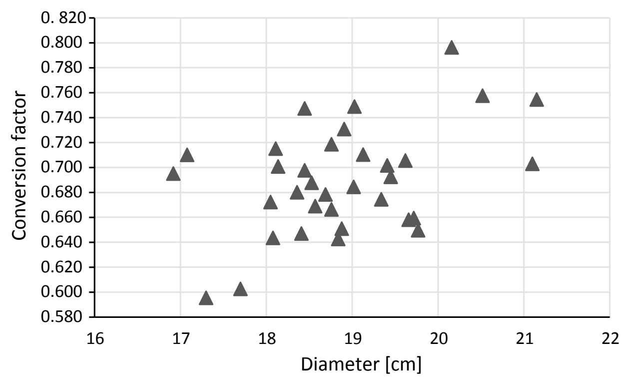

Figure 6. Dependency of the conversion factor on the mean spruce roller diameter with the length of 1.5 m

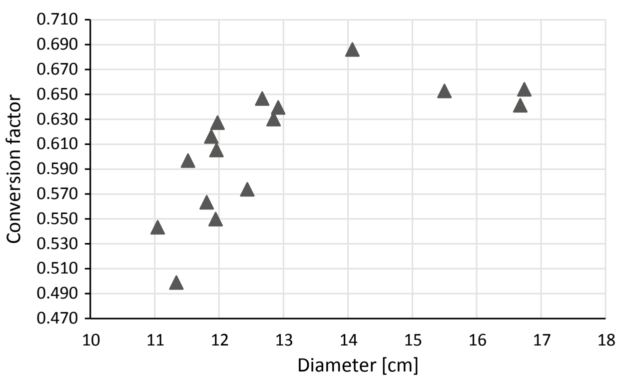

Figure 7. Dependency of the conversion factor on the mean spruce roller diameter with the length of 2.4 m

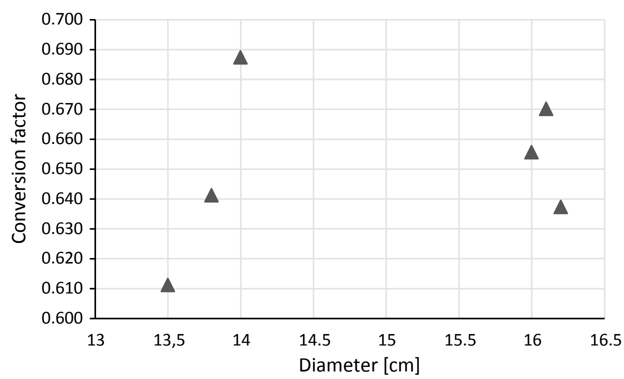

Figure 8. Dependency of the conversion factor on the mean spruce roller diameter with the length of 2.5 m

Acknowledgment and source of funding

The study was performed as a part of a research project entitled 'Determining the conversion factors for selected lengths of pine and spruce long wood and medium-sized logs' commissioned by the General Directorate of State Forests.

The authors would like to thank the employees of the State Forests organisational units where the study was conducted – the regional directorates of the State Forests in Białystok, Katowice, Radom, Wrocław and Zielona Góra and the Forest Districts of Maskulińskie, Gidle, Lądek, Pińczów and Przytok.

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Author's contribution

J.W. – performing the research, concept of the article, literature review, data analysis, writing and correcting the text; K.J. – performing the research, data analysis, statistical calculations, correcting the text, preparing the final version of the article.

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