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STEM VOLUME AND ABOVEGROUND WOODY BIOMASS IN NOBLE FIR (*ABIES PROCERA* REHDER) STANDS IN THE ROGÓW ARBORETUM (POLAND)

Andrzej M. Jagodziński[1,2], Piotr Banaszczak[3]
[1]Poznań University of Life Sciences
[2]Polish Academy of Sciences in Kórnik
[3]Warsaw University of Life Sciences – SGGW, Rogów Arboretum

Abstract. The study was carried out in 39- and 43-year-old stands of noble fir (*Abies procera* Rehder) grown in the Rogów Arboretum of the Warsaw University of Life Sciences (Poland). The main objectives of our study were (1) to estimate stem volume over bark of noble fir grown out of its natural range, (2) to develop suitable allometric equations for estimating aboveground woody biomass components and (3) to estimate aboveground woody biomass components using site-specific allometric equations and to compare them with biomass estimated using allometric equations developed in stands grown within natural range of noble fir. The study showed that the mean DBH of trees was 20.14 cm in the younger stand and 22.25 cm in the older stand. The basal area of the 39-year-old stand was 49.01 $m^2 \cdot ha^{-1}$ and 43-year-old stand was 47.53 $m^2 \cdot ha^{-1}$. Based on the developed equation stem volume over bark was 374.87 $m^3 \cdot ha^{-1}$ and 356.24 $m^3 \cdot ha^{-1}$ in the 39- and 43-year-old stands, respectively. Based on the developed site-specific allometric equations total aboveground woody biomass in the 39-year-old stand was 189 $Mg \cdot ha^{-1}$ whereas in the 43-year-old stand it was 184 $Mg \cdot ha^{-1}$. Branch biomass in both stands equaled 19.9% of total aboveground wood biomass. Total aboveground woody biomass, estimated by allometric equations published by Ter-Mikaelian and Korzukhin [1997], equaled 233 $Mg \cdot ha^{-1}$ and 228 $Mg \cdot ha^{-1}$ in the 39- and 43-year-old stands, respectively. This means that the aboveground woody biomass is overestimated by ca. 23% in comparison with biomass estimated by our site-specific allometric equation. Generally, the existing equations published by Ter-Mikaelian and Korzukhin [1997] overestimated total aboveground woody biomass and stem biomass, while branch biomass was underestimated across all tree sizes compared to directly obtained biomass data.

Key words: noble fir, stand structure, stem volume, woody biomass, allometric equations

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Corresponding author – Adres do korespondencji: Dr inż. Andrzej M. Jagodziński, Department of Forest Protection of Poznań University of Life Sciences, Wojska Polskiego 71 C, 60-625 Poznań, Poland, e-mail: amj@man.poznan.pl

INTRODUCTION

Noble fir (*Abies procera* Rehder; Pinaceae) is an upper-elevation forest tree. Its native range covers the mountains of northern Oregon and Washington between the McKenzie River and Stevens Pass (latitudes 44° and 48°N). Most of its distribution is within the Cascade Mountains, particularly on the western slopes and along the crest, however isolated populations are found on peaks in the Oregon Coast Ranges and in the Willapa Hills of southwestern Washington [Franklin 1964]. The natural range of noble fir lies entirely within a maritime climate with cool summers and mild, wet winters [Franklin 1983, 1990, Grier and Lee 1983]. Annual temperatures average 4.4 to 7.2°C, the mean temperature in January ranges from –4.4 to –1.1°C and in July from 13.3 to 16.1°C, and the annual precipitation averages 1960 to 2650 mm. Most of the precipitation (ca. three-fourths) occurs between October and March [Franklin 1990, Grier and Lee 1983].

Noble fir grows well on a variety of sites. It inhabits rugged, steep slopes, on all landforms, from valley bottom to ridgetop, but grows best on gentle slopes and warm southern aspects. In the northern part of its range, noble fir shows a preference for warm, moist exposures. Water supply appears to be of more importance than soil quality [Fowells 1965, Tumiłowicz 1977, Gessel and Olivier 1982, Franklin 1983]. It is generally found at elevations between 1070 and 1680 m in the Cascade Range in Oregon and 910 and 1520 m in the Cascade Range in central Washington [Franklin 1982, Filip and Schmitt 1990]. However, it is occasionally found at much lower elevations and shows excellent growth on such sites. Noble fir is associated with most other Pacific Northwest conifers at some point in its natural range.

Noble fir is considered a seral or pioneer tree species and one of the most shade intolerant of the American firs [Franklin 1990]. It is an early colonizer after stand-replacing fires. Under a dense closed forest canopy it cannot regenerate successfully [Franklin 1983, 1990]. As with other firs, initial juvenile growth is slow [Franklin 1982, 1983, Harrington and Murray 1982]. It requires 5-12 years to reach breast height, depending on site condition. Growth from a sapling stage to maturity is rapid, allowing noble fir to attain site dominance [Harrington and Murray 1982, Stewart 1986]. As the tree ages, growth slows. Initial growth of noble fir is typically slower than that of associated tree species. It grows most frequently in mixed stands with other species, such as Douglas-fir, western hemlock, and Pacific silver fir [Franklin and Dyrness 1973, Brockway et al. 1985]. It is valuable for timber and greenery products [Betts 1945, Tumiłowicz 1977, Rasmussen et al. 2005]. Noble fir has a greater volume for a given diameter and height than any of its associates and dominates such stands, contributing volume out of proportion to the number of trees. It does grow in nearly pure stands, however, and is capable of producing high standing volumes and good growth over a wide range of ages and site qualities [Fujimori et al. 1976, Franklin 1983, Maze and Parker 1983, Doede and Adams 1998]. In a mixed stand of the Cascade Range in northern Oregon, the average size of noble fir trees grown under favourable conditions was as follows: 10 years – ca. 1.2 m tall, 20 years – ca. 3.6 m tall and 8 cm diameter at breast height, 50 years – ca. 16.1 m tall and 52 cm diameter and 200 years – 44.3 m tall and 84.3 cm in diameter [Hanzlik 1925].

Noble fir is also of interest as an exotic species in Europe and Canada, where provenance evaluations are underway in Great Britain, Germany, and British Columbia

[Fletcher and Samuel 1990, Ying 1992, Xie and Ying 1994, Ruetz et al. 1998]. Foreign species of firs are very rare in Polish forest plantations. From the study conducted by Tumiłowicz and Wodzicki [1990/1991] it appears that *Abies grandis* (Douglas ex D. Don) Lindl. is the best growing and best adapted to the Polish environmental conditions. Similar results were found for that species in Kulej [2003] and Kulej and Socha [2005]. Other fir species, e.g. *A. amabilis* (Douglas ex Loudon) Douglas ex J. Forbes, *A. homolepis* Siebold et Zucc., *A. procera* and *A. veitchii* Lindl. were recognised by Tumiłowicz and Wodzicki [1990/1991] as tolerant to Polish environmental conditions and a potential valuable supplement to timber production. However, the authors stated that *A. balsamea* (L.) Mill., *A. fraseri* (Pursh) Poir., *A. lasiocarpa* (Hook.) Nutt., *A. nordmanniana* (Steven) Spach, *A. sachalinensis* (F. Schmidt) Mast. and *A. sibirica* Ledeb. were not growing well and were not recommended for silvicultural purposes. In an earlier study Tumiłowicz [1965] concluded that there was no reason for introducing *Abies balsamea* and *Abies concolor* (Gordon et Glend.) Lindl. ex Hildebr. into Polish forests on a broader scale since those species grow more slowly than local species and produce wood with lower value. The other studies concerning frost resistance observations on *Abies procera* trees in the Rogów Arboretum of the Warsaw University of Life Sciences showed no injuries during 2005/2006 winter (one of the coldest in recent years). The lowest temperature recorded during the winter was –31.0°C 2 m above the ground level on January 23rd [Banaszczak and Tumiłowicz 2007].

Reliable estimation of stand biomass is essential for a wide range of ecological and land-management applications including primary production, nutrient cycling and forest management. Thus, data on the amount of woody biomass in a stand are necessary to answer many ecological and economic questions. Since detailed measurements are laborious and thus cannot be carried out on a broad scale, allometric equations are developed to estimate tree and stand biomass from diameter at breast height. These allometric models are important for quantifying biomass and carbon storage in forest ecosystems and are widely applied [Ter-Mikaelian and Korzukhin 1997, Zianis et al. 2005, Muukkonen and Mäkipää 2006].

We developed allometric equations for estimating total aboveground woody biomass, as well stem and branch biomass of noble fir (*Abies procera*) trees grown in the Rogów Arboretum of the Warsaw University of Life Sciences. Measurements on model trees can be readily converted to aboveground biomass using site-specific allometric regression equations. Allometric equations for noble fir were previously developed based on trees grown in natural sites by Fujimori et al. [1976] and then summarized by Gholz et al. [1979] and transformed by Ter-Mikaelian and Korzukhin [1997]. Fujimori et al. [1976] and Gholz et al. [1979] developed logarithmic equations for stemwood, stembark, foliage and branch biomass of *Abies procera* based on 6 model trees with DBH range equals 19-111 cm harvested in Wildcat Mountain Research Natural Area (north of Blue River, Oregon, 1300 m a.s.l). Ter-Mikaelian and Korzukhin [1997] converted the Gholz's et al. [1979] equations parameters back to the arithmetic units to make them comparable with those fitted using nonlinear regression of the form $Y = aDBH^b$, where Y is dry biomass of the particular tree component (kg), DBH is diameter at breast height in cm, and a and b are constant equation coefficients. Since site-specific allometric models are generally more accurate for biomass estimation than equations developed in other site conditions, we compared both equations types with directly measured biomass of model trees to check for potential differences between the biomass of model trees and biomass estimates using site-specific equations and equations published by Ter-Mikaelian and Korzukhin [1997].

Thus, the specific aims of our study were:

1) to estimate the stem volume over bark of the noble fir in stands grown out of its natural range,
2) to develop suitable allometric equations for estimating aboveground woody biomass components in noble fir stands,
3) to estimate aboveground woody biomass components using site-specific allometric equations and to compare them with biomass estimated using allometric equations developed in stands grown within the natural range of this species.

The study focuses on biomass estimation but shall serve as the basis for further investigations of the dependence of nutrient balances on environmental conditions and management intensity.

MATERIAL AND METHODS

The study was conducted in two noble fir (*Abies procera* Rehder) stands with ages of 39 and 43 years in the Rogów Arboretum of the Warsaw University of Life Sciences (SGGW), Poland (51°49'N, 19°53'E). The study plots were located in the central part of the Arboretum. The detailed information for both stands is shown in Table 1.

Table 1. The characteristics of experimental plots (2009)
Tabela 1. Charakterystyka powierzchni doświadczalnych (2009)

Characteristics Charakterystyka	39-year-old stand Drzewostan 39-letni	43-year-old stand Drzewostan 43-letni
Year of stand establishment Rok założenia drzewostanu	1975	1970
Year of seed sprouting Rok skiełkowania nasion	1971	1967
Area in the year of stand establishment Powierzchnia w roku założenia drzewostanu	0.09 ha	0.15 ha
Initial seedling density Zagęszczenie początkowe	3 133 trees$\cdot$ha^{-1}	3 860 trees$\cdot$ha^{-1}
Seed origin Pochodzenie nasion	Hood River Co., Oregon, USA, 45°10’ N, 121°30’ W, ca. 1350 m a.s.l.	Wirty Arboretum, Poland, 53°54’ N, 18°23’ E, ca. 120 m a.s.l.
Initial spacing Więźba początkowa	1.5 m × 1.5 m	1.5 m × 1.5 m

According to long-term meteorological observations (55 years) from the closest meteorological station in Strzelna, mean annual temperature is 7.2°C (January: –3.2°C, July: 17.3°C), mean annual precipitation is 596 mm (404-832 mm, ca. 70% of annual precipitation is in the growing season), and mean growing season length (calculated as the number of days with mean temperature ≥ 5°C) is 212 days [Bednarek 1993].

The study plots are located on flat terrain ca. 189 m a.s.l. The soils were developed on a postglacial formation, in the region of a ground moraine. In the study area, there are forest soils, grey-brown podzolic with horizons O-A-Eet-Bt-C. The pH is 5.0 in the humus layer, 4.2 in the topsoil and 4.8 in the eluvial horizon. They are rich, mesic, with the groundwater level beyond the reach of tree roots [Czępińska-Kamińska et al. 1991].

From the detailed description of the development of the 39-year-old stand, it appears that the culture was protected against pine weevil *Hylobius abietis* L. (Curculionidae) and weed development by mowing. There were 208 trees in the stand in September 1981, 202 trees in September 1982, 196 trees in September 1983 and 185 trees in September 1984 (with 117 trees taller than 1.5 m at the latter date). In September 1984, the mean DBH was 3.8 cm (DBH range: 1-9 cm) and the mean height was 2.5 m. In January 1990, 17 dead trees (most of them less than 0.5 m tall) were harvested. In February 2000 all the trees were pruned up to 2 m height and the next 19 trees were harvested; thus 142 trees remained in the stand. The mean DBH of the trees was 15.6 cm (DBH range: 2-32 cm) while the height of trees ranged from 2 to 12 m. In January 2003 and May 2005, 13 and 5 trees, respectively, were removed from the stand thus 131 trees remained in the stand. The mean DBH of trees was 18.0 cm (DBH range: 4-37 cm) and mean height was 11 m (maximum height was 14 m).

In the first stage of the 43-year-old stand management history, the forest culture was also protected against pine weevil *Hylobius abietis* L. and weed expansion by mowing. There were 424 trees in the stand in September 1984, with a mean DBH equal to 8.2 cm (DBH range 1-16 cm) and mean height of trees equal to 4.3 m. In December 1989, 117 trees were harvested (including 66 trees that were dead), and 307 trees remained in the plot. The mean DBH of trees was 11.3 cm (1-21 cm). In December 1996 all the trees were pruned up to 2 m height. In October 1997, 72 trees were harvested (in that number 17 were dead), and 223 trees remained in the plot. Mean DBH of trees was 16.2 cm (DBH range was 7-31 cm). In the period 2001-2005 the next 45 trees were harvested because of the fir bark beetle *Ips* (*=Pityokteines*) *spinidens* Reitter herbivory. In October 2001, 192 trees were present in the stand; mean DBH was 19.3 (DBH range: 9-36 cm). In May 2005, 170 trees were left in the stand.

At the end of September 2009 we measured diameters at breast height (DBH) and heights of all trees in both stands. All the dead and dying trees (as a result of *Ips* (*=Pityokteines*) *spinidens* Reitter herbivory) were chosen for destructive harvest in each stand, thus we were not able to fully represent the diameter classes present in each stand. In total 28 model trees were harvested for the study. Since the model trees were needleless, we were able to estimate aboveground woody biomass. In two dying trees we noticed some green needles thus the branches were taken to the laboratory and needles were separated from branches for the further study. Dead branches were separated from the main stem and were weighed in the field to obtain their fresh mass. In order to obtain the dry biomass of branches, 3-5 samples from each model tree were taken, weighed in the field and then dried to constant mass at 65°C. The stems were divided into 2.50 m long sections and weighed in the field. To calculate stem dry biomass 10 cm thick cross-sections of stems were cut from the middle of each segment (e.g. 1.25, 3.75, 6.25 m, etc.). The stem samples were oven dried to a constant mass (65°C) in a drier with forced air circulation (ULE 600; Memmert GmbH + Co. KG, Germany). Based on the water content and fresh biomass of the sampled branches and stems, the fresh biomass of the model trees was used to calculate their dry biomass.

To calculate aboveground woody biomass of the trees per stand area we developed best fit allometric equations of the form $Y = aDBH^b$, where Y is the dry biomass of the particular tree component (kg), DBH is diameter at breast height in cm, and a and b are constant equation coefficients. For each of the particular biomass components, we tested different models, and selected the one with the best fit by judging the resulting MSE (mean squared error) and the adjusted coefficient of multiple determination (R^2). The biomass functions were solved for all standing trees to provide an estimate of the plot biomass, which was then scaled up to estimate the biomass per hectare. Allometric equations were developed separately for branch and stem biomass and total aboveground woody biomass. Next we compared the biomass of model trees measured in the field with results of model tree biomass estimated by site specific equations and those published by Ter-Mikaelian and Korzukhin [1997].

We developed an equation for volume calculation of a single tree based on the model trees, and subsequently used that equation to determine stand volume ($m^3 \cdot ha^{-1}$). For this purpose for all model trees, sectional measurements of diameters were made (two perpendicular diameters in the middle of each section with the length of 1 m, e.g. 0.5 m, 1.5 m, 2.5 m, ...) and the stem volume over bark was calculated by the section method of Huber [Bruchwald 1999]. To determine stem volume, the empirical equation was worked out, with tree DBH and height as independent variables of the form:

$$V = a + b\,(DBH)^2\,H + \varepsilon$$

where:

V – stem volume, m^3,
H – tree height, m,
DBH – diameter at breast height, cm,
a, b – equation parameters,
ε – random error.

All statistical analyses were conducted using JMP 8.0 (SAS Institute Inc., Cary, NC, USA; http://www.sas.com/).

RESULTS

The current stand density was 1333 and 1119 trees ha^{-1} in 39- and 43-year-old stands, respectively. The basal area of the younger stand was 49.01 $m^2 \cdot ha^{-1}$ and the older stand was 47.53 $m^2 \cdot ha^{-1}$. The mean DBH of trees in 39-year-old stand was 20.14 cm (±0.72; Standard Error), whereas in 43-year-old stand it was 22.25 cm (±0.57). Diameter at breast height ranged from 4.7 to 48.0 cm in 39-year-old stand and from 10.0 to 47.5 cm in 43-year-old stand. The distribution of DBH in 2-cm wide diameter classes is shown in Figure 1. The mean height of trees in the 39-year-old stand was 12.18 m (±0.24), whereas in 43-year-old stand it was 12.46 m (±0.19). Heights of trees ranged from 4.3 to 17.9 m in the 39-year-old stand and from 7.1 to 18.2 m in the 43-year-old stand.

The empirical equation for stem volume determination of noble firs was as follows ($r^2 = 0.98$, $p < 0.0001$):

$$V = 0.00377849988944945 + 0.0000422950522415144\,(DBH^2)\,H.$$

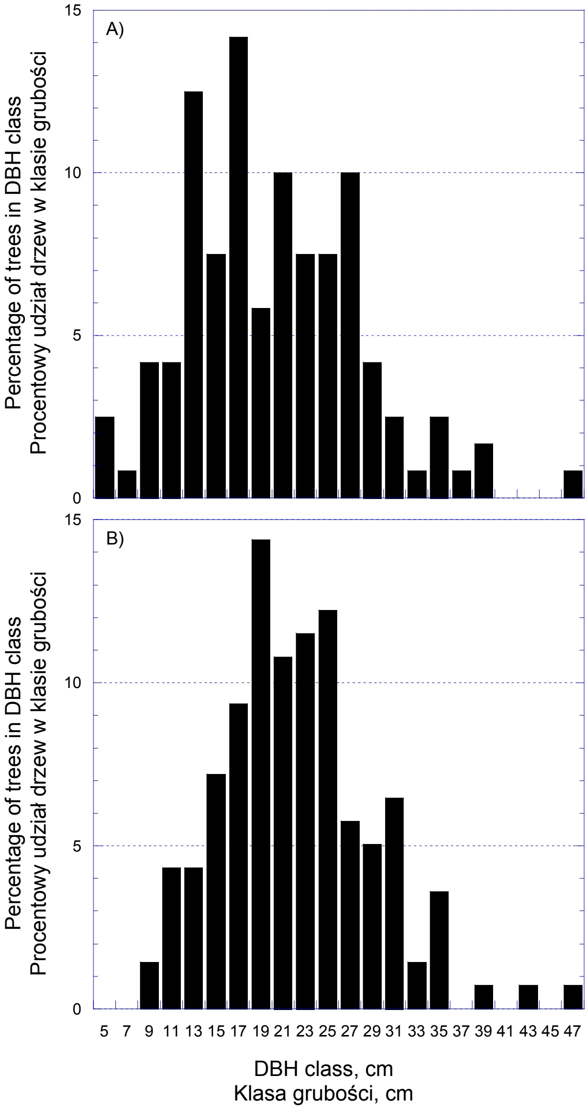

Fig. 1. DBH structure of the noble fir stand: A – 39-year-old, B – 43-year-old
Rys. 1. Struktura grubości drzewostanu jodły szlachetnej: A – 39-letni, B – 43-letni

Based on the equation stem volume over bark was 374.87 $m^3 \cdot ha^{-1}$ and 356.24 $m^3 \cdot ha^{-1}$ in 39- and 43-year-old stand, respectively.

The allometric equations for aboveground woody biomass estimation were developed based on 28 model trees with DBH from 5.2 to 27.45 cm and height from 3.94 to 15.09 m.

The best fitted allometric equation for total aboveground woody biomass (ABW, kg) estimation ($r^2 = 0.99$, $p < 0.0001$) was as follows:

$$ABW = 0.102933857011251 \times DBH^{2.33394904654183}.$$

The best fitted allometric equation for stem biomass (ST, kg) estimation ($r^2 = 0.98$, $p < 0.0001$) was as follows:

$$ST = 0.0879013226342359 \times DBH^{2.31423106485306}.$$

For branch biomass (BR, kg) estimation the best fitted allometric equation ($r^2 = 0.95$, $p < 0.0001$) was as follows:

$$BR = 0.0157376484593473 \times DBH^{2.41514507611827}.$$

Based on the developed site-specific allometric equations, total aboveground woody biomass in the 39-year-old stand was 188 659 $kg \cdot ha^{-1}$, whereas in 43-year-old stand it was 184 201 $kg \cdot ha^{-1}$. In the 39-year-old stand branch biomass was 37 553 $kg \cdot ha^{-1}$ and stem biomass was 151 124 $kg \cdot ha^{-1}$ whereas in the 43-year-old stand branch biomass was 36 707 $kg \cdot ha^{-1}$ and stem biomass was 147 509 $kg \cdot ha^{-1}$. Branch biomass in both stands equaled ca. 19.9% of total aboveground woody biomass. The distribution of total aboveground woody biomass in 2-cm wide diameter classes is shown in Figure 2. The highest proportion of total woody biomass in the 39-year-old stand is in the 27 cm DBH class (16.14%) while in the 43-year-old stand it is in the 25 cm DBH class (13.79%).

Total aboveground woody biomass, estimated by allometric equations published by Ter-Mikaelian and Korzukhin [1997], equaled 232 980 $kg \cdot ha^{-1}$ and 228 279 $kg \cdot ha^{-1}$ in 39- and 43-year-old stand, respectively. This means that aboveground woody biomass is overestimated by ca. 23% in comparison with biomass estimated by our site-specific allometric equation. In the 39-year-old stand, branch biomass was 27 808 $kg \cdot ha^{-1}$ and stem biomass was 205 172 $kg \cdot ha^{-1}$ whereas in the 43-year-old stand branch biomass was 27 151 $kg \cdot ha^{-1}$ and stem biomass was 201 128 $kg \cdot ha^{-1}$, when equations published by Ter-Mikaelian and Korzukhin [1997] were applied. From the comparison of branch and stem biomass of the stands estimated by equations developed by Ter-Mikaelian and Korzukhin [1997] with those estimated by site-specific equations it appeared that equations published previously underestimated the branch biomass by ca. 26% while stem biomass was overestimated by ca. 36%. Branch biomass in both stands equaled 11.9% of total aboveground wood biomass when the biomass components were estimated by those equations.

We also checked for potential differences between the biomass of individual model trees and biomass estimates using the site-specific equations and the equations published by Ter-Mikaelian and Korzukhin [1997]. The differences between measured total aboveground woody biomass of model trees and the biomass estimated by site-specific equations were generally less than the accepted level of 10% [Hamburg 2000]. Only 5 of the 28 model trees had differences that exceeded 10% of measured aboveground woody biomass (from –13.7% to +21.3%; Table 2). Similar differences were obtained for stem biomass where the differences ranged from –14.1% to +29.8% and only for 6 trees were greater than 10% of measured biomass. The greatest differences between the directly measured and estimated biomass were found for branches (from –44.7% to +41.6%). Most of the branch biomass estimations exceed 10% of measured biomass (19 trees).

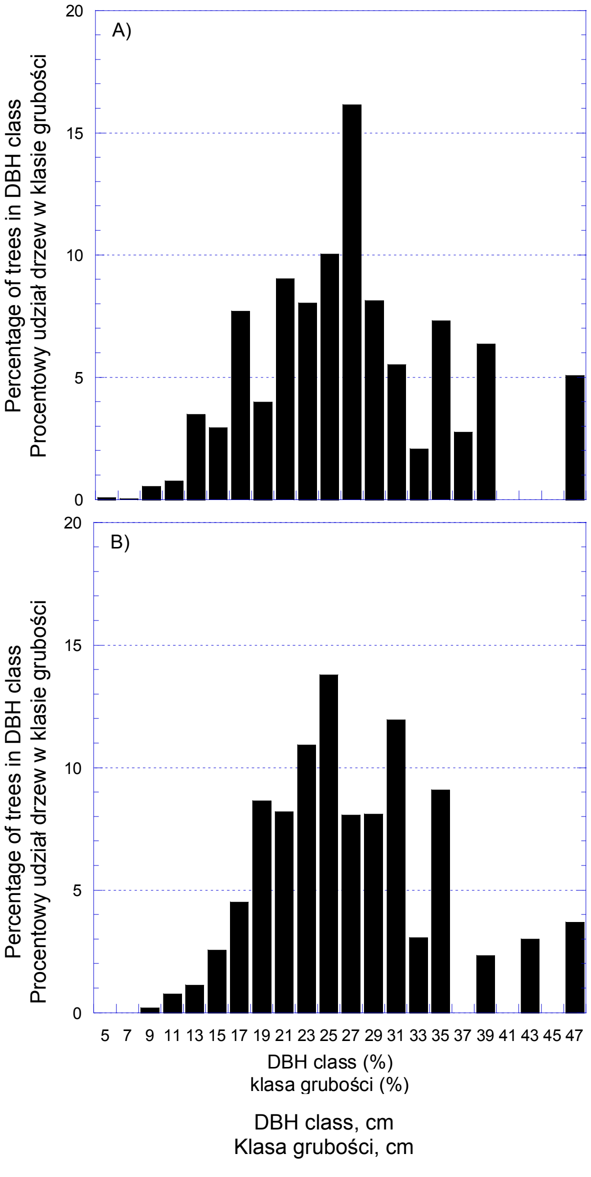

Fig. 2. Percentage of aboveground woody biomass in DBH classes of the noble fir stand: A – 39-year-old, B – 43-year-old

Rys. 2. Udział biomasy zdrewniałej w poszczególnych klasach grubości w stosunku do sumarycznej nadziemnej biomasy zdrewniałej drzewostanu jodły szlachetnej: A – 39-letni, B – 43-letni

Table 2. Diameter at breast height, height, stem volume and biomass of model trees harvested in the study

Tree no. Numer drzewa	Mean DBH Średnia pierśnica cm	Height Wysokość m	Volume Miąższość m^3	Measured biomass of model tree Rzeczywista masa drzewa modelowego kg		
				ABW	ST	BR
1	5.20	4.33	0.0074	5.24	4.24	1.00
2	5.30	3.94	0.0058	4.17	3.21	0.96
3	9.70	6.76	0.0304	22.54	15.67	6.87
4	10.10	6.39	0.0325	22.06	16.98	5.08
5	11.00	7.76	0.0418	28.44	22.23	6.20
6	11.95	8.40	0.0550	32.39	27.65	4.74
7	13.30	9.37	0.0650	35.62	29.86	5.77
8	13.45	9.13	0.0741	47.26	36.66	10.60
9	14.05	9.04	0.0786	51.90	40.49	11.41
10	16.40	11.49	0.1302	71.39	59.63	11.76
11	16.45	12.05	0.1236	61.84	51.87	9.97
12	17.10	11.16	0.1228	70.34	54.87	15.47
13	17.15	11.66	0.1507	83.21	68.61	14.60
14	17.90	11.54	0.1572	78.70	64.60	14.10
15	18.35	11.95	0.1859	89.33	76.81	12.52
16	19.45	10.71	0.1984	105.51	83.94	21.58
17	19.85	12.45	0.2239	112.86	93.35	19.51
18	20.20	12.28	0.2189	116.81	97.14	19.67
19	20.30	11.70	0.2245	115.99	90.04	25.95
20	21.20	13.33	0.2357	133.51	108.12	25.38
21	21.60	12.80	0.2573	132.41	103.81	28.60
22	23.25	13.08	0.3215	160.47	128.38	32.09
23	23.50	12.96	0.3426	189.03	152.41	36.62
24	24.15	14.02	0.3477	186.67	147.51	39.16
25	24.35	13.41	0.3613	172.05	137.05	35.00
26	25.20	12.36	0.3121	178.28	134.73	43.55
27	25.55	14.36	0.3526	186.87	151.25	35.62
28	27.45	15.09	0.4904	233.46	192.15	41.31

Explanations: ABW – total aboveground woody biomass, ST – stem biomass, BR – branch biomass. Percentage values denote differences among particular biomass components estimated by our site-specific allometric equations and by the equations published by Ter-Mikaelian and Korzukhin [1997] and measured values of model tree (100%).

Tabela 2. Pierśnica, wysokość, miąższość strzały oraz masa drzew modelowych pozyskanych na powierzchniach doświadczalnych

Estimated biomass of model trees by our site-specific allometric equations Biomasa drzewa modelowego obliczona za pomocą specyficznych równań allometrycznych kg						Estimated biomass of model trees by Ter-Mikaelian and Korzukhin [1997] equations Biomasa drzewa modelowego obliczona za pomocą równań opracowanych przez Ter-Mikaeliana i Korzukhina [1997] kg					
ABW	%	ST	%	BR	%	ABW	%	ST	%	BR	%
4.83	–7.92	3.99	–5.91	0.84	–15.72	3.28	–37.36	2.57	–39.40	0.71	–28.75
5.05	20.93	4.17	29.83	0.88	–8.07	3.46	–17.20	2.71	–15.64	0.75	–22.41
20.68	–8.22	16.89	7.81	3.80	–44.65	17.54	–22.17	14.49	–7.52	3.05	–55.56
22.73	3.06	18.55	9.23	4.19	–17.42	19.56	–11.30	16.21	–4.54	3.36	–33.92
27.74	–2.45	22.60	1.63	5.15	–16.94	24.63	–13.38	20.54	–7.62	4.09	–34.00
33.66	3.90	27.37	–1.02	6.29	32.74	30.81	–4.89	25.84	–6.54	4.97	4.75
43.21	21.30	35.06	17.44	8.15	41.36	41.16	15.54	34.78	16.50	6.38	10.57
44.35	–6.15	35.98	–1.84	8.37	–21.00	42.43	–10.23	35.88	–2.12	6.54	–38.26
49.11	–5.37	39.81	–1.68	9.31	–18.41	47.75	–7.99	40.50	0.03	7.25	–36.47
70.46	–1.30	56.94	–4.51	13.52	14.94	72.61	1.70	62.21	4.33	10.39	–11.64
70.96	14.75	57.34	10.55	13.62	36.66	73.21	18.39	62.74	20.95	10.47	5.03
77.68	10.43	62.72	14.31	14.96	–3.35	81.32	15.61	69.86	27.33	11.46	–25.96
78.21	–6.01	63.15	–7.96	15.06	3.14	81.97	–1.49	70.43	2.66	11.54	–21.01
86.43	9.82	69.72	7.93	16.70	18.47	92.06	16.98	79.32	22.78	12.75	–9.59
91.58	2.53	73.85	–3.85	17.73	41.63	98.48	10.25	84.98	10.64	13.51	7.87
104.91	–0.57	84.50	0.67	20.41	–5.40	115.35	9.33	99.88	19.00	15.47	–28.29
110.02	–2.51	88.58	–5.11	21.44	9.89	121.91	8.02	105.69	13.22	16.22	–16.84
114.60	–1.89	92.23	–5.05	22.36	13.72	127.84	9.44	110.94	14.20	16.90	–14.07
115.93	–0.06	93.29	3.61	22.63	–12.79	129.56	11.70	112.47	24.91	17.09	–34.13
128.28	–3.92	103.14	–4.60	25.13	–0.99	145.78	9.19	126.86	17.33	18.91	–25.49
134.00	1.20	107.70	3.75	26.29	–8.06	153.38	15.84	133.62	28.72	19.76	–30.92
159.12	–0.84	127.71	–0.53	31.41	–2.13	187.37	16.76	163.91	27.68	23.46	–26.90
163.14	–13.70	130.91	–14.11	32.23	–11.98	192.90	2.05	168.85	10.79	24.05	–34.32
173.87	–6.86	139.44	–5.47	34.43	–12.10	207.77	11.30	182.14	23.48	25.63	–34.55
177.25	3.02	142.13	3.70	35.12	0.33	212.49	23.50	186.36	35.98	26.13	–25.35
192.02	7.71	153.87	14.20	38.15	–12.39	233.29	30.85	204.98	52.14	28.31	–35.00
198.31	6.12	158.86	5.03	39.45	10.73	242.21	29.62	212.98	40.82	29.23	–17.94
234.45	0.42	187.55	–2.39	46.91	13.54	294.47	26.13	259.92	35.27	34.55	–16.36

Objaśnienia: ABW – sumaryczna nadziemna biomasa części zdrewniałych drzew modelowych, ST – biomasa strzały, BR – biomasa gałęzi. Wartości procentowe wskazują różnice pomiędzy masami uzyskanymi na podstawie równań allometrycznych specyficznych oraz opublikowanych przez Ter-Mikaeliana i Korzukhina [1997] w stosunku do rzeczywistych mas drzew modelowych (100%).

The differences between the measured total aboveground woody biomass of model trees and biomass estimated by equations published by Ter-Mikaelian and Korzukhin [1997] were generally greater than 10% (Table 2). The differences ranged from –37.4% to +30.9% for total aboveground woody biomass, from –39.4% to +52.1% for stem biomass and from –55.6% to +10.6% for branch biomass. Generally, the existing equations published by Ter-Mikaelian and Korzukhin [1997] overestimated total aboveground woody biomass and stem biomass, while branch biomass was underestimated across all tree sizes compared to directly obtained biomass data.

DISCUSSION

Young stands of noble fir can be highly productive. For example, Murray [1988] found that standing volume of noble fir grown in western Washington was ca. 241 $m^3\cdot ha^{-1}$ 30 years after planting and more than half of this volume was in trees 25.4 cm in diameter at breast height or larger. In the mentioned study diameters at breast height ranged from 17.78 to 30.48 cm (mean DBH was 24.13 cm) and stand density was 740 $trees\cdot ha^{-1}$. Moreover, Murray [1988] estimated noble fir volume in 50-year-old stand as ca. 680 $m^3\cdot ha^{-1}$, stand density as ca. 640 $trees\cdot ha^{-1}$, and mean DBH as 33.27 cm. Noble fir also grows well in European countries. For example in Northern Ireland it grows straight and vigorous even on dry sites at relatively high elevations [Redmond 1950], while in France it has had good stem form, height increment, and high timber quality [Laurens and Kazandjian 1985]. Thirty-two to thirty-four year old noble fir stands in Great Britain produce total yields (e.g. standing crop plus cumulative thinning volume) of ca. 210 to 560 $m^3\cdot ha^{-1}$, depending on yield class [Edwards and Christie 1981]. A highly productive 50-year-old Noble fir stand was also described from Germany – on the best site conditions it reached a stem volume of 635 $m^3\cdot ha^{-1}$ and a tree height of 26.2 m [Schübeler et al. 1990]. Another study conducted in 30-year-old noble fir – western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stand in Washington Cascade Range (at elevation ca. 850 m a.s.l.) showed that total stand volume was ca. 510 $m^3\cdot ha^{-1}$, of which noble fir volume was ca. 410 $m^3\cdot ha^{-1}$ [Murray 1978]. In our study, standing volume was 375 $m^3\cdot ha^{-1}$ in the 39-year-old stand and 356 $m^3\cdot ha^{-1}$ in the 43-year-old stand. Thus total stand volume obtained in the study was fairly similar to the results described in other studies.

Our data shows that *Abies procera* grown in the Rogów Arboretum has higher mean diameter at breast height and total basal area and lower mean heights of trees than native silver fir (*Abies alba* Mill.) of the same age given as model values from yield tables by Szymkiewicz [1966]. For example according to Szymkiewicz [1966] in a high quality 39-year-old silver fir stand, the mean height of trees was 12.64 m, the mean diameter at breast height was 11.22 cm, stand density equaled 3520 $trees\cdot ha^{-1}$ and basal area was 33.58 $m^2\cdot ha^{-1}$. Total stem volume of all trees in the stand equaled 338 $m^3\cdot ha^{-1}$. In a 43-year-old silver fir stand, the mean height of trees was 15.04 m, the mean diameter at breast height was 13.76 cm, stand density equaled 2690 $trees\cdot ha^{-1}$ and basal area was 39.0 $m^2\cdot ha^{-1}$. Total stem volume of all trees in the stand equals 437 $m^3\cdot ha^{-1}$. The differences among dimensions of noble fir and silver fir of the same age may be a result of variable growth dynamics in the youngest phases of stand development and variable stand management trajectories. It is reflected to a considerable degree in stand density –

model values of stand density for silver fir from yield tables by Szymkiewicz [1966] are ca. 2.5 fold higher than for the noble fir stands studied.

Results of the study showed considerable differences between aboveground woody biomass estimated using site-specific equations and equations developed by Ter-Mikaelian and Korzukhin [1997]. The data revealed that the total aboveground woody biomass of 39- and 43-year-old stands was ca. 188.7 $\mathrm{Mg{\cdot}ha^{-1}}$ and 184.2 $\mathrm{Mg{\cdot}ha^{-1}}$, respectively, when biomass was estimated by our site-specific allometric equation and 233.0 $\mathrm{Mg{\cdot}ha^{-1}}$ and 228.3 $\mathrm{Mg{\cdot}ha^{-1}}$, respectively, when biomass was estimated by allometric equations developed by Ter-Mikaelian and Korzukhin [1997]. This means that aboveground woody biomass is overestimated by ca. 23% in comparison with biomass estimated by our site-specific allometric equation. These differences may be due to differences in environmental conditions in which stands grow, and stand structure resulting from changes in tree growth trajectory, age and forest management history. During ca. 50 years of noble fir cultivation in the Rogów Arboretum, high natural mortality of trees resulted in gap development. This may be a result of relatively low precipitation (ca. 600 mm annually) in comparison with natural range of this species (1960 to 2650 mm) and periodic freezing of the youngest shoots in spring [Tumiłowicz, personal communication]. As a consequence the trees are weakened and thus more susceptible to bark beetle herbivory.

It is evident that biomass equations published by Ter-Mikaelian and Korzukhin [1997] may not be suitable to satisfactorily estimate biomass accumulation and proportional allocation in stands growing in the Rogów Arboretum. Our allometric equations were developed based on model trees with DBH from 5.2 to 27.5 cm and height from 3.9 to 15.1 m, while Ter-Mikaelian and Korzukhin [1997] developed allometric equations based on trees with diameters range from 19 to 111 cm. The differences between measured total aboveground woody biomass of individual model trees and estimated by site-specific equations were generally lower than the accepted level of 10% [Hamburg 2000]. This indicates that the differences in the DBH range of the model trees may be partly responsible for the obtained differences in total woody biomass and its components. Our study provided evidence that the previously published biomass equations may not be suitable to estimate aboveground wood biomass accumulation in noble fir stands growing in the Rogów Arboretum.

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MIĄŻSZOŚĆ STRZAŁ I NADZIEMNA BIOMASA ZDREWNIAŁA DRZEWOSTANÓW JODŁY SZLACHETNEJ (*ABIES PROCERA* REHDER) W ARBORETUM W ROGOWIE (POLSKA)

Streszczenie. Badania wykonano w dwóch drzewostanach jodły szlachetnej (*Abies procera* Rehder), 39- i 43-letnim, rosnących w Arboretum SGGW w Rogowie (Polska). Celem badań było (1) określenie miąższości strzał w korze drzewostanów jodły szlachetnej rosnącej poza granicami naturalnego zasięgu występowania, (2) opracowanie równań allometrycznych służących do obliczania nadziemnej zdrewniałej biomasy jodeł oraz (3) obliczenie sumarycznej nadziemnej biomasy drzew z wykorzystaniem specyficznych równań allometrycznych i jej porównanie z biomasą obliczoną na podstawie równań allometrycznych opracowanych dla drzewostanów rosnących w granicach naturalnego zasięgu występowania jodły szlachetnej. Na podstawie uzyskanych danych wykazano, że średnia pierśnica drzew w młodszym drzewostanie wynosi 20,14 cm, natomiast w starszym 22,25 cm. Sumaryczne pole powierzchni przekroju pierśnicowego 39-letniego drzewostanu wynosi 49,01 $m^2 \cdot ha^{-1}$, a drzewostanu 43-letniego – 47,53 $m^2 \cdot ha^{-1}$. Miąższość strzał w korze 39-letniego drzewostanu wynosi 374,87 $m^3 \cdot ha^{-1}$, a drzewostanu 43-letniego – 356,24 $m^3 \cdot ha^{-1}$. Na podstawie równań allometrycznych, opracowanych w oparciu o 28 drzew modelowych, określono nadziemną biomasę zdrewniałą, która w młodszym drzewostanie wynosi 189 $Mg \cdot ha^{-1}$, a w starszym – 184 $Mg \cdot ha^{-1}$. Biomasa gałęzi stanowi w obu drzewostanach 19,9% sumarycznej nadziemnej biomasy zdrewniałej drzew. Sumaryczna nadziemna biomasa zdrewniała obliczona z wykorzystaniem równań allometrycznych opublikowanych przez Ter-Mikaeliana i Korzukhina [1997] wynosi 233 $Mg \cdot ha^{-1}$ i 228 $Mg \cdot ha^{-1}$, odpowiednio dla 39- i 43-letniego drzewostanu jodły szlachetnej. Uzyskane wyniki wskazują, że sumaryczna nadziemna biomasa zdrewniała jest przeszacowana o ok. 23% w porównaniu z wynikami uzyskanymi na podstawie równań allometrycznych specyficznych dla badanych drzewostanów. Zastosowanie równań opublikowanych przez Ter-Mikaeliana i Korzukhina [1997] prowadzi do przeszacowania sumarycznej nadziemnej biomasy zdrewniałej oraz biomasy strzał przy jednoczesnym niedoszacowaniu biomasy gałęzi drzew modelowych.

Słowa kluczowe: jodła szlachetna, struktura drzewostanu, miąższość strzał, biomasa, równania allometryczne

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