Additive allometric model of *Quercus* spp. stand biomass for Eurasia

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Abstract. When using the unique in terms of the volume of database on the level of stand of the genus *Quercus*, the trans-Eurasian additive allometric models of biomass of stands for Eurasian *Quercus* forests are developed for the first time, and thereby the combined problem of model additivity and generality is solved. The additive model of forest biomass of *Quercus* is harmonized in two ways: it eliminated the internal contradictions of the component and the total biomass equations, and in addition, it takes into account regional differences of forest stands not only on total, aboveground and underground biomass, but also on its component structure, i.e. it reflects the regional peculiarities of the component structure of biomass.

Keywords: model’s harmonizing, dummy variables, biological productivity, biomass of forests, genus *Quercus*, sample plots.

1. Introduction

In recent years, the world forest ecology is experiencing unprecedented information splash in the assessment of forest biological productivity in relation to climate change observed since 1960-80-ies (Budyko, 1977). The current hype surrounding the problem of breached the carbon balance of the biosphere passes into the common paradigm of sustainable development, which the first is biosphere-stabilizing function of forests, but traditional resource forest management is seen as a subordinate task (Utkin, 1995). Estimating of biological productivity or carbon-depositing ability of forests is going on the global level, and its increase is one of the major factors of climate stabilization.

The modern methods of modelling the biological productivity of trees and tree stands have been developed towards additivity of biomass components (Bi et al., 2010; Dong et al., 2015) and towards transition from “pseudo-generic” allometric models to really generic, involving regionalization of biomass model by introducing dummy variables (Fu et al., 2012), that usually fulfilled on local sets of actual biomass of trees and tree stands. Because different biomass components are characterized by different rates both their growth and mortality, they make a different contribution to matter cycling in the forest ecosystem and should be estimated not only in total but also separately. Information on component composition of forest biomass was needed in other applications too, in particular, when assessing fire danger and modelling of forest fires (De-Miguel et al., 2014). Additivity of biomass components supposes that the total biomass (stem, branches, foliage, roots), obtained from component equations, should be equal (but usually not equal) to the value obtained using the equation for total biomass. We generated the database of forest stand biomass for the main forest species in Eurasia (Usoltsev, 2010; Usoltsev, 2013), that has enabled these
modern methodologies to be implemented on the entirely different, higher level, namely on modelling additive biomass according to transcontinental level.

In this article, the first attempt to develop transcontinental harmonized allometric model of vicar species oak (genus Quercus) forest stand biomass, which combine both mentioned by Jacobs and Cunia (1980) approaches, namely, ensuring the principle of additivity of biomass component composition and localizing of biomass additive model on regions of Eurasia by introducing dummy variables. In other words, an attempt is made to solve the problems of combining additivity and totality of models. These models will provide the basis for the development of transcontinental regional standards for evaluation biomass of forest stands.

2. Material and methods

Of the database mentioned the material in a number of 367 sample plots with estimations of Quercus forest stand biomass (t/ha) is extracted. Genus Quercus is introduced by five vicarage species (correspondingly Q. robur L., Q. petraea (Matt.) Liebl., Q. mongolica Fisch. ex Ledeb., Q. mongolica subsp. crispula (Blume) Menitsky and Q. glauca Thunb.), distributed across 6 eco-regions and designated respectively with the 6 dummy variables from $X_0$ to $X_5$ (Table 1).

Analysis of biomass forest stands is made on the basis of allometric additive models. According to the structure of disaggregation three-step model (Tang et al., 2000; Dong et al., 2015), biomass value, estimated by the total biomass equation, exploded into components according to the scheme presented in Figure 1. The coefficients of the regression models for all three steps are evaluated simultaneously, which ensures additivity of biomass of all the components – total, intermediate (steps 1 and 2) and initial (step 3a,b) (Dong et al., 2015).

Figure 1. The pattern of disaggregating three-step proportional weighting additive model. Designation: $P_t$, $P_r$, $P_a$, $P_c$, $P_b$, $P_w$, and $P_{bk}$ are stand biomass respectively: total, underground (roots), aboveground, crown (leaves and branches), stems above bark (wood and bark), needles, branches, stem wood and stem bark correspondingly, t per ha

The distribution of sample plots, on which the oak forest biomass is measured in ecoregions of Eurasia, is shown in Figure 2.

Table 1. The encoding scheme of the regional actual biomass data sets of 367 Quercus stands

| Eco-region* | Species** of Quercus | Block of dummy variables | stand age, yrs | tree number, 1000/ha | mean diameter, cm | mean height, m | Plot quantity |
|-------------|----------------------|--------------------------|----------------|----------------------|------------------|----------------|---------------|
| WCE         | Q. robur L.          | 0 0 0 0 0              | 5÷220          | 0.166÷7.00          | 0.9÷55.3         | 2.0÷32.8        | 170           |
| WCE         | Q. petraea (Matt.) Liebl. | 1 0 0 0 0     | 17÷140         | 0.163÷14.92        | 2.3÷46.7         | 3.2÷28.8        | 26            |
| ERn         | Q. robur L.          | 0 1 0 0 0              | 10÷280         | 0.129÷41.19        | 1.5÷70.0         | 2.2÷32.4        | 110           |
| ERs         | Q. robur L.          | 0 0 1 0 0              | 15÷60          | 0.427÷5.67         | 3.9÷23.1         | 4.2÷21.5        | 46            |
| SFE         | Q. mongolica Fisch. ex Ledeb. | 0 0 0 1 0  | 38÷190         | 1.116÷4.91         | 6.7÷28.8         | 6.2÷19.8        | 6             |
| Jap         | Q. mongolica subsp. crispula (Blume) Menitsky Q. glauca Thunb. | 0 0 0 0 1 | 4÷80           | 0.917÷6.78         | 4.2÷18.9         | 4.3÷11.5        | 9             |

* Designates regions hereafter: WCE – Western and Central Europe; ERn – European Russia, northern part; ERs – European Russia, southern part; SFE – South of Far East, Primorie; Jap – Japanese islands.
**nomenclature according to World Flora Online. An Outline Flora of All Known Plants. http://www.worldfloraonline.org
3. Results and discussion

The initial allometric model is calculated;

\[
\ln P_i = a_i + b_i (\ln A) + c_i (\ln A)^2 + d_i (\ln H) + e_i (\ln D) + f_i (\ln N) + \sum g_{ij} X_j,
\]  

(1)

where \( P_i \) – biomass of \( i \)-th component, t per ha; \( A \) – stand age, years; \( H \) – mean stand height, m; \( D \) – mean tree diameter, cm; \( N \) – tree number, 1000/ha; \( a-g \) – regression coefficients; \( i \) – index of biomass component: total (t), aboveground (a), roots (r), crowns (c), stems above bark (s), needles (f), branches (b), stem wood (w) and stem bark (bk); \( j \) – index (code) in the block of dummy variables coding the eco-regions, from 0 to 5 (see Table 1).

Model (1) after anti-log transformation is given to the form:

\[
P_i = a_i A^{b_i} e^{c_i H + d_i D + e_i N + f_i \sum g_{ij} X_j},
\]  

(2)

Characteristic of equations (1) obtained by its approximation using actual biomass data, after the introduction of correction to the logarithmic transformation after Baskerville (1972) and the subsequent anti-log transformation to (2) are given in the Table 2. All the regression coefficients of the equations (2) with numerical variables are significant at the level of probability of 0.95 or higher, and the equations are adequate to actual data.

The equations (2) are modified according to the algorithm proposed by Dong et al. (2015) (Table 3), and the final transcontinental additive model of oak biomass component composition on the level of forest stand is given in the Table 4. The model is valid in the range of actual data of stand age, mean tree height, mean stem diameter and tree density, listed in the Table 1, and is characterized by a double harmonization: one of which provides the principle of biomass component additivity, and the second one relates to the introduction of dummy variables, localizing the model according to ecoregions of Eurasia.

At the next stage of the study a comparison of the adequacy of additive model (Table 4) and independent equations shown in the Table 2. For their correct comparing the sample plots with incomplete biomass component structure are deleted from the initial harvest data, i.e. only those records are left in which the data are available on both aboveground and underground biomass. The equations (2) are approximated according to such “methodized” data, and their final forms are given in the Table 5. As the “methodized” additive model, and “methodized” independent equations, are tabulated according to actual mass-forming indices of the modified data and the obtained values are compared with harvest biomass data using the formula:

\[
R^2 = 1 - \frac{\sum (Y_i - \hat{Y}_i)^2}{\sum (Y_i - \bar{Y})^2},
\]  

(3)

where \( Y_i \) is observed value; \( \hat{Y}_i \) is predicted value; \( \bar{Y} \) is the mean of \( N \) observed values for the same component.

The results of comparison of the adequacy of two modeling methods are summarized in the Table 6 and they indicate that the adequacy of the two systems of equations for
aboveground biomass, underground one and stem biomass are similar.

The ratio of actual values and derived ones by tabulating independent and additive stand biomass models (Fig. 3) shows the degree of correlativeness of the actual and calculated values and, in many cases, the absence of visible differences in the structure of residual variances obtained on two named models. More or less the value of $R^2$ of one or the other model is determined by the random position of actual values of maximum stand biomass in confidence range and uneven dispersion, namely accidental because of their small number and the greatest contribution to the residual variance (see Fig. 3).

Table 2. Characteristic of initial allometric equations for _Quercus_ stands

| Biomass component | Independent variables and the regression model coefficients | $adjR^2$ |
|-------------------|-----------------------------------------------------------|---------|
| $P_{a}$           | $A$ 0.2782 $H$ 0.2576 $D$ 1.0297 $N$ 0.4446 $c$ 0.1913 $x_2$ $c$ 0.1768 $x_5$ | 0.838   |
| $P_{s}$           | $A$ 0.2485 $H$ 0.6724 $D$ 1.0102 $N$ 0.5025 $c$ 0.0950 $x_2$ $c$ 0.0113 $x_3$ | 0.905   |
| $P_{r}$           | $A$ 0.5019 $H$ -0.4844 $D$ 1.0320 $N$ 0.4851 $c$ 0.1441 $x_2$ $c$ 1.1147 $x_3$ | 0.376   |
| $P_{c}$           | $A$ 0.2046 $H$ -0.0329 $D$ 0.9648 $N$ 0.2594 $c$ 0.2557 $x_3$ $c$ -0.2080 $x_3$ | 0.701   |
| $P_{s}$           | $A$ 0.2552 $H$ 0.8867 $D$ 1.0191 $N$ 0.5759 $c$ 0.0554 $x_2$ $c$ 0.0450 $x_3$ | 0.906   |
| $P_{f}$           | $A$ 0.2036 $H$ -0.0256 $D$ 0.7932 $N$ 0.4959 $c$ 0.0914 $x_2$ $c$ -0.0955 $x_3$ | 0.403   |
| $P_{b}$           | $A$ 0.1757 $H$ 0.0475 $D$ 1.0889 $N$ 0.2139 $c$ 0.2846 $x_3$ $c$ -0.2060 $x_3$ | 0.716   |
| $P_{w}$           | $A$ 0.2494 $H$ 1.0440 $D$ 1.0714 $N$ 0.6450 $c$ 0.1402 $x_2$ $c$ 0.1680 $x_3$ | 0.905   |
| $P_{wb}$          | $A$ 0.4244 $H$ 0.2712 $D$ 1.2246 $N$ 0.6314 $c$ -0.0658 $x_3$ $c$ -0.1520 $x_3$ | 0.851   |

Table 3. The structure of three-step additive model built by proportional weighting (Dong et al., 2015). Symbols here and further see Figure 1 and equation (1)
Table 4. Three-step additive model of biomass component composition for *Quercus* forest stands, built by proportional weighing.

| Component | Independent variables and the regression coefficients of the model | $\text{adj}R^2$ |
|-----------|---------------------------------------------------------------|-----------------|
| $P_t$     | $1.3132 A^{0.2782} H^{0.2576} D^{1.0297} N^{0.4448} e^{-0.1913 X_7} e^{0.1274 X_7} e^{0.4569 X_7} e^{0.1768 X_7} e^{0.6994 X_7}$ | 0.838 |
| Step 1    | $P_a = 1.1083 A^{0.4080} H^{-0.0159} D^{1.075} e^{-0.0548 X_7} e^{-0.0852 X_7} e^{0.3569 X_7} e^{-0.5778 X_7}$ | 0.827 |
|           | $P_r = 0.9023 A^{-0.4080} H^{1.0937} D^{0.0159} e^{0.0548 X_7} e^{0.0852 X_7} e^{-0.3569 X_7} e^{0.5778 X_7}$ | 0.841 |
| Step 2    | $P_c = 0.5161 A^{0.0744} H^{0.4267} D^{0.2012} N^{0.1906} e^{-0.5491 X_7} e^{0.0384 X_7} e^{0.6473 X_7} e^{0.1593 X_7} e^{-0.2692 X_7}$ | 0.866 |
|           | $P_s = 1.9377 A^{-0.0744} H^{-0.4267} D^{-0.2012} N^{0.1906} e^{0.5491 X_7} e^{-0.0384 X_7} e^{-0.6473 X_7} e^{-0.1593 X_7} e^{0.2692 X_7}$ | 0.876 |
| Step 3a   | $P_f = 1.1188 A^{-0.0203} H^{0.5680} D^{0.1137} N^{0.1704} e^{0.4780 X_7} e^{0.1106 X_7} e^{0.4056 X_7} e^{0.0355 X_7} e^{1.3188 X_7}$ | 0.627 |
|           | $P_b = 0.8938 A^{0.0203} H^{-0.5680} D^{-0.1137} N^{0.1704} e^{-0.4780 X_7} e^{0.1106 X_7} e^{-0.4056 X_7} e^{-0.0355 X_7} e^{1.3188 X_7}$ | 0.900 |
| Step 3b   | $P_w = 0.5197 A^{0.1740} H^{-0.7728} D^{0.1532} N^{-0.0136} e^{0.2060 X_7} e^{-0.1991 X_7} e^{0.6034 X_7} e^{-0.0428 X_7} e^{-0.7204 X_7}$ | 0.254 |
|           | $P_{bk} = 1.9240 A^{0.1740} H^{-0.7728} D^{0.1532} N^{-0.0136} e^{0.2060 X_7} e^{0.1991 X_7} e^{-0.6034 X_7} e^{0.0428 X_7} e^{0.7204 X_7}$ | 0.658 |

Table 5. The characteristics of “methodized” independent allometric equations for *Quercus* stands.

| Biomass component | Independent variables and the regression coefficients of the model | $\text{adj}R^2$ |
|-------------------|---------------------------------------------------------------|-----------------|
| $P_t$             | $0.6902 A^{0.1948} H^{0.5292} D^{1.0216} N^{0.4290} e^{0.2022 X_7} e^{0.0742 X_7} e^{0.2566 X_7} e^{0.0937 X_7}$ | 0.866 |
| Step 1            | $P_a = 0.7649 A^{0.6067} H^{-0.5645} D^{1.0096} N^{0.5345} e^{0.1474 X_7} e^{0.0596 X_7} e^{1.1419 X_7} e^{0.4956 X_7} e^{0.2704 X_7}$ | 0.376 |
| $P_r$             | $0.6916 A^{0.1242} H^{0.1710} D^{0.9070} N^{0.2832} e^{0.6328 X_7} e^{0.0608 X_7} e^{0.2601 X_7} e^{-0.0123 X_7} e^{1.1205 X_7}$ | 0.627 |
| Step 2            | $P_s = 0.3569 A^{0.1986} H^{-0.5077} D^{1.1082} N^{0.4738} e^{0.0837 X_7} e^{0.1032 X_7} e^{0.3782 X_7} e^{1.4498 X_7} e^{0.7593 X_7}$ | 0.900 |
| $P_f$             | $0.3497 A^{0.1277} H^{-0.2342} D^{0.9072} N^{0.4222} e^{0.1817 X_7} e^{0.1401 X_7} e^{0.0008 X_7} e^{0.0037 X_7} e^{0.0149 X_7}$ | 0.254 |
| Step 3a           | $P_b = 0.3912 A^{0.1074} H^{0.5338} D^{0.9206} N^{0.2518} e^{0.6598 X_7} e^{0.0300 X_7} e^{0.1148 X_7} e^{0.0392 X_7} e^{1.3335 X_7}$ | 0.658 |
| $P_w$             | $0.0858 A^{0.2494} H^{1.0440} D^{1.0714} N^{0.6490} e^{0.1402 X_7} e^{0.0471 X_7} e^{0.1680 X_7} e^{-0.0067 X_7} e^{0.6508 X_7}$ | 0.905 |
| Step 3b           | $P_{bk} = 0.0446 A^{0.4244} H^{0.2712} D^{1.2246} N^{0.6314} e^{-0.0656 X_7} e^{-0.1520 X_7} e^{-0.4154 X_7} e^{0.0362 X_7} e^{0.0896 X_7}$ | 0.851 |
Table 6. The comparison of adequacy indices of independent and additive equations for *Quercus* stand biomass calculated with their regionalization by introducing dummy variables

| Index | Biomass components | Independent equations | Additive equations |
|-------|--------------------|-----------------------|-------------------|
|       |                    | $R^2$                 | $R^2$             |
|       | $Pt$               | 0.746                 | 0.746             |
|       | $Pa$               | 0.798                 | 0.799             |
|       | $Pc$               | 0.571                 | 0.571             |
|       | $Pf$               | 0.292                 | 0.293             |
|       | $Pb$               | 0.570                 | 0.571             |
|       | $Pr$               | 0.249                 | 0.238             |
|       | $Ps$               | 0.803                 | 0.804             |
|       | $Pw$               | 0.856                 | 0.871             |
|       | $Pbk$              | 0.643                 | 0.660             |

Table 7. Characteristics of auxiliary recursive equations for mass-forming indices

| Mass-forming indices | Independent variables and the regression coefficients of the model | $adjR^2$ |
|----------------------|---------------------------------------------------------------|---------|
| $H$                  | $-15.9489 \times 8.6068 \ln A -1.9231 X1 0.4346 X2 -3.5626 X3 -5.3695 X4 -8.6083 X5$ | 0.768   |
| $\ln D$              | $-1.0586 \times 0.3531 \ln A 0.9160 \ln H -0.0426 X1 -0.0576 X2 0.1867 X3 -0.1181 X4 -0.0180 X5$ | 0.936   |
| $\ln N$              | $3.9068 \times -0.0184 \ln A 0.6613 \ln H -1.9590 \ln D 0.0798 X1 -0.0923 X2 -0.2702 X3 0.4303 X4 0.4947 X5$ | 0.913   |

Table 8. Fragment of additive transcontinental table of *Quercus* stand biomass for the age of 60 years, localized on the ecoregions of Eurasia

| Eco-region | Species of *Quercus* | $H$, m | $D$, cm | $N$, 1000/ha | Stand biomass, t/ha |
|------------|----------------------|--------|---------|--------------|---------------------|
|            |                      | $Pt$   | $Pa$    | $Pc$         | $Pf$    | $Pb$    | $Pr$    | $Ps$    | $Pw$    | $Pbk$   |
| WCE        | *Q. robur* L.        | 19.3   | 22.5    | 0.774        | 193.7   | 164.1   | 30.3    | 3.5     | 26.8    | 29.7    | 133.8   | 113.9   | 19.9    |
| WCE        | *Q. petraea* (Matt.) Liebl. | 17.4   | 19.6    | 1.027        | 224.4   | 185.1   | 40.3    | 4.4     | 35.9    | 39.2    | 144.8   | 125.9   | 18.9    |
| ERn        | *Q. robur* L.        | 19.7   | 21.7    | 0.769        | 212.6   | 174.0   | 30.6    | 3.9     | 26.7    | 38.6    | 143.4   | 125.8   | 17.6    |
| ERs        | *Q. robur* L.        | 15.7   | 22.5    | 0.517        | 242.4   | 141.8   | 27.5    | 3.3     | 24.2    | 100.6   | 114.2   | 102.7   | 11.6    |
| SFE        | *Q. mongolica* Fisch. ex Ledeb. | 13.9   | 14.8    | 2.172        | 218.9   | 151.4   | 26.3    | 4.6     | 21.6    | 67.6    | 125.1   | 102.8   | 22.3    |
|            | *Quercus mongolica* subsp. *crispula* (Blume) Menitisky *Q. glauca* Thunb. | 10.7   | 12.9    | 2.570        | 320.9   | 246.4   | 60.3    | 6.5     | 53.8    | 74.5    | 186.1   | 165.9   | 20.1    |
Figure 3. The ratio of observed values and the values derived by calculation of independent (a) and additive (b) models of *Quercus* stand biomass.
The additive model built (Table 4) includes four numeric independent variables. When its tabulating, there is a problem, which is that we can know and give the value of stand age only of four variables, and the remaining three variables can be entered into the table in the form of calculated values obtained by the system of auxiliary recursive equations (Usoltsev, 1989). Such equations are approximated using the original data and are shown in the Table 7.

The results of sequential tabulations of the equations of the Tables 7 and 4 give the unacceptably voluminous table, the size of which exceeds the format of journal article. Therefore, a comparative analysis of the biomass structure of Quercus stands of different ecoregions we limit by the stand age of 60 years (Table 8). According to the Table 8, the greatest values of total biomass (321 t/ha) correspond to oak forests Q. crispula and Q. glauca in Japan, and the lowest (194 t/ha) – to stands of oak forests Q. robur in West Europe. The intermediate position in terms of total biomass (213-242 t/ha) is occupied by oak stands in other ecoregions.

The biomass indices of different ecoregions differed not only in absolute value but also in biomass ratios of different components; for example, the proportion of foliage in the aboveground biomass is maximum (2.6-3.0%) at oak forests of Primorie and Japan, and minimum one (2.1%) in oak forests of Western and central Europe, and in other regions it is at a stable level of 2.2-2.4%.

4. Conclusions

When using the unique in terms of the volume of database on the level of a stand of the genus Quercus, the trans-Eurasian additive allometric model of biomass for oak forests is developed for the first time, and thereby the combined problem of model additivity and generality is solved. The model is harmonized in two levels, one of which provides the principle of additivity of biomass components, and the second one is associated with the introduction of dummy independent variables localizing model according to ecoregions of Eurasia. The proposed model and corresponding table for estimating stand biomass make them possible to calculate Quercus stand biomass on Eurasian forests when using measuring taxation.

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