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ORIGINAL PAPER

Equations for estimating the above-ground biomass of *Larix sibirica* in the forest-steppe of Mongolia

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Abstract: Biomass functions were established to estimate above-ground biomass of Siberian larch (*Larix sibirica*) in the Altai Mountains of Mongolia. The functions are based on biomass sampling of trees from 18 different sites, which represent the driest locations within the natural range of *L. sibirica*. The best performing regression model was found for the equations $y = (D^2 H)/(a+bD)$ for stem biomass, $y = aD^b$ for branch biomass, and $y=aD^b H^c$ for needle biomass, where D is the stem diameter at breast height and H is the tree height. The robustness of the biomass functions is assessed by comparison with equations which had been previously published from a plantation in Iceland. There, $y=aD^b H^c$ was found to be the most significant model for stem and total above-ground biomasses. Applying the equations from Iceland for estimating the above-ground biomass of trees from Mongolia resulted in the underestimation of the biomass in large-diameter trees and the overestimation of the biomass in thin trees. The underestimation of thick-stemmed trees is probably attributable to the higher wood density, which has to be expected under the ultracontinental climate of Mongolia compared to the euoceanic climate of Iceland. The overestimation of the biomass in trees with low stem diameter is probably due to the high density of young growth in the not systematically managed forests of the Mongolian Altai Mountains, which inhibits branching, whereas the plantations in Iceland are likely to have been planted in lower densities.

Keywords: allometry; biomass functions; Central Asia; forest-steppe; Siberian larch

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Introduction

Siberian larch (*Larix sibirica* Ledeb.) is Mongolia's dominant tree species, which covers 80 % of the forested area of the country (Tsogtbaatar 2004). Forests in Mongolia are not systematically managed with a methodology that would ensure sustainability. Rather, logging is largely driven by the demand for construction timber and fuelwood, for which permits are sold by the government. The logging itself is not carried out by foresters, but local stakeholders, including pastoral nomads and wood traders (Lkhagvadorj et al. 2013). A considerable part of wood is harvested illegally (Erdenechuluun 2006).

So far no equations have been empirically established to estimate tree biomass in Mongolian forests. There is a published paper on the assessment of the above-ground biomass in *L. sibirica* forests of southern Siberia and north-eastern Mongolia (Danilin 1995), but this paper just presents area-based estimates without providing any methodical details on the calculation of the biomass data. Models for estimating the above-ground biomass of *Larix sibirica* (Bjarnadottir et al. 2007) or other larch species (e.g. Shi et al. 2002; Novák et al. 2011; Zhao et al. 2011) from stem diameter and height data have been repeatedly published. However, since the Mongolian forests differ from other boreal forests by their location at the southernmost distribution limit of the Eurosiberian taiga forests, we were interested in the question whether the regression models from other areas are transferable to the Mongolian larch forests. The *L. sibirica* forests in Mongolia occur in a vegetation mosaic with steppe grasslands, where forests are limited to relatively moist north-facing slopes, moist valleys or all aspects at high elevation (Hilbig 1995;

Dulamsuren et al. 2005). From south-facing slopes, trees are excluded due to drought. Since *L. sibirica* and other conifers occur in the forest-steppe ecotones of Mongolia at their drought limit, their growth is rather slow as shown by the small annual diameter increment; at many places the annual stem increment is even decreasing due to climate warming (Dulamsuren et al. 2010a, b).

Low annual increment in habitats where woody plants frequently experience drought stress is usually linked with high wood density (Wiemann & Williamson 2002; Martínez-Cabrera et al. 2009). Therefore, we tested the hypothesis that above-ground biomass in *L. sibirica* from Mongolian forests is underestimated by applying regression models obtained in less arid regions. To test this hypothesis, we compared the relationships of above-ground biomass with stem diameter and tree height between *L. sibirica* from the driest conifer forests in Mongolia (located in the Altai Mountains in westernmost Mongolia) and a plantation exposed to very oceanic climate in Iceland, where *L. sibirica* was the most often planted tree species since 1945 and relevant data have been published by Bjarnadottir et al. (2007). The testing of the influence of oceanity on the applicability of the biomass functions was an additional objective in addition to our main aim to development regional biomass equations for *L. sibirica* for the Mongolian forest-steppe. Reliable estimates of tree biomass are not only essential as a planning basis for a sustainable forest management, but also mandatory for future carbon balances of the Mongolian forests.

Materials and methods

Study area and sample plot selection

Trees of *L. sibirica* were sampled in 18 stands of the Altai Mountains in western Mongolia (Fig. 1). The Altai Mountains, located in Central Asia in the border regions of Russia, Mongolia, Kazakhstan and China, stretch out over more than 2,000 km in northwest-southeast direction and reach an elevation of up to 4,500 m a.s.l. Due to their high elevation and the location in Central Asia, the Altai massif creates a highly continental climate in its leeward eastern declivity in western Mongolia. The south-eastern part of the Altai Mountains, the Gobi Altai (up to 3957 m), borders on the Gobi Desert. The more humid north-western part of the Altai Mountains within Mongolia (the Mongolian Altai), which include Mongolia's highest summit of 4,374 m a.s.l. Precipitation in the larch forests of the Mongolian Altai is less than 250 mm·a^{-1}; permafrost is thought to be an important water source for these forests (Sharkhuu and Sharkhuu 2012; Dulamsuren et al. 2013). Most of the precipitation is received in summer.

Eighteen sample plots were selected, 14 of which were located in the western Gobi Altai (in the eastern Gobi Altai only birch forests are found; Miehe et al. 2007) and four of which were located in the Mongolian Altai (Fig. 1; Table 1). Elevation of the plots varied between 2,180 and 2,690 m a.s.l. All plots were located on north-facing (to NW or NE-facing) slopes, as taiga forests in Mongolia's forest-steppe avoid the more xeric south-facing slopes. Since forests in the Gobi Altai and Mongolian Altai consist of often small isolated patches, stands were non-randomly selected for sampling to represent different age and, with it, size classes of larch trees. The mean size of sample plots amounted to 845±140 m^2, but plot sizes varied between 100 and 2,500 m^2 depending on tree size and density (Table 1) to ensure similar sample sizes of trees.

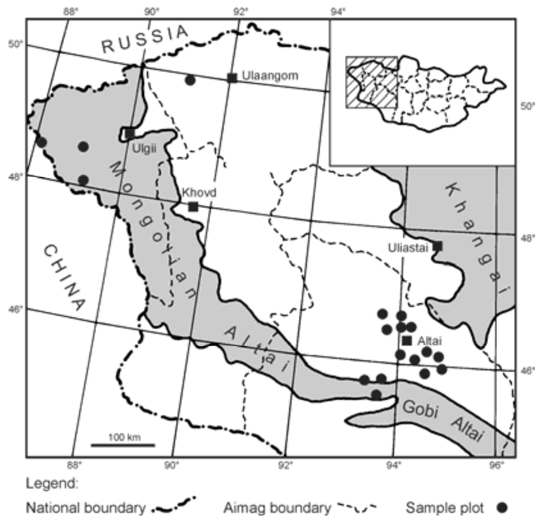

Fig. 1 Location of sample plots in the Mongolian Altai Mountains

Table 1 Geographical data and stand density of the studied larch forests in the Altai Mountains

Plot	Latitude (°N)	Longitude (°E)	Altitude (m a.s.l.)	Aspect	Inclination (°)	Stand density (tree ha^{-1})
1	48°35'	88°35'	2265	N	15	7300
2	46°51'	95°48'	2395	N	15	5350
3	46°50'	95°48'	2550	NE	15	4225
4	46°7'	96°17'	2360	N	10	5400
5	46°5'	96°16'	2330	N	20	1135
6	45°51'	95°50'	2510	N	25	1875
7	49°56'	91°13'	2180	NW	30	555
8	48°15'	88°56'	2375	N	20	820
9	46°50'	95°49'	2545	N	10	210
10	46°50'	95°47'	2500	NE	5	2260
11	46°8'	96°17'	2430	N	20	4000
12	46°50'	95°50'	2470	NE	20	275
13	46°51'	95°51'	2690	N	35	760
14	46°50'	95°48'	2520	N	15	265
15	46°50'	95°48'	2480	NE	15	235
16	48°42'	88°49'	2280	N	25	900
17	45°50'	96°6'	2400	N	30	515
18	46°16'	96°10'	2525	N	30	1030

Stand surveys and biomass sampling

Tree diameter at breast height (1.3 m; DBH) was measured for each tree (*N*=2268) on the sample plots with a caliper. After recording tree diameters in 2-cm classes, one tree per plot representing the mean diameter of the individual site was selected for felling. Felled trees were divided into stem, living branches and dead branches. All branches were removed from the trunks and stems were cross-cut at 1 m intervals. The fresh weight of stem sections as well as living and dead branches was separately determined with a hanging scale in the field with a precision of ±100 g. About 3 cm thick cross-sections from the stem collected each 1 m and branches representing the mean size of branches of the individual sample trees were sampled for determining fresh weight and dry weight after drying the material in the drying oven for 7 days at 105°C. Selected random samples were weighted daily and dried for more than 7 days to ensure that a constant weight had been reached after the 7-days interval. Stem wood and bark as well as branches and their needles were weighted separately. These dry weights were used to estimate the dry weight of the whole tree from the fresh weight using the rule of proportion. Tree height was measured with a Haga Altimeter (Haga Metallwarenfabrik, Nürnberg, Germany) in all felled trees as well as 25±1 trees per plot selecting trees of all available stem diameter classes. Tree age was determined in the harvested trees by counting the tree rings of the basal stem section under the dissecting scope. Destructive sampling in the field was carried out in summer at full foliation.

Statistical analysis

The selection of allometric regression models for estimating the above-ground biomass y (in kg dry weight) of larch from DBH D (in cm) and tree height H (in m) followed Hosoda & Iehara (2010), who modeled the above-ground biomass in *Larix kaempferi* and two further species of coniferous trees:

$$y = aD^b \tag{1}$$

$$y = a(D^2 H)^b \tag{2}$$

$$y = aD^b H^c \tag{3}$$

$$y = (D^2 H)/(a+bD) \tag{4}$$

Especially the equations (1) to (3) are commonly used for modeling above-ground tree biomass in many studies (Zianis et al. 2005; Cienciala et al. 2006). The parameters a, b and c in the models were calculated with SAS 9.13 software (SAS Institute Inc., Cary, North Carolina, U.S.A.). The parameters were determined through nonlinear regression following Payandeh (1981) and Zianis and Mencuccini (2003) assuming an additive error. Models were calculated separately for the stem, branch, and needle biomass. The residuals were tested for homoscedasticity with the Breusch-Pagan test (with $p \leq 0.05$ indicating heteroscedasticity). If heteroscedasticity was found, the data were forced to homoscedasticity by weighted nonlinear regression analysis with the term 1/DBH^2; this term was selected empirically among several relevant functions.

The accuracy of the different biomass estimates from equations (1) to (4) was validated against the measured biomass data using four indices, viz. the root mean square error (RMSE; in kg or %), the mean bias (in kg), and the Fit index (FI):

$$RMSE(\%) = \sqrt{\sum_{i=1}^{n}((y_i - y'_i)/y_i)^2 / n} \cdot 100 \tag{5}$$

$$RMSE(kg) = \sqrt{\sum_{i=1}^{n}(y_i - y'_i)^2 / n} \tag{6}$$

$$Bias(kg) = \sum_{i=1}^{n}(y_i - y'_i)/n \tag{7}$$

$$FI = 1 - \frac{\sum_{i=1}^{n}(y_i - y'_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{8}$$

The independent parameters used in equation (5) to (8) include the observed biomass (y_i), the mean of the observed biomass ($\bar{y}$), the biomass estimated using the Equations 1 to 4 (y'_i), and the number of sample trees (n). The indices used are related parameters to test the deviation of the modeled biomass values from the ones estimated for the harvested trees. The validation procedure also follows closely Hosoda and Iehara (2010).

The total above-ground biomass was calculated as the sum of the best models for stem, branch, and needles biomass $y = y_{stem} + y_{branches} + y_{needles}$ (procedure 1 in Parresol 2001). The biomass equations were then used to analyze the relationships of above-ground biomass with stem diameter and tree height in a larger collective of trees from the studied stands (Table 2).

Table 2. Stand characteristics of the studied larch forests in the Altai Mountains

Plot	Felled trees			Additionally surveyed trees		
	Tree age (year)	DBH (cm)	Tree height (m)	N	DBH (cm)	Tree height (m)
1	53	6	10	20	11.7±0.9	10.1±0.6
2	85	11	10	28	13.6±1.0	9.4±0.4
3	86	7	9	24	14.0±1.1	12.4±0.7
4	93	10	11	19	18.5±1.3	16.5±1.2
5	94	17	15	23	20.0±1.3	14.9±1.0
6	96	12	13	28	15.2±1.1	11.2±0.5
7	98	20	16	24	12.1±0.9	11.0±0.5
8	105	11	11	22	9.8±0.9	10.8±0.5
9	106	12	12	22	9.9±0.9	10.9±0.6
10	108	9	11	21	12.8±1.0	9.0±0.4
11	121	22	14	32	30.3±1.9	15.3±0.4
12	124	10	10	26	9.6±1.0	7.6±0.3
13	128	16	11	27	13.7±1.0	9.4±0.4
14	136	17	12	23	13.1±1.1	11.3±0.7
15	143	12	9	34	19.4±1.3	9.7±0.3
16	145	12	13	23	9.8±0.8	10.4±0.5
17	172	20	17	27	16.5±1.6	13.5±0.7
18	173	20	14	24	14.0±1.1	12.4±0.7

Arithmetic means ± standard errors are presented throughout the paper. The above-ground biomass was calculated with both our own model and the model of Bjarnadottir et al. (2007). For either model, linear regression lines were calculated for logarithmized data of the above-ground biomass versus DBH.

Results

The age range of the 18 harvested larch trees varied between 53 and 173 years, as did the stem diameter (DBH) between 6 and 22 cm and tree height between 9 and 17 cm (Table 2). Diameter and height of these trees matched well with the larger sample of trees which were surveyed for diameter and height, but not harvested (Table 2). In the 18 felled larch trees, tree age was only weakly correlated with DBH (r=0.59, p=0.005) and tree height (r=0.39, p=0.05). Stem diameter could be used to explain 65% of the variation of tree height in linear regression (r=0.81, $p < 0.001$). Total above-ground biomass in the 18 harvested trees varied between 12 kg in a 53-year old tree and 130–155 kg in 172 to 173-year old trees (Table 3). Three-quarters (76±2%) of the total above-ground biomass was allocated in the trunk, whereas the branches accounted for 19±1% and the foliage 5±0% (Table 3).

Table 3 Above-ground biomass (in kg dry weight and percent of the total above-ground biomass) of harvested trees of *L. sibirica* from the Altai Mountains (one tree per plot)

Plot	Total	Stem		Branches		Needles	
1	11.64	9.13	(78 %)	2.07	(18 %)	0.44	(4 %)
2	38.73	26.84	(69 %)	9.34	(24 %)	2.56	(7 %)
3	11.57	8.06	(70 %)	2.94	(25 %)	0.56	(5 %)
4	22.68	20.12	(89 %)	2.04	(9 %)	0.52	(2 %)
5	90.61	73.28	(81 %)	12.84	(14 %)	4.84	(5 %)
6	47.96	37.78	(79 %)	8.30	(17 %)	1.88	(4 %)
7	109.64	94.00	(86 %)	12.38	(11 %)	3.26	(3 %)
8	42.78	26.73	(62 %)	12.10	(28 %)	3.94	(9 %)
9	45.61	35.03	(77 %)	7.49	(16 %)	3.09	(7 %)
10	22.82	18.41	(81 %)	3.44	(15 %)	0.97	(4 %)
11	147.33	101.10	(69 %)	39.12	(27 %)	7.10	(5 %)
12	26.89	18.48	(69 %)	6.95	(26 %)	1.45	(5 %)
13	57.23	46.70	(82 %)	8.10	(14 %)	2.43	(4 %)
14	87.27	59.30	(68 %)	22.81	(26 %)	5.68	(7 %)
15	39.90	25.93	(65 %)	10.75	(27 %)	3.22	(8 %)
16	40.12	31.61	(79 %)	6.85	(17 %)	1.66	(4 %)
17	154.15	128.72	(84 %)	21.67	(14 %)	3.76	(2 %)
18	129.92	96.09	(74 %)	27.42	(21 %)	6.41	(5 %)

Most regression models calculated with the equations (1) to (4) revealed heteroscedasticity in the Breusch-Pagan test (Table 4). Exceptions included the models for branch and needle biomass with equation (3), which were thus selected for examining the goodness of the fit. In all other cases, weighted least square regression was applied to enforce homoscedasticity, which was successful except for the branch biomass in the models with equations (2) and (4). In all cases, except the two models where the original data were homoscedasdic, weighted regression reduced the standard error of the parameter estimates. Therefore, the parameters from the weighted regressions were selected for further quality check in these cases.

The evaluation indexes clearly excluded equation (1) for estimating stem biomass, whereas the three other models yielded rather similar results for stem biomass (Table 5). Since equation (4) with the parameters calculated in weighted regression had the lowest values for bias and percentage RMSE, and the second highest values for absolute RMSE and FI, we selected this equation for estimating stem biomass. For branch biomass, equation (1) with parameter estimates from weighted regression was selected, which had the lowest percentage RMSE and the lowest bias, the second lowest absolute RMSE and the second highest FI. For needle biomass, equation (3) with the parameters estimated with ordinary least square regression yielded the best fit, as indicated by the lowest values for RMSE (percentage and absolute) and bias as well as the highest FI for this equation. The precision of the dry weight estimates was much better for the stem biomass than for branch and needle biomass.

Estimating the above-ground biomass of larch trees from the Mongolian Altai Mountains with the biomass equations obtained from the 18 trees sampled by us in the Altai or with the functions published by Bjarnadottir et al. (2007) from Iceland resulted in similar results (Fig. 2). Biomass was overestimated at low DBH and underestimated at high DBH, when it was calculated with the equations from Iceland. The slope of linear regression lines calculated for the logarithmized biomass versus the logarithmized DBH was steeper if biomass was calculated with the functions from the Altai than with the published functions from Iceland. Overestimation of the total above-ground biomass by applying the equation from Iceland instead of that from Mongolia was much more pronounced in thin trees, where biomass was overestimated by up to 92%, than was the underestimation in large-diameter trees (up to 19%; Fig. 3). The DBH of the larch trees from the sample plots ranged from 2–42 cm (Fig. 4).

Table 4. Regression equations for modeling the stem, branch and needle biomass (in kg dry weight) of Siberian larch with diameter (*D*) at breast height and height (*H*) data

No.	Model	Type[1]	Parameters	SE[2]	R^2	BP[3]
Stem:						
1	$y=aD^b$	N	a=0.1142, b=2.2672	a: 0.07, b: 0.20	0.94	0.01
		W	a=0.1264, b=2.2255	a: 0.04, b: 0.12	0.96	**0.06**
2	$y=a(D^2 H)^b$	N	a=0.0348, b=0.9202	a: 0.01, b: 0.04	0.99	0.008
		W	a=0.0387, b=0.9073	a: 0.01, b: 0.02	0.99	**0.08**
3	$y=aD^b H^c$	N	a=0.0270, b=1.6585, c=1.2143	a: 0.01, b: 0.11, c: 0.14	0.99	0.001
		W	a=0.0320, b=1.7242, c=1.0786	a: 0.01, b: 0.08, c: 0.13	0.99	**0.06**
4	$y=(D^2 H)/(a+bD)$	N	a=40.984, b=0.8401	a: 5.25, b: 0.28	0.99	0.006
		W	a=39.908, b=0.9081	a: 2.99, b: 0.18	0.99	**0.06**
Branches:						
1	$y=aD^b$	N	a=0.0180, b=2.4268	a: 0.02, b: 0.43	0.78	0.008
		W	a=0.0431, b=2.1211	a: 0.04, b: 0.29	0.79	**0.07**
2	$y=a(D^2 H)^b$	N	a=0.0197, b=0.8200	a: 0.03, b: 0.18	0.68	0.002
		W	a=0.0225, b=0.8011	a: 0.02, b: 0.13	0.72	0.03
3	$y=aD^b H^c$	N	a=0.0447, b=3.1777, c=-1.1761	a: 0.06, b: 0.55, c: 0.62	0.83	**0.21**
		W	a=0.1226, b=2.5532, c=-0.8742	a: 0.14, b: 0.43, c: 0.65	0.81	0.25
4	$y=(D^2 H)/(a+bD)$	N	a=243.1, b=-0.5086	a: 159, b: 8.38	0.66	0.002
		W	a=133.0, b=5.6032	a: 82.7, b: 5.11	0.70	0.02
Needles:						
1	$y=aD^b$	N	a=0.0412, b=1.6331	a: 0.04, b: 0.33	0.70	0.04
		W	a=0.0282, b=1.7692	a: 0.02, b: 0.30	0.72	**0.87**
2	$y=a(D^2 H)^b$	N	a=0.0311, b=0.5911	a: 0.04, b: 0.14	0.62	0.008
		W	a=0.0148, b=0.6810	a: 0.02, b: 0.13	0.66	**0.76**
3	$y=aD^b H^c$	N	a=0.1262, b=2.1798, c=-1.0294	a: 0.14, b: 0.45, c: 0.61	0.76	**0.46**
		W	a=0.0955, b=2.2050, c=-0.9464	a: 0.12, b: 0.45, c: 0.73	0.75	0.98
4	$y=(D^2 H)/(a+bD)$	N	a=116.2, b=49.50	a: 334, b: 20.5	0.56	0.008
		W	a=244.3, b=41.09	a: 284, b: 19.8	0.63	**0.49**

[1] N, ordinary least square regression; W, weighted least square regression; [2] Standard error (SE) of parameter estimates a, b, c; [3] Results (*p* value) of Breusch-Pagan test for homoscedasticity (data are heteroscedastic at $p \leq 0.05$); test results which pivotal for the selection of the relevant regression model for further examination are printed in bold.

Table 5. Evaluation indexes according to phytomass components and regression model

Model[1]	RMSE (kg)	RMSE (%)	Bias (kg)	FI
Stem:				
1 (W)	8.9	11.8	0.761	0.936
2 (W)	4.1	5.0	0.046	0.987
3 (W)	3.6	5.1	–0.051	0.989
4 (W)	3.8	4.8	0.001	0.988
Branches:				
1 (W)	4.6	36.3	0.008	0.985
2 (W)	5.4	39.3	0.270	0.979
3 (N)	4.0	56.2	0.529	0.988
4 (W)	5.6	40.7	0.348	0.977
Needles:				
1 (W)	1.1	44.1	0.003	0.999
2 (W)	1.2	45.6	0.049	0.999
3 (N)	1.0	42.6	–0.004	1.000
4 (W)	1.3	47.6	0.008	0.999

[1] Parameters used derive from (N) ordinary least square regression or (W) weighted least square regression.

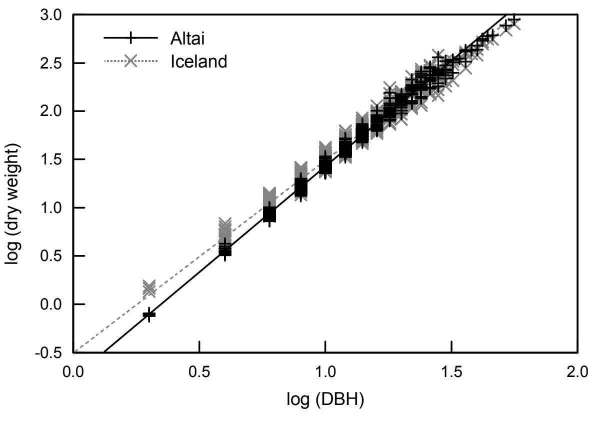

Fig. 2 Total above-ground biomass versus stem diameter at breast height (DBH) in *L. sibirica* (*N*=2268) calculated with the best regression models determined with trees sampled in the Altai Mountains, Mongolia (this study) or Iceland (Bjarnadottir et al. 2007).

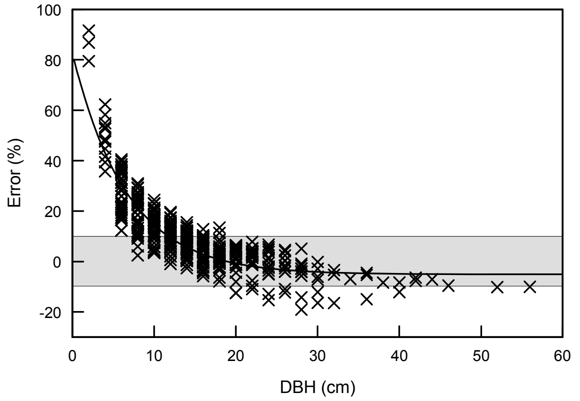

Fig. 3 Error for estimating the total above-ground biomass of *L. sibirica* (*N*=2268) in the Altai Mountains, Mongolia (this study) after the best regression model ($y = aD^b H^c$) from Iceland (Bjarnadottir et al. 2007) instead of Mongolia at varying stem diameters at breast height (DBH). Correlation coefficient of fit: r=0.88, $p<0.001$. Shaded area indicates diameter range within ±10 % estimation error.

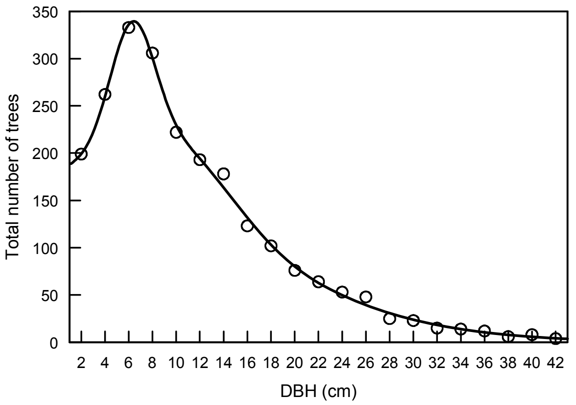

Fig. 4 Stem diameter (DBH) distribution of the sample trees (*N*=2268) growing in the 18 sample plots in the Altai Mountains, Mongolia.

Discussion

Different regression models were found as best fits for above-ground biomass in *L. sibirica* in populations from the Mongolian Altai Mountains (this study) and Iceland (Bjarnadottir et al. 2007). However, except for very thin trees (DBH <10 cm), even the estimates made with the equations of Bjarnadottir et al. (2007) from trees growing under very different climatic conditions in Mongolia lead to similar results as with the functions resulting from tree harvesting in Mongolia. This suggests that the biomass functions are quite robust with respect to varying climatic conditions in the medium-diameter range (especially from ca. 10-30 cm) and can thus be transferred as approximations for biomass estimates even in other parts of the large distribution range of *L. sibirica*. At least our equations can probably also be used in other regions of the Mongolian forest-steppe. Biomass functions which include both stem diameter and tree height as in our models for stem and needle biomass have repeatedly been found to be more precise than equations that are solely based on stem diameter, though the latter type of functions is also often applied because stem diameter is easier to record than tree height (Wirth et al. 2004; Zianis et al. 2005).

The underestimation of the above-ground biomass in the large-diameter trees from Mongolia by using the biomass functions from Iceland (Bjarnadottir et al. 2007) supports the hypothesis that the trees develop a higher wood density in the arid climate of Mongolia than under the oceanic climate of Iceland. This finding is in line with many reports of increased wood density at increased drought from other tree or shrub species (Hacke & Sperry 2001). The overestimation of the above-ground biomass of larch trees from Mongolia with the biomass equations from Iceland might be attributable to differences in the nature of the larch stands at the two places. If regeneration is not suppressed by climate or heavy livestock grazing, young growth of *L. sibirica* in Mongolia often occurs in high densities which are beyond stand densities in silvicultural plantations. The fierce competition of the saplings for space results in a low density of branches and with it low above-ground biomass (Novák et al. 2011).

To our knowledge, the here presented biomass functions are the first ones for *L. sibirica*, which are based on biomass sampling within the natural range of this tree species at least in the English-speaking literature. Biomass production in forests of the Mongolian forest-steppe in currently subjected to substantial increases in temperature and spatially heterogenic changes in precipitation (Li et al. 2009; Dulamsuren et al. 2010b). Tree-ring analyses suggest that larch forests of the Altai Mountains in western Mongolia have increased wood formation as the result of increased temperatures at constant precipitation (D'Arrigo et al. 2000; Dulamsuren et al. 2013). In most areas of central Mongolia, however, increased aridity has resulted in reduced formation of forest biomass (Dulamsuren et al. 2010a, b).

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