MATHEMATICAL BIOMASS MODELS FOR YOUNG INDIVIDUALS OF FOREST TREE SPECIES IN THE REGION OF THE WESTERN CARPATHIANS

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Edition: First
Number of pages: 89 pages
Number of printed copies: 120 copies
Printing and book binding: National Forest Centre
Published by: National Forest Centre
Authors are responsible for the content.

ISBN 978 - 80 - 8093 - 241 - 1

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1. Introduction

We present the target subject, i.e. the development and presentation of mathematical models for tree species biomass estimation in the introductory chapter in a broader context in order to understand its socio-economic importance. We outline the importance of forest biomass in the process of climate change mitigation and the related requirements for the exact quantification of biomass, or the amount of carbon sequestered in the tree layer. The term “climate change” is commonly used to refer to the changes in the Earth‘s atmosphere that have both regional and global implications. The inherent phenomena of the climate change are gradually becoming the main risks for further development of human civilisation, or for the existence of some species of flora and fauna. Thus, this issue is still gaining its importance and from the long-term perspective it will be the subject of research (including forestry) or implementation of scientific knowledge into practice.

The United Nations Framework Convention on Climate Change (UNFCCC; known as the “Kyoto Protocol”) from the year 1997 set the target of stabilising greenhouse gas concentrations in the atmosphere. At the same time, it prescribed a gradual reduction of dangerous anthropogenic interference in the Earth‘s climate system. Approximately 20 years later, specifically in December 2015, the United Nations Paris Conference on Climate Change took place. The Paris Agreement will replace the Kyoto Protocol after its ratification by national parliaments in 2020. The Paris Conference has committed the countries to keep global warming well below the two degrees Celsius above the state in the pre-industrial era.

The climate change and its inherent phenomena have various negative impacts on environment including its destructive effects on forest ecosystems. However, here we have to note that forests are not only passive objects affected by climate change, but thanks to their ability to absorb and accumulate carbon they can significantly influence this process. Carbon sequestration of forests as one of the complex factors can play an important role in climate change mitigation. Forests are estimated to store as much as 80% of above-ground and 40% of below-ground (i.e. roots, plant litter, and soil) terrestrial carbon in their biomass (Dixon et al. 1994). It is also widely known that European forests represent a globally important carbon sink. Although their stocks are increasing, carbon sequestration forest function needs to be further strengthened.

In forest ecosystems, carbon is stored in soil, as well as in plant biomass, particularly in trees. It is the carbon in forest biomass that a man can efficiently influence by its intentional activities. In practice it means that the stand growing stock is gradually increasing thanks to the improvement of production characteristics of forest trees and stands. At the same time, the occurrence of natural disturbances in forests should be avoided or at least reduced. Apart from promoting the sequestration function of forests we need to provide reliable information on the amount of carbon stored in forest biomass, or on the trends of its previous development and future estimates. Thus, the importance of precise determination of biomass in forest trees has been increasing.

In the past, merchantable biomass (the stem part of the tree, or the timber over a certain diameter threshold) was primarily evaluated. A number of practical methods have been developed for the (volume or mass) quantification of merchantable biomass. However, with regard to the climate change, the researchers have started to evaluate all tree components from the point of their energy utilisation, as well as their carbon stocks. This created the need to develop and improve technologies for rapid and statistically representative evaluation of other than stem biomass. One of the most efficient ways to achieve this goal is to use allometric equations based on easily measured (traditionally used) tree characteristics.

According to our literature review, the research in this field has predominantly concentrated on older developmental phases (e.g. Eckmüllner 2006; Seidl et al. 2010; Vejpustková et al. 2015; Krejza et al. 2017). Young trees or forest stands have usually not been included in this research.

Some models developed for young individuals of selected tree species often do not include below-ground parts of the biomass (e.g. Annighöfer et al. 2016).

De facto, mathematical models for the biomass estimation of tree components in young (small) trees are still missing. They are necessary because our observations (e.g. Konôpka et al. 2011) suggested that biomass allocation to individual tree components in mature individuals substantially differs from the allocation in young trees. Due to this, the already existing equations for biomass estimation of mature trees and stands are not generally applicable to young trees. Hence, the need to develop specific models for the biomass estimation of all tree components (roots, stem, branches, and foliage) of young trees of different tree species has been identified. They will be useful for quantifying biomass stocks of young regenerated stands, the area of which has substantially increased over the last years.

For these reasons, the presented work focuses on the presentation of mathematical models for the estimation of biomass of young individuals in different tree species. The publication summarises our results, which have been achieved during the last ten years. The prevailing part of the work has been funded by the Slovak Research and Development Agency. The particular projects were: Quantification of biomass in forest stands of 1st age class (2005–2007), Comparative studies of structure of net primary production in beech and spruce stands (2011–2014), Mathematical models of biomass allocation in young stands of selected broadleaved tree species (2013–2017) and Production and ecological studies of tree and ground vegetation after large-scale disturbances (2015 onwards).

The research material (whole tree samples) originated from the vast majority of the territory of Slovakia. Hence, the results can be generalised to the conditions of the Western Carpathians. The samples represented eleven tree species. The publication does not deal only with the main commercial tree species, but it also contains the data on some other tree species, which have various functions for the ecological balance of landscape, including their importance for carbon sequestration. Apart from the summary of the existing knowledge on the biomass structure of tree species, this work has an ambition to compare inter-species differences in biomass allocation to individual tree components, and to interpret the differences from production and ecological aspects. In addition, we also wanted to outline the possibilities of further scientific implementation of biomass models of young trees in different tree species.

2. Analysis of the subject field and goals of work

As we have already mentioned in the introduction, the volume of merchantable timber was the main subject of interest in the calculation of biomass in forest stands. In Slovakia, this category is characterised by the volume of timber with minimum diameter of 7 cm under bark. Its main proportion is in a stem, the volume of which can be determined using a great number of methods (Hakkila 1989; Petráš & Pajtík 1991; Husch et al. 2003). Since the time when it was found that biomass allocation significantly determines carbon sequestration and its cycle in a forest ecosystem (Litton et al. 2007), the interest in developing methods for the assessment of non-stem forest biomass has been growing (e.g. Pregitzer & Euskirchen 2004; Lehtonen 2005).

Models created for older (big) trees are generally not applicable to young individuals (Wirth et al. 2004). Hence, formulas for the calculation of biomass of individuals in initial growth stages need to be derived. The unsuitability of models developed for older trees results from different patterns of biomass allocation in young and old stands. For example Lehtonen et al. (2004) showed that the ratios of individual components of tree biomass depend on the age (or size). In addition, it also reflects different growth strategies of individual tree species and the impact of different forest management or the genesis of previous development. Another reason why the models of older trees cannot be applied to young individuals is the fact that stem diameter at 1.3 m height above ground level is the most common independent variable used to derive the biomass of older trees. This characteristic is not available or cannot be recorded in the case of the youngest trees.

Under the Slovak conditions, Pajtík et al. (2008) emphasised the growing importance of biomass models specifically constructed for young trees. This is related to the increasing area of young stands over the last years (Konôpka et al. 2014). The observed increase is caused by natural disturbances (especially by wind) and secondary pests (in spruce forests mainly bark-beetles; Kunca et al. 2015). Another argument is the concept of uneven-aged forest stands, i.e. often with some proportions of young trees, which is nowadays preferred in many European countries.

The calculation of biomass stock of individual tree components is usually performed using one of the basic methods:

1) regression equations,
2) biomass expansion factors.

The advantage of using regression equations for biomass calculation is that they are frequently based on a larger data set than biomass expansion factors. Another advantage is that they use easily measurable tree characteristics (stem diameter and/or tree height). The regression equations cover the differences in stand structures and can be easily applied to national inventories of carbon stocks. On the other hand, the advantage of biomass expansion factors is their simplicity and more general usage. However, in the case of young stands this advantage is lost because they are derived from stem volume (which is the most readily available information in the case of mature trees, but not for young trees). Another disadvantage is that the values of biomass expansion factors significantly vary in young age classes. On the contrary, the values of mature individuals are more or less stabilised in relation to the tree size, and can be used as a single default (i.e. constant, stable) value (Lehtonen 2004). Our research confirmed significant disadvantages of applying biomass expansion factors to young tree individuals (Pajtík et al. 2008). Due to this, the publication presents only the results related to regression equations.

Biomass regression equations for individual tree species occurred in ecological and forestry literature in the 50s of the last century as a response to the requirement on biomass assessment. Biomass estimates are necessary pre-conditions for the studies of forest production, biochemical or nutrient cycles, biomass energy use, carbon stocks, and carbon sequestration in forests.

The first studies that arose from the need to determine biomass production of different tree species were the works of Burger (1945, 1953) dealing with larch and spruce in Switzerland. Subsequently, the scientists started to focus on dry mass determination of individual tree components (usually differentiated to: roots, stem over or under bark, stem bark, branches, foliage), but most frequently of those that were more important to forestry companies.

Ecological and physiological works of that period showed the interest of scientists to contribute to the development of simple methods for biomass determination, especially for the quantification of foliage (Kittredge 1944; Ovington 1957). A number of forestry works have developed regression equations for specific geographic areas and tree species. Biomass equations of a tree as well as of its components are usually based on the relationship to stem diameter (most commonly measured at 1.3 m height above the ground). Some authors used a tree height as an input variable, or a combination of both independent variables (e.g. Satoo & Madgwick 1982; Ter-Mikaelian & Korzukhin 1997; Khan & Faruque 2010; Vahedi et al. 2014). Less frequently, other independent variables are used, e.g. crown length, crown width, ratio of crown length to tree height, ratio of crown width to crown length or h/d ratio, i.e. ratio of tree height to stem diameter (e.g. Eckmüllner 2006; Hochbichler et al. 2006; Ledermann & Neuman 2006; Cienciala et al. 2008).

In the cases when the equations were derived for the biomass calculation at a stand level, site or stand variables were used. Out of them the most frequently applied variables were: number of trees per hectare, basal area, stand top height at a specific stand age, elevation. The number of studies dealing with the assessment of forest biomass has increased over the last decades. They often account for the importance to include a wide number of tree species and different site conditions (Zeide 1987). At the same time, an attempt to create generalised biomass models universally applicable to large regions has also occurred. For example Zianis et al. (2005) made a review of biomass and volume equations for tree species of Europe. In the work they included more than 600 equations, out of which a substantial part originated from Central and Northern Europe. The majority of the studies in this category deals not only with biomass quantification but also with more global aspects. From them we can name e.g. timber utilisation (for the production of pulp, fuel timber, etc.) and application of acquired knowledge in related research areas (e.g. in the studies of carbon cycle, or nutrient balance of forest ecosystems).

The issue of biomass estimation of young stands gained attention only several years ago. Dutca et al. (2010) derived biomass conversion expansion factors (BCEF) for young spruce stands grown on non-forest sites of the Eastern Carpathians. Blujdea et al. (2012) derived allometric equations for the calculation of biomass of young broadleaved trees growing on plantations of Romania. Under the Slovak conditions, Pajtík et al. (2008, 2011) derived regression equations and BCEF for spruce, pine, beech, and oak stands in the 1st age class, i.e. younger than 10 years old. Over the last years, the equations for young stands of the following tree species were developed: European ash (*Fraxinus excelsior* L.), Sycamore (*Acer pseudoplatanus* L.; e.g. Konôpka et al. 2012, 2015), European larch (*Larix decidua* Mill.; Pajtík et al. 2015), Goat willow (*Salix caprea* L.) and Rowan (*Sorbus aucuparia* L.; Pajtík et al. 2015). The newest summary work focusing on biomass estimation of 19 European tree species in a juvenile stage based on stem base diameter d_0 (also called root-collar diameter abbreviated as RCD) and tree height was written by Annighöfer et al. (2016). However, the authors of this work did not include the below-ground part of tree biomass.

Several authors (Kozak 1970; Cunia & Briggs 1984; Parresol 1999; Bi 2004) pointed out at the shortage of many published equations because they did not include the additivity between the equations of individual components and hence were not efficiently determined. It means that the equations were derived for every component separately without accounting for:

1) the correlation between the biomass components measured at the same sample trees,
2) the logical restriction between the sum of the predicted biomass of tree components and the prediction for the whole tree.

The missing additivity in the models causes inconsistency in the predicted values calculated by summing up the equations of individual tree components and the values predicted from the equation for the whole tree biomass. To eliminate this incompatibility, several models and calculation methods were proposed (Chyienda & Kozak 1984; Cunia & Briggs 1985).

Allometric equations have an important role among the regression functions. Allometry is the study of varying proportions of organisms dimensions associated with the changes in their size either in the context of the individual growth (ontogenetic allometry), or in comparison to related organisms of different sizes (phylogenetic allometry). This term is also often used to indicate imbalanced growth (development) as an opposite to isometry - balanced growth. Growth allometry is expressed using the allometric equation with the following basic form:

$$Y = a \,.\, X^{b} \qquad [1]$$

where Y = a dependent variable, X = an independent explanatory variable, a, b are model coefficients.

Kittredge (1944) was among the first who applied this equation in forestry. Over time, this method has become the most common approach in the studies dealing with biomass quantification (e.g. Marklund 1987; Neumann & Jandl 2005; Gschwantner & Schadauer 2006; Ledermann & Neumann 2006). The reason for its popularity is its flexibility, because it can be easily expanded to a multiple power function in the form:

$$Y = a_0 . X_1^{b_1} . X_2^{b_2} . X_3^{b_3} ..... X_n^{b_n} . \theta \qquad [2]$$

where Y = a dependent variable, $X_1 - X_n$ = independent explanatory variables, $a_0 - b_n$ = model coefficients, and θ is the error (multiplicative error term).

Frequently, the logarithmic form of the equation is used, because parameters can be estimated using a linear regression. Apart from this advantage, the logarithmic transformation compensates for the tendency to the accelerating increase of the dependent variable with the tree size (the heteroscedasticity of residuals, which is always present in the case of this type of data). Thanks to this approach, the model satisfies the assumption of constant variance. Based on this we can write the equation as follows:

$$\ln Y = b_0 + b_1 . \ln X_1 + b_2 . \ln X_2 + b_3 . \ln X_3 + ... + \ln X_n + \varepsilon \qquad [3]$$

where $b_0 = \ln a_0$, and $\varepsilon = \ln \theta$ is the error (additive error term). The logarithmic transformation of the dependent variable causes bias. The bias occurs after the inverse transformation of the logarithmic form to the original one (Baskerville 1972; Ledermann & Neumann 2006). Hence, when the equations are transformed back, they need to be corrected for the logarithmic bias. For this purpose, a correction factor referred to as λ is used.

Finney (1941) and Baskerville (1972) were the first authors who dealt with the calculation of the correction factor for logarithmically transformed allometric equations. However, in spite of the right intention, the formulation of the correction factor was often incorrect at that time. The bias is eliminated by multiplying the result with the correction factor, which is calculated from the standard error of estimates SEE of the regression calculated using the formula:

$$SEE = \sqrt{\frac{\Sigma\left(lny_i - \widehat{lny_i}\right)^2}{DF}} \qquad [4]$$

where lny_i is the value of the dependent variable, $\widehat{lny_i}$ is the respective predicted value calculated from the equation, and DF is the degrees of freedom, which is calculated as $N–p$, where N is the number of observations and p is the number of equation parameters.

Sprugel (1983) pointed out at the incorrect derivation of SEE by some authors (Snedecor & Cochran 1967; Whittaker & Woodwell 1968), who used the values of $N–1$ in the denominator.

The correction factor is then expressed using SEE as follows:

$$CF = exp(SEE^2 / 2) \qquad [5]$$

However, the application of this correction factor requires normal logarithmic distribution of the dependent variable Y, otherwise it causes its overestimation (Marklund 1987). Therefore, instead of this correction factor the method presented by Marklund (1987) is used, who calculates the correction factor using the formula:

$$\lambda = \frac{\sum_{i=1}^{n} Y_i}{\sum_{i=1}^{n} e^{\widehat{\ln Y_i}}} \text{, where } n \text{ is the number of trees.} \qquad [6]$$

In the case of biomass calculation at a tree level, Ledermann & Neumann (2006) recommend to use the formula:

$$\bar{\lambda} = \frac{1}{n} \sum_{i=1}^{n} \frac{Y_i}{e^{\widehat{\ln Y_i}}} \qquad [7]$$

The calculation of different types of correction factors used for the logarithmic transformation of power functions and their mutual comparison were thoroughly studied by Clifford et al. (2013).

Using a linearised model requires that a user obtains non-transformed biomass values back. For this, the following retransformation is used:

$$Y = e^{(b_0 + b_1 . \ln X_1 + b_2 . \ln X_2 + b_3 . \ln X_3 + ... + b_n . \ln X_n)} . \lambda \qquad [8]$$

Recently, the development of non-linear regression methods has raised the question whether it is not more convenient to use allometric equations in their power forms. With this approach we can avoid their logarithmic transformation. Linearisation allows us to use common regression analysis methods, and the calculation process is simpler, especially if several independent variables are included. The disadvantages of this approach are that the logarithmic transformation deforms original data, and the correction factor needs to be used for its retransformation. Cienciala et al. (2006) analysed the effect of linearisation on the calculation of biomass in pine components while deriving regression equations. The authors found that the average biomass predicted using the non-linear regression coincides with the measured values better than when the linearised regression is applied. Other regression statistics, namely the standard error of estimates (SEE), coefficient of determination (R^2), and the mean square of residuals (MSR), were slightly better for the linearised two-parameter equations used for calculating the above-ground biomass. On the other hand, the non-linear approach gave better values of the statistical indicators in the case of more complex equations with at least four parameters. On the contrary, Lai et al. (2013) found that in the case of the models for calculating root biomass from tree diameter a linear regression of logarithmically transformed data is more accurate than a non-linear regression. In addition, they revealed that inappropriately used non-linear regressions lead to great inaccuracies in determined biomass at a stand level. This was especially true in the case of stands dominated by small trees. Mascaro et al. (2014) answered the question if logarithmic transformation is necessary in allometry as follows: “Ten, hundred, thousand times yes”. Since the opinions about these two methodical approaches still differ, scientific attention should be paid to this issue also in the future.

The main goal of this work was to summarise and clearly present the results of the long-term scientific work in the field of tree species allometry in juvenile stages of their development, which mainly focused on the development of regression equations for the calculation of biomass of individual tree components, volume, and density of stem and bark. Next, the attention was paid to the inter-species differences in the amount of the total biomass and its allocation to tree components.

The goals set out for this work are related to important commercial tree species, i.e. Common beech, Norway spruce, Sessile oak, and Scots pine. In addition, the research also covered some other tree species, namely European hornbeam, Sycamore, European ash, Goat willow, European larch, Rowan, and Common aspen. These tree species were chosen for our research purposes due to their relatively significant proportion in the tree species composition of our forests or for some other ecological (e.g. pioneer tree species on disturbed plots, amelioration effects on soil) or biological (e.g. their trophic importance for wildlife, or biological protection of target tree species) reasons.

The order of the analysed tree species was selected on the base of the assessment of their importance on the overall (i.e. regardless of age) tree species composition of Slovakia derived from the results of the second round of the National Forest Inventory and Monitoring (NFIM2) of the Slovak Republic (SR). We preferred their area-based occurrence on the whole territory to the traditional comparison based on the contribution to volume or basal area, which are more important from the production view of wood biomass utilisation. The eleven selected tree species are ordered on the base of the relative frequency values from the most to the least common species, while the first six tree species dominate also in the absolute values of all tree species in the Slovak forests, the total number of which is approximately 70 according to the NFIM2 SR.

Based on the area coverage (as well as volume), Common beech (1st) is the most common tree species in Slovakia followed by Norway spruce (2nd). The third most common tree species is European hornbeam (3rd) that is commercially less important, but currently covers a larger area than the Sessile oak (4th) or Scots pine (5th). Sycamore (6th) occurs in the Slovak forests much more frequently than the European ash (7th). Relatively equal proportions were found for the pioneer tree species Goat willow (8th), commercially important European larch (9th), and Rowan (10th) that is an important admixed amelioration species. The lowest share among the assessed tree species was found for the Common aspen (11th).

Here we have to note that our allometric equations for young individuals of tree species should complement already existing models for older (bigger) trees. The existing models usually represent the biomass of individual tree components of trees with stem diameter (measured at 1.3 m height above ground) exceeding 7 cm. The persistent problem is that older models usually do not include the amount of stump and roots.

In the following text we present short characterisations of the individual tree species included in this study to better understand their importance. Some information is derived from the most recent data of NFIM2 SR performed in the years 2015–2016.

3. Material and methods

We selected several naturally-regenerated stands for each assessed tree species that were in the initial developmental stages from the regeneration stage up to the thicket stage (mostly at the age of 2 to 10 years) from the current national database of young forest stands created from the Forest Management Plans. The proportion of the particular tree species in the area of the selected stands was from 90 to 100%. Basic characteristics of the selected sites are presented in Table 1. Their position inside the area of Slovakia is in Fig. 1.

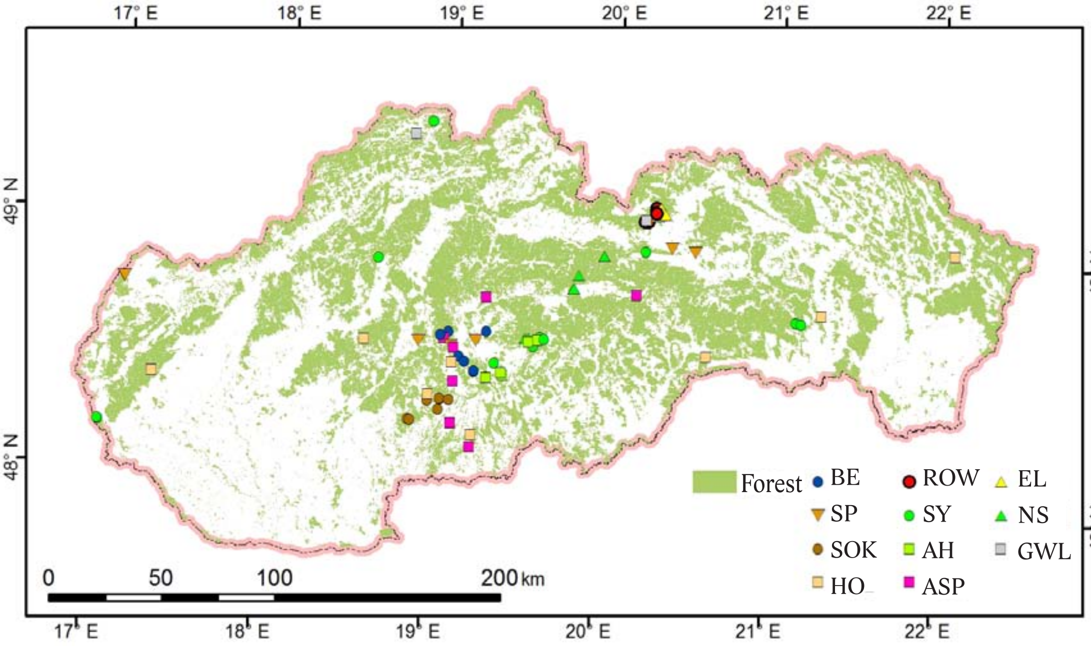

Fig. 1. *Map of the Slovak Republic showing the forest area and the position of sample sites for the following tree species: Common beech (BE), Norway spruce (NS), European hornbeam (HO), Sessile oak (SOK), Scots pine (SP), Sycamore (SY), European ash (AH), Goat willow (GWL), European larch (EL), Rowan (ROW), and Common aspen (ASP).*

During the project aims solution, i.e. from the year 2005 to 2016 the methodology was modified and the number of assessed variables increased. At the beginning, when we focused on commercial tree species, i.e. spruce, beech, oak, pine, and larch, the sample trees were not debarked (the methodology was gradually clarified). Hence, the data on dry mass weight of stem bark, volume of stem under bark, bark density, mass and volume proportions of bark are missing. We did not determine the relationship of stem diameter at breast height (hereafter referred to as $d_{1.3}$ diameter) to stem base diameter (hereafter referred to as d_0 diameter) for spruce, beech, oak and pine. The empirical material is mostly of a national character, only in the case of several tree species it is only of a local character (rowan, goat willow, and larch). The list of sites, from which the sample trees of individual tree species were taken, is presented in Table 1.

In each stand we selected three circular plots, which should represent the whole stand. Their radii varied depending on the stand density to ensure that at least 30 trees occurred within the plot area, which is the number appropriate for statistical evaluation with sufficient confidence. At each plot, we determined the number of individuals and we measured stem base diameter d_0 (two perpendicular measurements) and height of all trees. From these data we calculated the number of trees per hectare and volume per hectare (the results of these measurements are not included in this monograph). At the same time, these measurements were used to derive diameter and height structures of the stands needed for the subsequent selection of the sample trees.

The stands, from which the sample trees were taken, were selected to ensure that they covered the entire age range from the youngest (1–2 years old) up to the oldest ones (10–12 years). At each site we dug out 20 – 25 sample trees that represented the diameter and height range of the individuals at the entire plot. To ensure good coverage of size distribution, we divided the trees to 10 stand-specific height classes of equal widths. Afterwards, we randomly selected and dug out 2 or 3 sample trees from each height class. The trees that were deliberately selected grew in typical stand conditions. For example, we avoided solitary trees, individuals at the vicinity of paths, or those at the forest edge. We also excluded the individuals that were deformed, damaged, or with reduced foliage.

The trees were sampled at the end of the growing season, when the growth of all components was finished. The sample trees were divided to roots, stem, branches, foliage, and stem bark. The samples were packed into the marked paper bags and transported to laboratories for further processing. Every sample was stored in a dry, ventilated room for one month. Afterwards, it was dried in an electric oven at a temperature of 105 °C until it reached constant weight.

The described method of sample tree selection ensured that at each plot we chose trees from all sociological positions (dominant, co-dominant, sub-dominant, suppressed). On the other hand, this approach led to substantially left-skewed distributions of diameters and heights of the whole set of measured trees, where the greatest diameters and heights were represented only by the trees from the main canopy. The sub-dominant and suppressed trees of such dimensions would have had to be searched for in older stands. However, that was not the goal of this work, which aimed at evaluating only the stands of juvenile growth stages. In the case of the left-skewed distribution of the values, the linearisation of the allometric equation and its reverse re-transformation can in some cases cause that the predicted values substantially differ from the measured values, which is true mainly for the high values.

Model development was primarily focused on the calculation of dry mass weight of tree components using regression functions as well as biomass conversion expansion factors (not shown in this work). Only gradually, in the course of the project solution, we began to develop also the models for the volume of stem, and density and proportion of bark.

When calculating dry mass of tree components, the biomass of individual tree components given in mass units was the dependent variable. Due to the small tree dimensions, $d_{1.3}$ diameter could not be used as an independent variable. Instead, stem base diameter d_0 was applied. Although the models with height as the only independent variable are used only rarely, we applied also this model. The reason for this was that in the youngest developmental stages height is more easily measured than d_0 diameter. At the same time, height can be used to couple the models of mature stands with the models of the stands in the initial growth stages. We tested three functions, in which the independent variables were d_0 diameter, tree height, and their combination.

$$W_i = e^{(b_0 + b_1 . \ln d_0)} . \lambda \qquad [9]$$

$$W_i = e^{(b_0 + b_1 . \ln h)} . \lambda \qquad [10]$$

$$W_i = e^{(b_0 + b_1 . \ln d_0 + b_2 . \ln h)} . \lambda \qquad [11]$$

where:

W_i = biomass weight of i^{th} tree component (g of dry matter expressed at a tree level),
d_0 = stem base diameter (mm),
h = tree height (m),
b_0, b_1, b_2 = equation coefficients,
λ = correction factor.

Prior to the calculation of stem volume, a stem was divided to at least 3 – 4 sections. The sections were measured before drying, i.e. the volume represents the fresh state. The section diameters were measured in two perpendicular directions with a vernier calliper with a precision of one tenth of millimetre. Tree height was determined with a precision of one centimetre. The stem section volume was calculated using the Newton formula:

$$V = \frac{L(A_b + 4A_m + A_s)}{6} \qquad [12]$$

where:

V = stem volume (cm^3),
L = section length (cm),
A_b = cross-sectional area at the bottom end of the section (cm^2),
A_m = cross-sectional area in the middle of the section (cm^2),
A_s = cross-sectional area at the top end of the section (cm^2).

The total stem volume was calculated as a sum of volumes of all sections.

The Newton formula is considered to be the most accurate and flexible formula for the calculation of volume of stem parts (logs, sections), because it is suitable for the volume calculation of cylindrical and conical objects, but also of paraboloids and neloids (Wiant et al. 1992; Harmon & Sexton 1996; Woldendorp et al. 2002). The calculated values were validated using a pycnometer (a cylinder filled with a liquid used for measuring an object volume). The differences between the calculated and measured volumes were from −2 to +5%. Since such a volume determination is appropriate only in laboratory conditions, in forestry practice stem volume is usually calculated using one or two easily measurable characteristics. Most stem volume equations use $d_{1.3}$ diameter and tree height as independent variables. Because equations with $d_{1.3}$ as an independent variable are not applicable to young stands, we derived three allometric equations to determine stem volume. In the first case, stem base diameter d_0 was used as an independent variable; in the second case it was the tree height (h), and in the third case we used both variables (d_0, h). Due to the above-mentioned shortages of logarithmically transformed equations we used non-linear formulas:

$$V = b_0 d_0^{b_1} \qquad [13]$$

$$V = b_0 h^{b_1} \qquad [14]$$

$$V = b_0 d_0^{b_1} h^{b_2} \qquad [15]$$

where:

V = stem volume (cm^3),
d_0 = stem base diameter (mm),
h = tree height (m), and
b_0, b_1 and b_2 = equation coefficients.

Stem volume was determined in the fresh (moist) state after the sample trees were dug out as the volume of stem over bark (hereafter as SOB), and after debarking we calculated also the volume of stem under bark (hereafter as SUB). Bark volume was calculated as the difference between these two values. Stem volume was calculated as a sum of volumes of individual sections [equation 12]. Wood density was determined as a reduced wood density ρ_{rf} in the fresh state (reduced wood density) defined as a ratio of wood mass in the absolutely dry state m_0 to the fresh wood volume V_{max}:

$$\rho_{rf} = \frac{m_0}{V_{\max}}.1000 \qquad [16]$$

where:

ρ_{rf} = reduced wood density in fresh state (kg.m^{-3}),

m_0 = wood mass in absolutely dry state (g),

$V_{\max}$ = volume of wood with moisture above the hygroscopic threshold (cm^3).

The fresh wood moisture is above the hygroscopic threshold. Reduced wood density above this threshold reaches its minimum value. This is caused by the fact that at these values it does not depend on wood moisture, because wood does not swell any longer and its volume is at maximum V_{max}.

For the calculation of volume, basic density and proportion of bark we used allometric equations [13] – [15] with one independent variable d_0, or h, and two independent variables d_0 and h. The relationship of $d_{1.3}$ diameter to d_0 diameter was described using the following linear equation:

$$d_{1,3} = b_0 d_0 + b_1 \qquad [17]$$

where:

$d_{1,3}$ = stem diameter at a height of 1.3 m above ground (mm),

d_0 = stem base diameter (mm),

b_0 and b_1 are equation coefficients,

and the relationship of tree height h to stem base diameter d_0 was described using the following equation:

where:

$$h = \frac{d_0^2}{b_0 + b_1 d_0 + b_2 d_0^2} \qquad [18]$$

h = tree height (m),

d_0 = stem base diameter (mm),

b_0, b_1 and b_2 are equation coefficients.

Stem bark mass proportion was calculated using the formula:

where:

$$R_{wb} = \frac{100\, w_b}{m_{SOB}} \qquad [19]$$

R_{wb} = bark mass proportion (%),

w_b = dry mass of stem bark (g),

m_{SOB} = dry mass of stem over bark (g).

Stem bark volume proportion was calculated using the formula:

where:

$$R_{Vb} = \frac{100\ V_b}{V_{SOB}} \qquad [20]$$

R_{Vb} = volume proportion of bark (%),

V_b = fresh bark volume after debarking (cm^3),

V_{SOB} = volume of fresh stem over bark (cm^3).

Root/shoot ratio represents the ratio of the dry root mass (below-ground part) to the above-ground dry mass, i.e:

$$\frac{R}{S} = \frac{w_r}{w_{abvg}} \qquad [21]$$

$\frac{R}{S}$ = the ratio of the dry root mass (below-ground part) to the above-ground dry mass,

where:

w_r = dry root mass (g),
w_{abvg} = aboveground dry mass (g).

Mass proportion of a component *i* (foliage, branches, stem over bark, roots) was calculated using the formula:

$$R_{wi} = \frac{100 \ w_i}{w} \qquad [22]$$

where:

R_{wi} = mass proportion of i^{th} component (%),
w_i = dry mass of i^{th} component (g),
w = dry mass of the whole tree (g).

When visualising the data in graphs, we followed the principle of applying the same range of the values of dry matter of a particular component to y axis for all assessed tree species. This allows simple comparison of the component quantities between tree species.

Table 1. *List of sites, from which the sample trees of individual tree species were taken.*

Tree species	No.	Name of site	Elevation (m)	N latitude (°)	E longitude (°)	Aspect	Slope (%)	Soil	Bedrock	Site order	Group of forest types
BE – Common beech (*Fagus sylvatica*)	1	ŠLP I	710	48.6318	19.0048	W	41	Mesotrophic cambisols	Andesites	Fertile	*Fagetum typicum*
	2	ŠLP II	675	48.6454	19.0531	SW	19	Mesotrophic cambisols	Andesites	Fertile	*Fagetum typicum*
	3	Zvolen	460	48.5523	19.1251	N	30	Mesotrophic cambisols	Andesites	Fertile	*Fagetum pauper*
	4	Kráľová	550	48.5343	19.1584	NW	30	Mesotrophic cambisols	Andesites	Fertile	*Fagetum pauper*
	5	Sekier I	670	48.4987	19.2223	N	31	Mesotrophic cambisols	Andesites	Fertile	*Fagetum pauper*
	6	Sekier II	660	48.4990	19.2200	N	28	Mesotrophic cambisols	Andesites	Fertile	*Fagetum pauper*
	7	Hrochoť	620	48.6579	19.2820	N	13	Oligotrophic cambisols	Quartzites	Fertile	*Fagetum pauper*
NS – Norway spruce (*Picea abies*)	1	Poľana I	985	48.6415	19.5164	SW	34	Mesotrophic cambisols	Andesites	Fertile	*Fagetum typicum*
	2	Poľana II	790	48.6418	19.5358	NE	28	Mesotrophic cambisols	Andesites	Fertile	*Abieto-Fagetum*
	3	Drakšiar I	625	48.8490	19.7897	SE	11	Mesotrophic cambisols	Sandstones	Fertile	*Fageto-Abietum*
	4	Drakšiar II	635	48.8493	19.7919	S	16	Mesotrophic cambisols	Sandstones	Fertile	*Abieto-Fagetum*
	5	Bacúch	840	48.9009	19.8149	S	52	Rendzinic cambisols	Limestones	Fertile	*Abieto-Fagetum*
	6	Čierny Váh I	820	48.9840	19.9627	N	41	Mesotrophic cambisols	Melaphyres	Fertile	*Fageto-Abietum*
	7	Čierny Váh II	830	48.9837	19.9632	N	38	Mesotrophic cambisols	Melaphyres	Fertile	*Fageto-Abietum*
HO – European hornbeam (*Carpinus betulus*)	1	Píla	313	48.3941	17.2944	S	1	Typical paternia	Alluvium	Water-logged	*Fraxineto-Alnetum*
	2	Rudica	475	48.5935	18.5497	W	23	Mesotrophic cambisols	Andesites	Fertile	*Fageto-Quercetum*
	3	Antol	516	48.3955	18.9564	W	13	Ilimerised soil	Clay loess	Fertile	*Fageto-Quercetum*
	4	Breziny	432	48.5271	19.0816	NE	20	Mesotrophic cambisols	Andesites	Fertile	*Fageto-Quercetum*
	5	Cerovo	560	48.2475	19.2295	SW	8	Mesotrophic cambisols	Andesitic tuff	Fertile	*Querceto-Fagetum*
	6	Soroška	567	48.6109	20.6057	NW	9	Moder-rendzinas	Limestones	Fertile	*Fagetum pauper*
	7	Budimír	295	48.7938	21.2916	SW	3	Illimerised soils	No data	Fertile	*Fageto-Quercetum*
	8	Zubné	350	49.0459	22.0874	N	34	Illimerised soils	Sandstones	Fertile	*Fagetum pauper*
SOK – Sessile oak (*Quercus petraea*)	1	Ladzany I	480	48.2904	18.8576	S	9	Illimerised soils	Clay loess	Fertile	*Fageto-Quercetum*
	2	Ladzany II	500	48.2921	18.8473	SE	6	Illimerised soils	Clay loess	Fertile	*Fageto-Quercetum*
	3	Antol	560	48.3696	18.9534	E	30	Illimerised soils	Andesites	Fertile	*Fageto-Quercetum*
	4	Žibritov I	480	48.3790	19.0312	SW	16	Illimerised soils	Clay loess	Fertile	*Fageto-Quercetum*
	5	Krupina I	460	48.3382	19.0209	E	49	Mesotrophic cambisols	Andesites	Fertile	*Fageto-Quercetum*
	6	Žibritov II	480	48.3810	19.0267	S	20	Illimerised soils	Clay loess	Fertile	*Fageto-Quercetum*
	7	Krupina II	380	48.3785	19.0831	N	22	Illimerised soils	Clay loess	Fertile	*Fageto-Quercetum*

Tree species	No.	Name of site	Elevation (m)	N latitude (°)	E longitude (°)	Aspect	Slope (%)	Soil	Bedrock	Site order	Group of forest types
SP – Scots pine (*Pinus sylvestris*)	1	Kopčany	165	48.7539	17.0806	NW	1	Ranker cambisols	Drifted sand	Fertile	*Carpineto-Quercetum*
	2	Kopčany II	165	48.7547	17.0792	NW	0	Ranker cambisols	Drifted sand	Fertile	*Carpineto-Quercetum*
	3	Žiar n/Hr.	380	48.6026	18.8742	SE	4	Pseudogley	Andesites	Fertile	*Fageto-Quercetum*
	4	Kováčová	380	48.5934	19.0717	S	15	Illimerised soils	Andesites	Fertile	*Fageto-Quercetum*
	5	Zolná	430	48.6193	19.2209	S	1	Pseudogley	Andesites	Fertile	*Fageto-Quercetum*
	6	Kišovce	640	49.0282	20.3715	SW	20	Typical pararendzina	Calcareous sandstone	Limestone	*Pinetum dealpinum*
	7	Levoča	620	49.0182	20.5126	N	24	Mesotrophic cambisols	Sandstones	Fertile	*Piceeto-Pinetum*
SY – Sycamore (*Acer pseudoplatanus*)	1	Devínska Kobyla	456	48.1876	16.9991	SE	10	Illimerised soils	Clay loess	Nitrophillic	*Querceto-Fagetum tiliosum*
	2	Devínska Kobyla	415	48.1853	17.0022	SE	12	Illimerised soils	Clay loess	Fertile	*Querceto-Fagetum*
	3	Tužina	644	48.9151	18.5992	SW	38	Mesotrophic cambisols	Granites	Fertile	*Fagetum typicum*
	4	Oščadnica	684	49.4640	18.8723	NE	22	Mesotrophic cambisols	Sandstones	Fertile	*Abieto-Fagetum*
	5	Lohyňa	740	48.4780	19.2957	W	51	Mesotrophic cambisols	Andesites	Fertile	*Fagetum pauper*
	6	Chvojno	406	48.5360	19.3378	N	23	Mesotrophic cambisols	Andesites	Fertile	*Querceto-Fagetum*
	7	Snohy	790	48.6276	19.5384	SE	14	Mesotrophic cambisols	Granodiorites	Fertile	*Fagetum typicum*
	8	Nad nádržou	639	48.6106	19.5674	SW	27	Mesotrophic cambisols	Granodiorites	Fertile	*Fagetum typicum*
	9	Vrchslatina	970	48.6472	19.6037	W	2	Mesotrophic cambisols	Granodiorites	Nitrophillic	*Fageto-Aceretum*
	10	Lom	950	48.6407	19.6287	SW	28	Mesotrophic cambisols	Granodiorites	Fertile	*Abieto-Fagetum*
	11	Kravany	850	49.0088	20.2131	NE	52	Mesotrophic cambisols	Sandstones	Fertile	*Fageto-Abietum*
	12	Jahodná	550	48.7599	21.1380	SW	37	Mesotrophic cambisols	Rhyolites	Fertile	*Fagetum typicum*
	13	Čermeľ	480	48.7564	21.1704	NE	33	Mesotrophic cambisols	Rhyolites	Fertile	*Fagetum typicum*
AH – European ash (*Fraxinus excelsior*)	1	Lohyňa	736	48.4780	19.2963	W	48	Mesotrophic cambisols	Rhyolites	Fertile	*Fagetum pauper*
	2	Sliačska Poľana	731	48.4880	19.3914	SW	4	Mesotrophic cambisols	Andesites	Fertile	*Fagetum tiliosum*
	3	Sliačska Poľana	792	48.4998	19.3842	E	13	Mesotrophic cambisols	Andesites	Nitrophillic	*Fagetum typicum*
	4	Snohy	781	48.6277	19.5379	SE	13	Mesotrophic cambisols	Andesites	Fertile	*Fagetum typicum*
	5	Vrchslatina	848	48.6368	19.5914	SW	27	Mesotrophic cambisols	Granodiorites	Fertile	*Fagetum typicum*
	6	Vrchslatina	860	48.6374	19.5912	SW	25	Mesotrophic cambisols	Granodiorites	Fertile	*Fagetum typicum*
GWL – Goat willow (*Salix caprea*)	1	Husárik	800	49.4124	18.7693	SE	26	Mesotrophic cambisols	Sandstones	Fertile	*Fageto-Abietum*
	2	Tatry	1 030	49.1323	20.2032	S	13	Podsolic cambisols	Granites	Acidic	*Piceeto-Abietum*

Tree species	No.	Name of site	Elevation (m)	N latitude (°)	E longitude (°)	Aspect	Slope (%)	Soil	Bedrock	Site order	Group of forest types
EL – European larch (*Larix decidua*)	1	Smokovce-FIR	1 060	49.1351	20.1976	SE	24	Podsolic cambisols	Granites	Acidic	*Piceetum abietinum*
	2	Stará Lesná-Kolbach	840	49.1522	20.2691	S	11	Podsolic cambisols	Granites	Acidic	*Piceetum abietinum*
	3	Stará Lesná-nad campom	834	49.1520	20.2794	E	4	Podsolic cambisols	Granites	Acidic	*Pineto-Piceetum*
	4	Matliare-Biela Voda	910	49.1855	20.2923	E	7	Podsolic cambisols	Fluvioglacial	Acidic	*Piceetum abietinum*
	5	Matliare-Zubry	810	49.1656	20.3129	S	5	Oligotrophic cambisols	Granites	Acidic	*Pineto-Piceetum*
	6	Matliare-Rozengart	790	49.1604	20.3222	S	3	Oligotrophic cambisols	Granites	Acidic	*Pineto-Piceetum*
ROW – Rowan (*Sorbus aucuparia*)	1	Zruby	988	49.1284	20.1987	SE	10	Ranker cambisols	Granites	Acidic	*Piceeto-Abietum*
	2	Smokovec	950	49.1285	20.2161	S	11	Oligotrophic cambisols	Fluvioglacial	Fertile	*Piceeto-Abietum*
	3	Štart	1122	49.1839	20.2620	E	18	Podsolic cambisols	Fluvioglacial	Acidic	*Lariceto-Piceetum*
	4	Jamy	941	49.1628	20.2645	NE	10	Oligotrophic cambisols	Fluvioglacial	Acidic	*Piceetum abietinum*
	5	Nad nádržou	960	49.1692	20.2643	SE	15	Podsolic cambisols	Granodiorites	Acidic	*Piceetum abietinum*
ASP – Common aspen (*Populus tremula*)	1	Kašova Lehôtka	610	48.6204	19.0288	SW	12	Mesotrophic cambisols	Andesites	Fertile	*Fagetum typicum*
	2	Stráže	335	48.5864	19.0897	SW	13	Illimerised soils	Andesites	Fertile	*Fageto-Quercetum*
	3	Dobrá Niva	365	48.4522	19.1003	NE	7	Mesotrophic cambisols	Andesites	Fertile	*Fageto-Quercetum*
	4	Sucháň	540	48.2896	19.1023	N	14	Mesotrophic cambisols	Andesitic tuff	Fertile	*Fageto-Quercetum*
	5	Opava	525	48.1998	19.2235	SW	22	Mesotrophic cambisols	Andesitic tuff	Fertile	*Fageto-Quercetum*
	6	Podkonice	550	48.7930	19.2672	SW	15	Moder-rendzinas	Limestones	Limestone	*Querceto-Fagetum dealpinum*
	7	Telgárt	870	48.8359	20.1711	NE	9	Mesotrophic cambisols	Gneiss	Acidic	*Fageto-Abietum*

4. Results

The results about the biomass characteristics are presented in separate chapters for every tree species (i.e. chapters 4.1. to 4.11.). The order of the chapters corresponds to the occurrence frequency of tree species in Slovakia, i.e. from the most frequent (i.e. Common beech) to the least frequent tree species (Common aspen). The last chapter (4.12.) presents the summary results for all tree species together, and aims at comparing the inter-species differences.

4.1. Common beech

Common beech (*Fagus sylvatica* L.) is the most common tree species in Slovakia from the point of species composition and occurrence frequency. It is also commercially the most important tree species with approximately 30% proportion in total stock (or area). Naturally it grows at a variety of sites in a wide range of all forest elevation zones. Fertile sites suit beech best. It creates either homogeneous stands, or stands composed of two main tree species (mainly with hornbeam or oak). Beech is an important element of the so-called Carpathian mixture together with spruce and fir, though it also creates combinations with other tree species. It is an important component of biotopes protected at national or European levels. The most common forest biotope in Slovakia is Ls5.1 Beech and fir-beech flowery forests (NATURA 2000 defines it as 9130 *Asperulo-Fagetum* beech forests), which covers more than half a million of hectares. Other biotopes with a dominant proportion of beech are Ls5.2 Acidophilous beech forests (9110 *Luzulo-Fagetum* beech forests), Ls5.3 Maple beech mountainous forests (9140 *Medio-European subalpine beech woods with Acer and Rumex arifolius*), Ls5.4 Calcareous beech forests (9150 Medio- *European limestone beech forests of the Cephalanthero – Fagion*).

Beech occurs in all forest vegetation zones (fvz) from the 1st oak zone up to 7th spruce zone with the dominant proportion in 3rd and 4th zones. Its ecological optimum is in 4th beech forest vegetation zone, and its production optimum is in 5th fir-beech zone. On the base of the processed NFIM2 SR data from the years 2015–2016, the minimum and maximum elevations at which beech occurred were 130 m and 1,466 m a.s.l., respectively, and on average it grew at elevations 600 – 700 m a.s.l. According to the NFIM2 SR results, it grew at a reduced area of 666 ±39 thousand ha (the value following ± sign represents 95% confidence interval), and occurred at 62% of forested inventory plots.

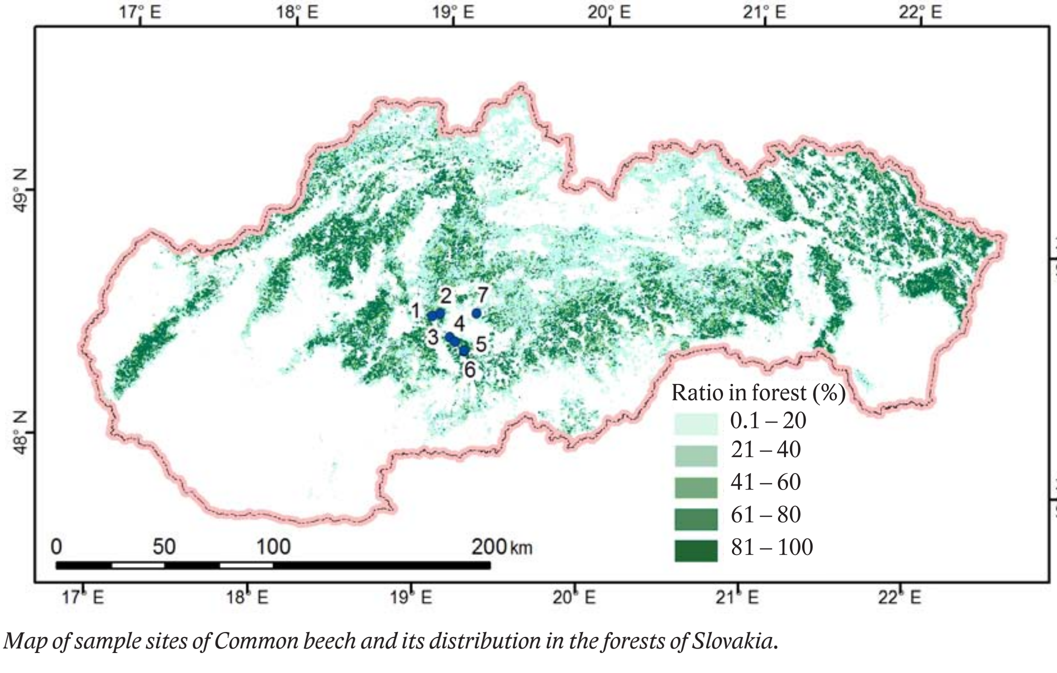

Fig. 2. *Map of sample sites of Common beech and its distribution in the forests of Slovakia.*

The set of beech trees used to derive the biomass regression models consisted of 170 whole tree samples. They were taken from seven sites (see Fig. 2) located in the orographic units of the Kremnické vrchy (sites 1 and 2), Štiavnické vrchy (3), Javorie (4, 5, 6) and Poľana (7). The sampled individuals had d_0 diameters from 4.20 mm to 68.50 mm, and heights from 0.24 m to 5.40 m (Table 2, Fig. 3a). The whole tree dry mass ranged from 2.61 g to 6,148.10 g, and the stem volume ranged from 1.23 cm^3 to 5,059.20 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 3. The models use two independent variables, namely d_0 diameter [Equation 9], tree height [Equation 10], or the combination of these two variables [Equation 11]. Next, we derived the volume of stem over bark, its density, as well as the root/shoot ratio (Table 4). Also in this case we used two independent variables, i.e. d_0 diameter [Equation 13], tree height [Equation 14], or the combination of both variables [Equation 15].

The scatter plots showing the biomass of individual components (or of the whole trees) of the whole set of the analysed trees in relation to d_0 diameter with the fitted regression curves (regression models 9) are presented in Fig. 3b – 3f. Similarly, we graphically presented the proportion of the total tree biomass in individual components in relation to d_0 diameter (Fig. 4a), the volume of stem over bark (Fig. 4b), and the density of stem over bark (Fig. 4c), as well as the ratio of below-ground to above-ground biomass (i.e. "root-shoot ratio" abbreviated as R/S; see Fig. 4d). Further comments on the biomass in individual components of beech and their proportions of the total tree biomass are presented in Chapter 4.12. (Inter-species comparison of biomass characteristics).

Table 2. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), foliage biomass (foliage), branch biomass (branches), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

				Common beech				
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	170	14.50	8.67	4.20	68.50	8.65	17.35	2.47
h (m)	170	1.25	0.81	0.24	5.40	0.70	1.56	1.78
SOB (g)	170	90.02	283.55	0.86	3 197.40	8.80	62.00	8.56
Foliage (g)	170	23.65	51.34	0.51	564.10	3.90	20.60	7.50
Branches (g)	170	32.45	127.96	0.80	1 533.60	2.20	19.00	10.04
Roots (g)	170	47.54	88.07	0.55	853.00	9.17	42.00	5.49
Aboveground	170	146.11	459.40	1.45	5 295.10	14.50	100.00	8.96
Whole tree (g)	170	193.65	542.87	2.61	6 148.10	25.36	146.18	8.47
V_{SOB} (cm^3)	170	178.04	470.12	1.23	5 059.20	13.50	135.42	7.39

Table 3. *Common beech, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficient of determination (R^2), mean square error (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−4.034	0.164	<0.001	2.852	0.063	<0.001				0.923	0.167	1.084	0.438
	Branches	−5.982	0.218	<0.001	3.117	0.084	<0.001				0.891	0.295	1.142	0.592
	Foliage	−3.750	0.183	<0.001	2.375	0.071	<0.001				0.871	0.207	1.102	0.486
	Roots	−2.960	0.179	<0.001	2.361	0.069	<0.001				0.874	0.199	1.098	0.495
	Aboveground part	−3.288	0.144	<0.001	2.777	0.056	<0.001				0.937	0.129	1.063	0.364
	Whole tree	−2.521	0.132	<0.001	2.639	0.051	<0.001				0.941	0.108	1.053	0.336
[10]	Stem over bark	3.108	0.043	<0.001	2.302	0.073	<0.001				0.854	0.318	1.166	0.672
	Branches	1.833	0.069	<0.001	2.324	0.117	<0.001				0.703	0.803	1.474	1.671
	Foliage	2.206	0.058	<0.001	1.712	0.098	<0.001				0.643	0.573	1.308	1.068
	Roots	2.964	0.061	<0.001	1.651	0.102	<0.001				0.607	0.620	1.298	0.949
	Aboveground part	3.669	0.048	<0.001	2.161	0.082	<0.001				0.806	0.396	1.216	0.855
	Whole tree	4.094	0.050	<0.001	2.000	0.085	<0.001				0.767	0.427	1.226	0.853
[11]	Stem over bark	−1.530	0.163	<0.001	1.848	0.065	<0.001	1.015	0.054	<0.001	0.975	0.054	1.026	0.222
	Branches	−4.768	0.364	<0.001	2.630	0.144	<0.001	0.423	0.121	<0.001	0.901	0.270	1.130	0.560
	Foliage	−3.286	0.317	<0.001	2.188	0.126	<0.001	0.188	0.105	0.076	0.873	0.205	1.100	0.479
	Roots	−2.898	0.314	<0.001	2.336	0.124	<0.001	0.025	0.104	0.809	0.874	0.200	1.098	0.493
	Aboveground part	−1.486	0.186	<0.001	2.054	0.074	<0.001	0.731	0.062	<0.001	0.966	0.070	1.034	0.266
	Whole tree	−1.236	0.197	<0.001	2.124	0.078	<0.001	0.521	0.065	<0.001	0.957	0.079	1.038	0.285

Table 3 presents statistical characteristics of the three models derived for the calculation of the dry mass of individual tree components using different independent variables (d_0, h, or their combination). Although d_0 diameter is a variable frequently affected by stem thickening, and it is very difficult to determine its precise position at the stem, our analyses showed that all models using this variable were from the point of their coefficients of determination R^2 more suitable for the calculation of the dry mass of individual components than the models containing height as an independent variable. The model, which contained both independent variables, had only a slightly higher value of R^2 if at all, and because the values of R^2 were high in the case of all the derived models, we did not consider using other independent variables (d^2, d/h, crown length, crown width, etc.).

This knowledge is generally valid for all tree species, and hence, we will not repeatedly comment the tables with the statistical characteristics of the models for the calculation of dry mass of individual tree components in the further text.

Table 4. *Common beech, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Dependent variable	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.034	0.005	<0.001	2.821	0.035	<0.001				0.977	4 613
	SOB density	720.637	35.433	<0.001	−0.038	0.019	0.050				0.022	6 418
	R/S ratio	1.366	0.219	<0.001	−0.374	0.066	<0.001				0.185	0.046
[14]	SOB volume	13.984	1.205	<0.001	3.490	0.055	<0.001				0.968	6 518
	SOB density	656.288	5.906	<0.001	−0.066	0.015	<0.001				0.099	5 912
	R/S ratio	0.530	0.015	<0.001	−0.444	0.046	<0.001				0.372	0.036
[15]	SOB volume	0.483	0.115	<0.001	1.679	0.102	<0.001	1.282	0.121	<0.001	0.987	2 551
	SOB density	527.902	43.144	<0.001	0.087	0.032	0.008	−0.124	0.027	<0.001	0.137	5 702
	R/S ratio	0.371	0.091	<0.001	0.142	0.097	0.145	−0.534	0.076	<0.001	0.381	0.035

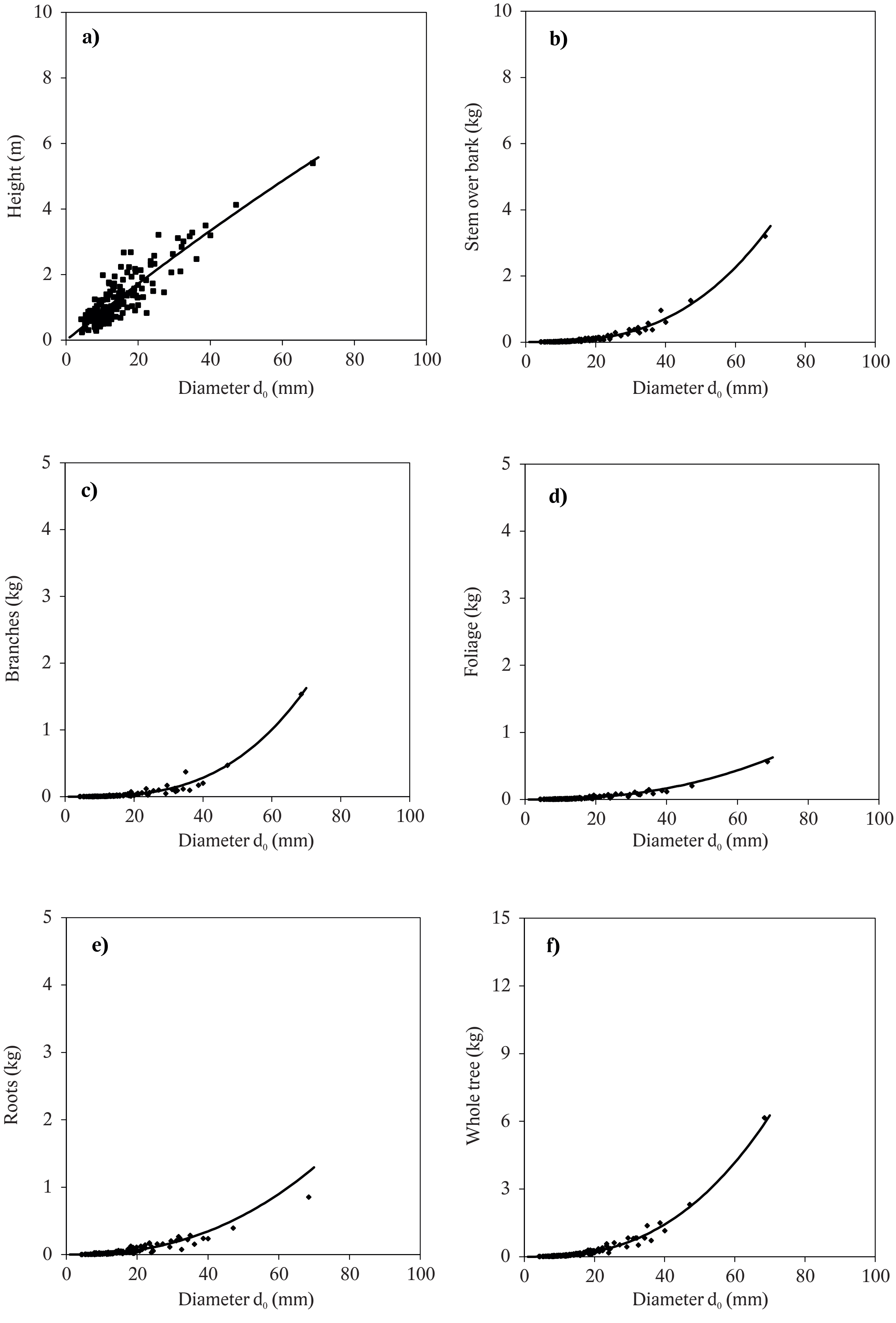

Fig. 3. *Relationship of height a), dry mass of stem over bark b), dry mass of branches c), dry mass of foliage d), dry mass of roots e) and dry mass of the whole tree f) to stem base diameter d_0 of Common beech.*

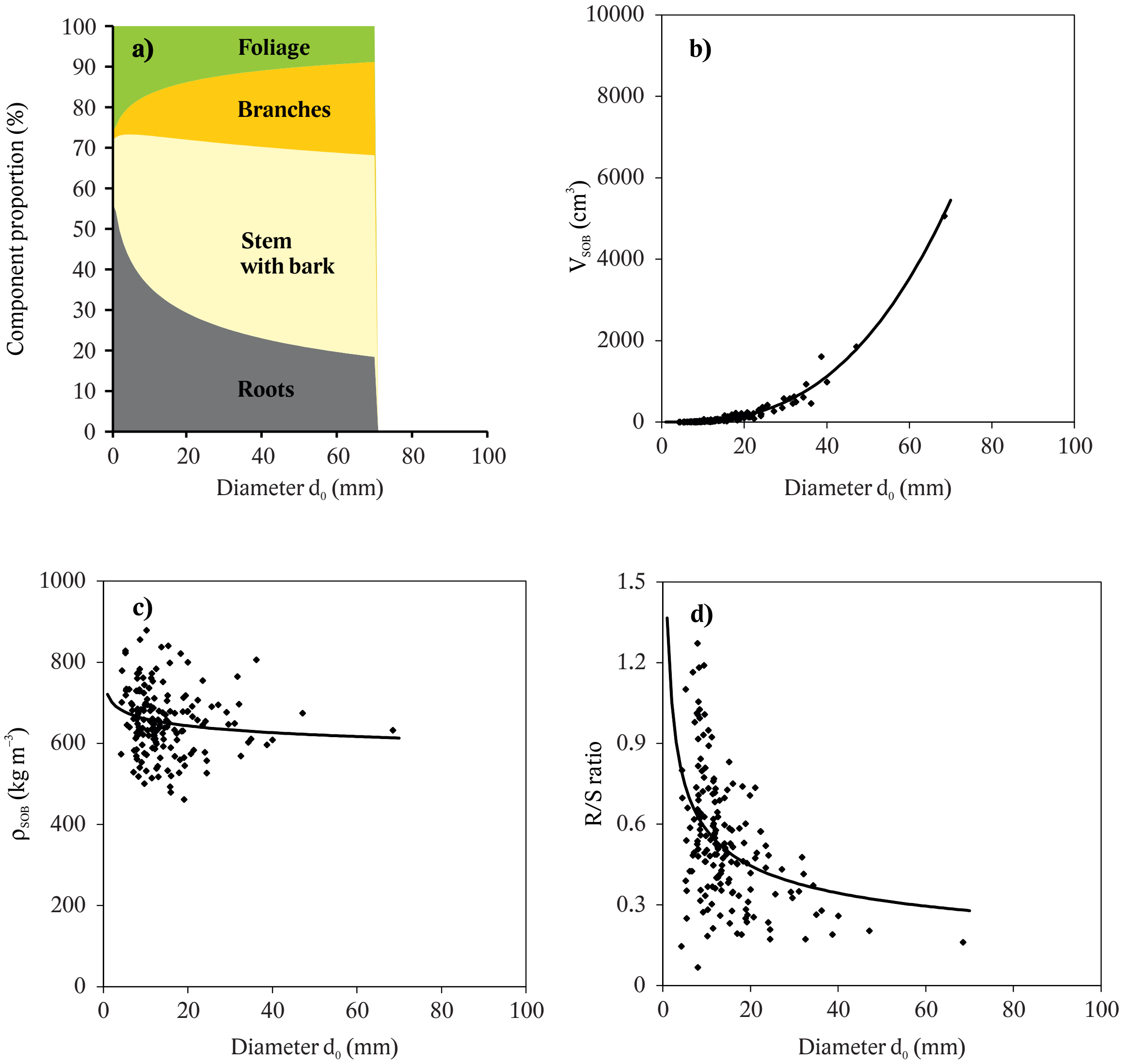

Fig. 4. *Relationship of the component proportion a), volume of stem over bark b), basic density of stem over bark c), R/S ratio d) to stem base diameter d_0 of Common beech.*

4.2. Norway spruce

Norway spruce (*Picea abies* [L.] H. Karst.) is the main and the most frequent coniferous tree species in the forests of Slovakia. Only a single tree species, the most common broadleaved species, i.e. beech, is more frequent. Ecological optimum of spruce is in 7th spruce fvz, where it creates naturally homogeneous stands. It is an important tree species in the forest biotopes of the national and European significance: Ls7.3 Bog spruce forests (*91D0 *Bog woodland*) Ls9.1 Bilberry spruce forests, Ls9.2 Spruce forests with tall herbs, and Ls9.3 Waterlogged spruce forests, all representing NATURA 2000 biotope 9410 *Addophilous Picea forests of the montane to alpine levels (Vaccinio-Piceetea)*.

On the base of the processed NFIM2 SR data, the minimum and maximum elevations at which spruce occurred were 114 m and 1,676 m a.s.l., respectively, while on average it most frequently grew at elevations 800 – 900 m a.s.l. As a commercially important tree species it occurs in all forest vegetation zones from 1st oak zone up to 8th dwarf pine zone. Naturally, it is distributed at higher elevations from 5th fir-beech forest vegetation zone. It grew at a reduced area of 415 ±32 thousand ha, and occurred at 45% of the forested inventory plots.

The biomass regression models were derived from the set of 154 spruce individuals. They were taken from seven sites (see Fig. 5) located in the orographic units of Poľana (sites 1 and 2), Slovenské rudohorie (3 and 4) and Nízke Tatry (5, 6, 7). The samples represented the individuals with d_0 diameters from 1.55 mm to 97.7 mm, and heights from 0.11 m to 5.3 m (Table 5, Fig. 6a). The dry mass of the whole trees ranged from 0.53 g do 8,757.2 g, and the stem volume ranged from 0.18 cm^3 to 8,694.4 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 6. The volume of stem over bark, its density, as well as the root-shoot ratio are presented in Table 7. The regression models, scatter plots, and fitted regression curves were summarised or visualised in a similar way as in the case of Common beech (Chapter 4.1.). More detailed comments on the biomass of the individual components and their proportions of the total tree biomass are presented in Chapter 4.12 (Inter-species comparison of biomass characteristics). The mentioned chapter contains also the interpretations of the volume and density of stem over bark, or of the root-shoot ratio.

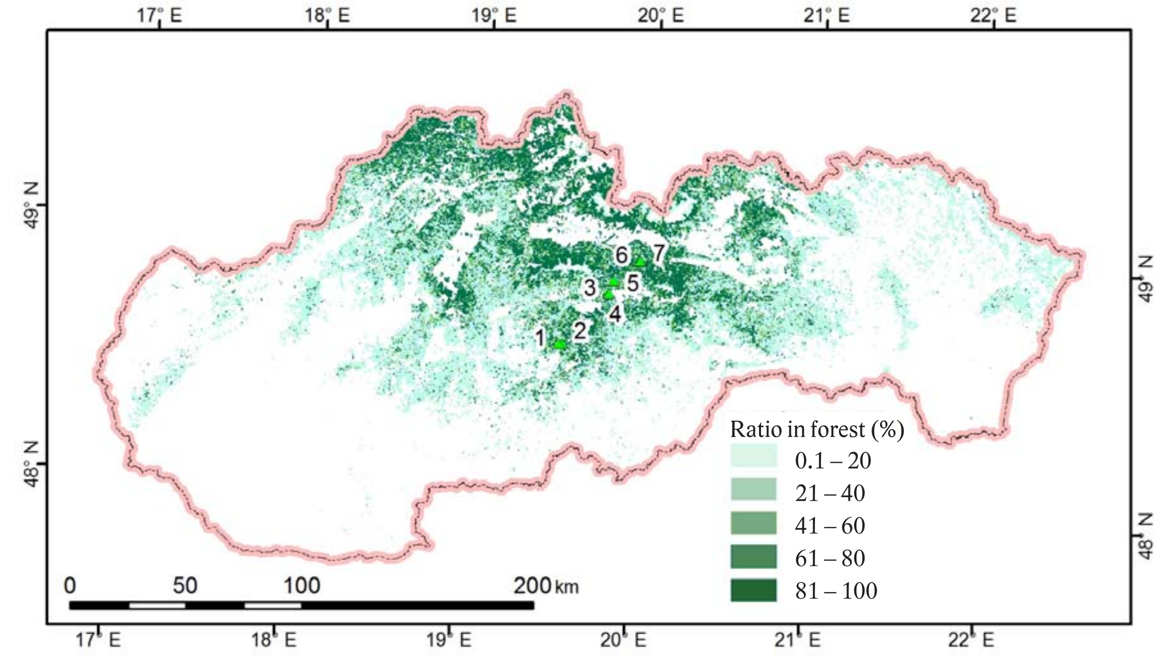

Fig. 5. *Map of sample sites of Norway spruce and its distribution in the forests of Slovakia.*

Table 5. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), foliage biomass (foliage), branch biomass (branches), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

				Norway spruce				
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0(mm)	154	23.15	22.30	1.55	97.7	7.30	33.35	1.42
h(m)	154	1.29	1.17	0.11	5.3	0.35	2.15	1.09
SOB (g)	152	272.96	506.38	0.20	3 158.5	5.85	287.00	2.84
Foliage (g)	151	229.70	425.70	0.03	2 402.5	8.40	269.00	2.88
Branches (g)	151	175.16	353.42	0.04	2 272.0	4.30	182.00	3.49
Roots (g)	151	128.34	214.40	0.23	1 090.0	5.52	135.00	2.34
Aboveground (g)	148	675.58	1 274.25	0.27	7 833.0	19.35	713.75	2.97
Whole tree (g)	145	807.24	1 490.44	0.53	8 757.2	24.86	795.69	2.83
V_{SOB} (cm^3)	154	649.73	1 300.94	0.18	8 694.4	7.85	652.90	3.14

Table 6. *Norway spruce, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficient of determination (R^2), mean square error (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−3.084	0.069	<0.001	2.459	0.024	<0.001				0.986	0.090	1.046	0.324
	Branches	−3.452	0.099	<0.001	2.482	0.035	<0.001				0.971	0.185	1.093	0.488
	Foliage	−2.589	0.099	<0.001	2.317	0.035	<0.001				0.967	0.185	1.082	0.397
	Roots	−2.460	0.070	<0.001	2.114	0.025	<0.001				0.980	0.095	1.046	0.309
	Aboveground part	−1.842	0.069	<0.001	2.398	0.024	<0.001				0.985	0.088	1.043	0.296
	Whole tree	−1.432	0.060	<0.001	2.333	0.021	<0.001				0.988	0.067	1.033	0.258
[10]	Stem over bark	4.010	0.035	<0.001	2.398	0.033	<0.001				0.972	0.178	1.092	0.484
	Branches	3.704	0.056	<0.001	2.376	0.054	<0.001				0.930	0.453	1.245	0.921
	Foliage	4.090	0.058	<0.001	2.200	0.055	<0.001				0.914	0.486	1.232	0.816
	Roots	3.640	0.052	<0.001	2.004	0.049	<0.001				0.919	0.386	1.198	0.748
	Aboveground part	5.072	0.047	<0.001	2.307	0.044	<0.001				0.949	0.308	1.160	0.684
	Whole tree	5.304	0.047	<0.001	2.239	0.044	<0.001				0.948	0.300	1.157	0.676
[11]	Stem over bark	−0.469	0.201		1.555	0.070	<0.001	0.913	0.068	<0.001	0.994	0.041	1.020	0.205
	Branches	−2.553	0.417	<0.001	2.171	0.144	<0.001	0.313	0.141	0.028	0.972	0.180	1.089	0.460
	Foliage	−2.487	0.426	<0.001	2.282	0.147	<0.001	0.036	0.144	0.805	0.967	0.186	1.082	0.396
	Roots	−2.869	0.304	<0.001	2.254	0.105	<0.001	−0.142	0.103	0.169	0.980	0.094	1.045	0.306
	Aboveground part	−0.696	0.281	0.014	2.002	0.097	<0.001	0.400	0.095	<0.001	0.987	0.079	1.037	0.274
	Whole tree	−0.579	0.251	0.023	2.039	0.087	<0.001	0.297	0.085	<0.001	0.989	0.062	1.030	0.248

Table 7. *Norway spruce, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p-values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Dependent variable	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.500	0.171	0.004	2.068	0.079	<0.001				0.913	148 956
	SOB density	1 205.436	37.282	<0.001	−0.254	0.013	<0.001				0.730	10 382
	R/S ratio	0.630	0.038	<0.001	−0.331	0.027	<0.001				0.493	0.008
[14]	SOB volume	108.084	9.163	<0.001	2.649	0.061	<0.001				0.958	72 011
	SOB density	577.291	8.493	<0.001	−0.254	0.012	<0.001				0.767	8 978
	R/S ratio	0.244	0.008	<0.001	−0.316	0.027	<0.001				0.505	0.008
[15]	SOB volume	6.194	0.919	<0.001	0.968	0.045	<0.001	1.709	0.051	<0.001	0.989	18 009
	SOB density	613.631	89.212	<0.001	−0.021	0.050	0.674	−0.234	0.049	<0.001	0.767	9 027
	R/S ratio	0.329	0.102	0.002	−0.105	0.108	0.335	−0.220	0.106	0.040	0.508	0.008

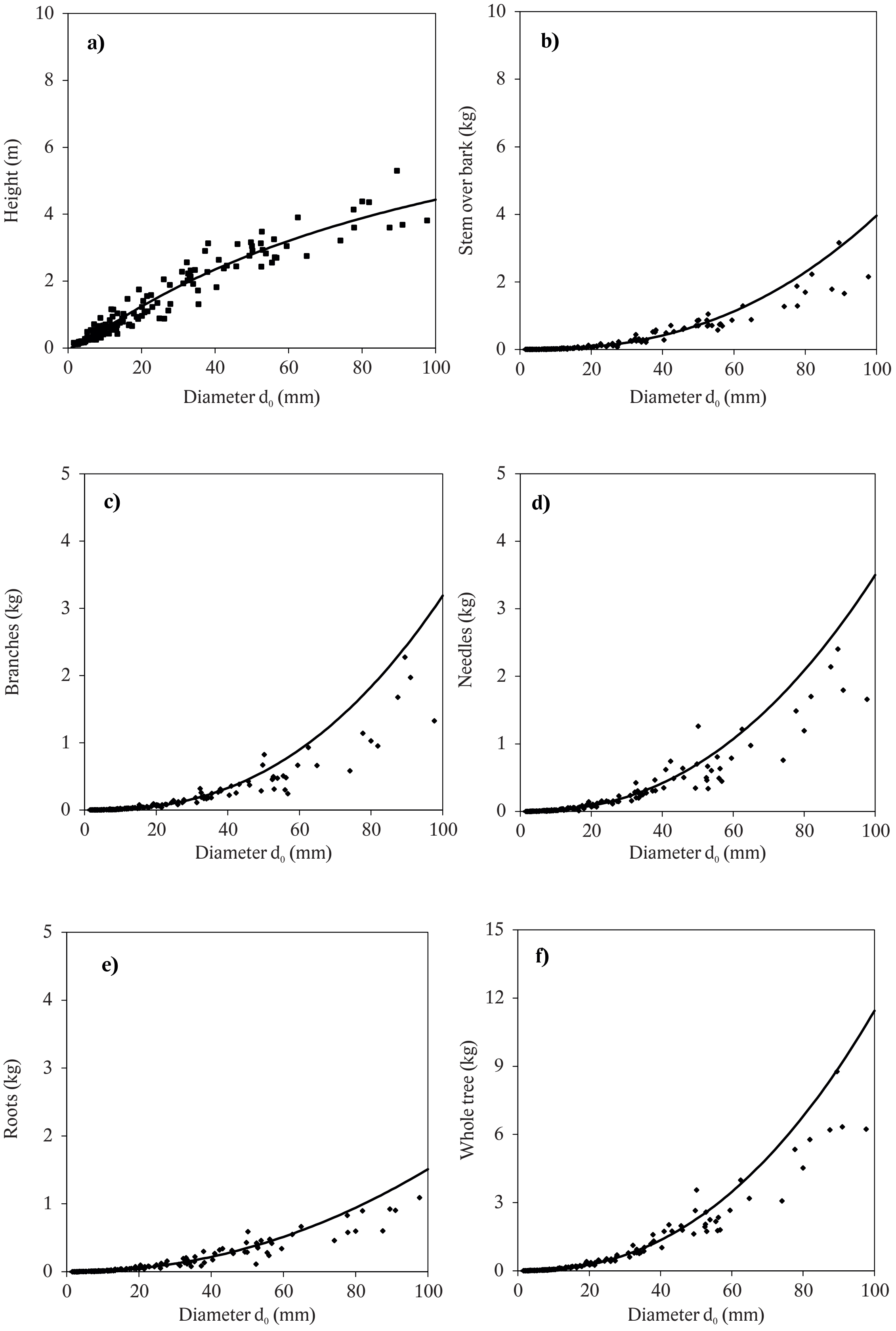

Fig. 6. *Relationship of height a), dry mass of stem over bark b), dry mass of branches c), dry mass of needles d), dry mass of roots e) and dry mass of the whole tree f) to stem base diameter d_0 of Norway spruce.*

Note: *See also the comment on Fig. 6b – 6f, which deals with the fitting of the scatter plot (placed at the end of this chapter, or more detailed information at the end of Chapter 5.).*

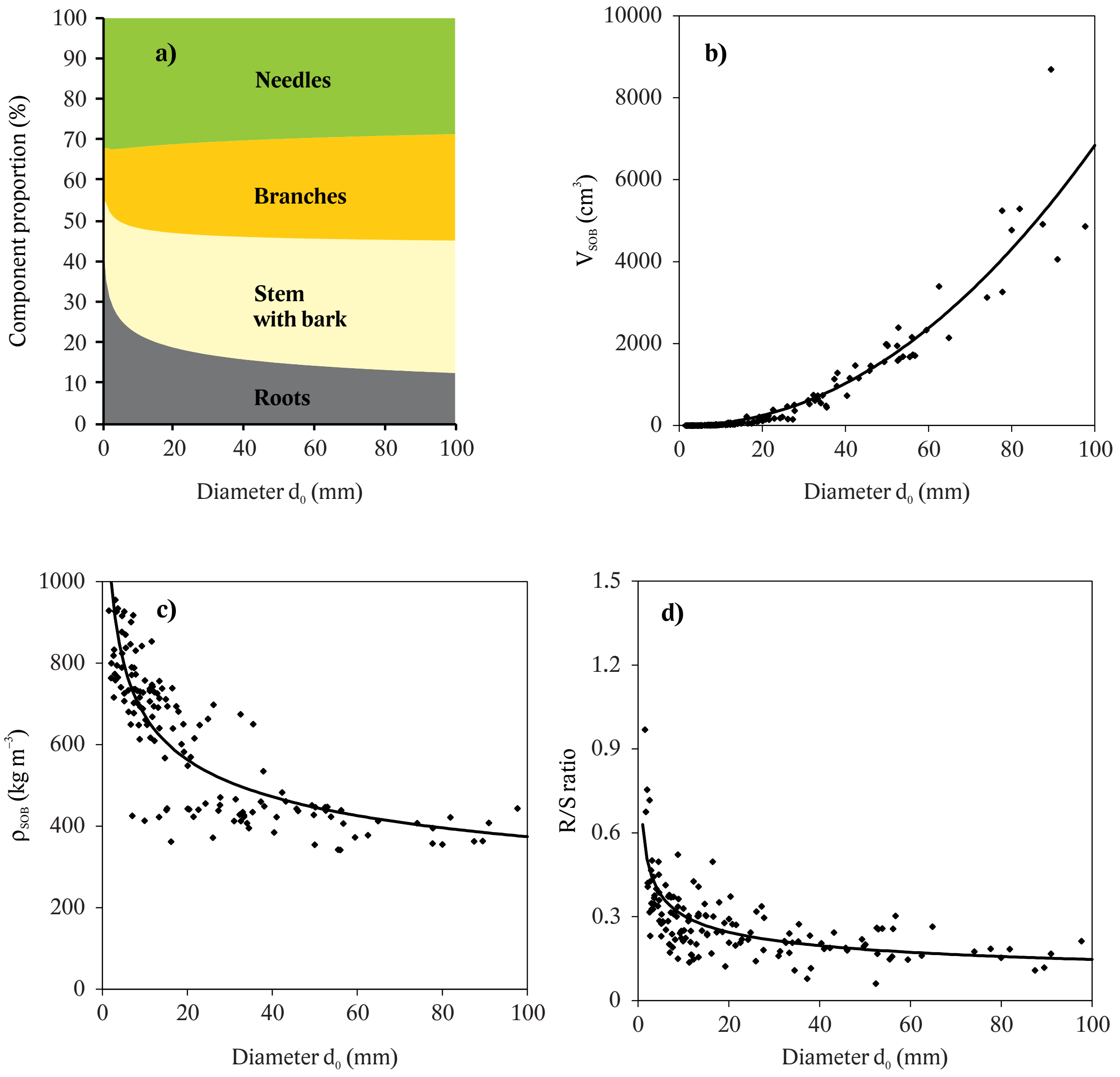

Fig. 7. *Relationship of the dry mass component proportion a), volume of stem over bark b), basic density of stem over bark c), and R/S ratio d) to stem base diameter* d_0 *of Norway spruce.*

Note to fitting the scatter plot:

We would like to point out at the deviation of the fitted regression curves from the actual distribution of the observations in the scatter plot in a particular interval of the values. It can be seen in the examples of the relationships of the biomass of some spruce components, namely stem outside bark, branches, foliage, roots, and the whole tree dry mass, to d_0 diameter for the thickest trees (see Fig. 6b – 6f). A similar situation can be observed also for some other tree species presented in the following chapters. A more detailed description of this phenomenon is presented at the end of Chapter 5 (Knowledge synthesis and conclusion).

4.3. European hornbeam

European hornbeam (*Carpinus betulus* L.) is a commercially less important tree species, particularly from the point of assortment quality. It is most frequently used as fuel-wood. Hornbeam occurs as a secondary stand-forming tree species in lower vegetation zones, mainly in 2nd beech-oak and in 3rd oak-beech zones, where it is most abundant, although from all tree species it reaches only a proportion of 20%. It often forms the under-storey of oak and beech stands. From the silvicultural point of view, it participates in the formation of high-quality assortments of these species. It is an important element of the forest biotopes of European and national significance: Ls 2.2 Pannonian oak-hornbeam forests (NATURA 2000 *91G0 *Pannonic woods with Quercus petraea and Carpinus betulus*), Ls 2.31 Oak-hornbeam forests with lime (9170 *Galio-Carpinetum oak-hornbeam forests*), Ls 2.33 Oak-hornbeam forests with lime.

Hornbeam occurred at elevations between 100 m (the lowest occurrence) and 809 m a.s.l. (the highest occurrence), most frequently between 350 – 450 m a.s.l. (NFIM2 SR data). It is the fourth most common tree species in the forests of Slovakia from the point of its occurrence, while from the point of the spatial proportion it is the third, and when considering the stand stock it is the 6th tree species in the tree species ranking. It grew at a reduced area of 187 ±22 thousand ha, and occurred at 32% of the forested inventory plots.

The biomass regression models were derived from the set of 200 hornbeam trees. They were taken from eight sites (see Fig. 8), which were located in the orographic units of Malé Karpaty (site 1), Tribeč (2), Štiavnické vrchy (3), Kremnické vrchy (4), Krupinská planina (5), Slovenské rudohorie (6 and 7) and Nízke Beskydy (8). The samples represented the individuals with d_0 diameters from 0.90 mm to 81.20 mm, and heights from 0.07 m to 7.56 m (Table 8, Fig. 9a). The dry mass of the whole trees ranged from 0.10 g do 5,399.22 g, and the stem volume ranged from 0.02 cm^3 to 8,402.30 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 9. In contrast to beech and spruce, for hornbeam we also derived the dry mass of the stem under bark and stem bark.

The regression models, scatter plots, and fitted regression curves were summarised or visualised in a similar way as in the case of Common beech (Chapter 4.1.). Unlike for beech, we graphically presented also bark density. Further comments on the biomass of individual components and their proportions in the total tree biomass are presented in Chapter 4.12. (Inter-species comparison of biomass characteristics).

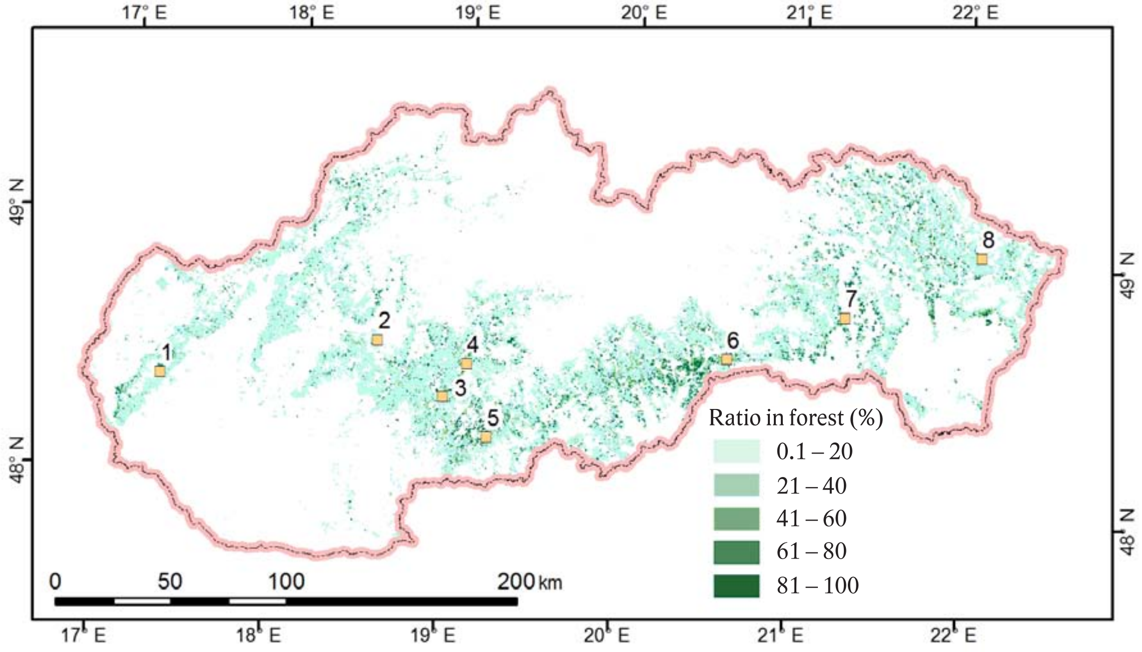

Fig. 8. *Map of sample sites of European hornbeam and its distribution in the forests of Slovakia.*

Table 8. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), biomass of stem under bark (SUB), foliage biomass (foliage), branch biomass (branches), bark biomass (bark), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

	European hornbeam							
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	200	17.84	13.94	0.90	81.20	7.90	23.03	1.70
h (m)	200	2.68	1.83	0.07	7.56	1.10	3.88	0.65
SOB (g)	199	299.34	656.22	0.03	4 429.74	9.60	223.62	3.78
SUB (g)	200	263.27	596.14	0.03	4 038.19	8.01	191.30	3.84
Foliage (g)	196	31.18	59.22	0.03	346.34	1.78	35.67	3.37
Branches (g)	199	56.10	138.84	0.00	953.15	1.65	43.15	4.28
Bark (g)	199	34.82	59.61	0.002	391.55	2.67	35.15	3.27
Roots (g)	197	78.40	185.46	0.04	1 473.50	5.83	60.50	4.61
Aboveground (g)	194	346.45	713.01	0.06	4 329.52	12.70	284.95	3.66
Whole tree (g)	191	414.91	858.13	0.10	5 399.22	19.44	341.31	3.68
V_{SOB} (cm^3)	200	552.55	1 224.93	0.02	8 402.30	17.31	448.09	3.92

Table 9. *European hornbeam, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−3.402	0.081	<0.001	2.809	0.030	<0.001				0.978	0.124	1.066	0.415
	Stem inside bark	−3.881	0.086	<0.001	2.904	0.032	<0.001				0.977	0.140	1.075	0.447
	Branches	−5.573	0.138	<0.001	2.924	0.050	<0.001				0.946	0.295	1.143	0.596
	Foliage	−4.127	0.165	<0.001	2.354	0.061	<0.001				0.884	0.497	1.225	0.700
	Bark	−4.090	0.085	<0.001	2.440	0.031	<0.001				0.971	0.110	1.056	0.356
	Roots	−3.105	0.078	<0.001	2.301	0.029	<0.001				0.968	0.138	1.069	0.410
	Aboveground part	−2.919	0.068	<0.001	2.745	0.025	<0.001				0.984	0.086	1.045	0.334
	Whole tree	−2.389	0.062	<0.001	2.640	0.023	<0.001				0.986	0.068	1.034	0.277
[10]	Stem over bark	2.281	0.048	<0.001	2.407	0.041	<0.001				0.946	0.308	1.163	0.678
	Stem inside bark	1.988	0.050	<0.001	2.487	0.044	<0.001				0.943	0.347	1.185	0.730
	Branches	0.419	0.089	<0.001	2.392	0.079	<0.001				0.826	0.950	1.525	1.505
	Foliage	0.733	0.092	<0.001	1.848	0.080	<0.001				0.732	1.153	1.619	1.570
	Bark	0.831	0.038	<0.001	2.111	0.033	<0.001				0.846	0.576	1.345	1.224
	Roots	1.613	0.066	<0.001	1.867	0.057	<0.001				0.955	0.195	1.099	0.492
	Aboveground part	2.668	0.053	<0.001	2.301	0.046	<0.001				0.929	0.377	1.203	0.778
	Whole tree	2.998	0.055	<0.001	2.186	0.048	<0.001				0.915	0.404	1.222	0.843
[11]	Stem over bark	−1.941	0.121	<0.001	1.922	0.058	<0.001	0.909	0.051	<0.001	0.991	0.054	1.029	0.270
	Stem inside bark	−1.486	0.106	<0.001	1.841	0.051	<0.001	0.896	0.044	<0.001	0.993	0.041	1.021	0.220
	Branches	−5.514	0.291	<0.001	2.893	0.140	<0.001	0.029	0.123	0.816	0.946	0.296	1.143	0.594
	Foliage	−5.423	0.366	<0.001	3.008	0.177	<0.001	−0.599	0.152	<0.001	0.893	0.463	1.211	0.696
	Bark	−2.026	0.106	<0.001	1.396	0.051	<0.001	0.965	0.045	<0.001	0.971	0.109	1.055	0.353
	Roots	−3.348	0.174	<0.001	2.424	0.084	<0.001	−0.114	0.073	0.121	0.991	0.041	1.018	0.183
	Aboveground part	−1.603	0.120	<0.001	2.083	0.058	<0.001	0.605	0.050	<0.001	0.991	0.049	1.025	0.239
	Whole tree	−1.445	0.121	<0.001	2.165	0.058	<0.001	0.433	0.050	<0.001	0.990	0.049	1.024	0.226

Table 10. *European hornbeam, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Dependent variable	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.837	0.156	<0.001	2.091	0.044	<0.001				0.944	122 079
	SUB volume	0.644	0.123	<0.001	2.133	0.045	<0.001				0.944	102 312
	Bark volume	0.333	0.064	<0.001	1.719	0.047	<0.001				0.899	1 526
	SOB density	880.710	26.524	<0.001	−0.155	0.012	<0.001				0.444	6 885
	SUB density	835.631	26.790	<0.001	−0.148	0.012	<0.001				0.391	6 913
	Bark density	910.292	33.268	<0.001	−0.109	0.014	<0.001				0.230	15 234
	Bark mass proportion	54.421	0.818	<0.001	−0.382	0.006	<0.001				0.631	21.17
	Bark volume proportion	50.321	1.460	<0.001	−0.406	0.014	<0.001				0.793	14.84
	R/S ratio	0.898	0.055	<0.001	−0.437	0.029	<0.001				0.501	0.019
[14]	SOB volume	0.432	0.155	0.006	4.844	0.184	<0.001				0.902	211 954
	SUB volume	0.297	0.112	0.009	4.991	0.193	<0.001				0.901	181 452
	Bark volume	0.412	0.111	<0.001	3.594	0.141	<0.001				0.877	1 857
	SOB density	645.813	6.400	<0.001	−0.139	0.009	<0.001				0.522	5 915
	SUB density	623.866	6.327	<0.001	−0.140	0.009	<0.001				0.508	5 587
	Bark density	726.468	10.301	<0.001	−0.087	0.012	<0.001				0.196	15 911
	Bark mass proportion	23.889	0.345	<0.001	−0.247	0.012	<0.001				0.662	19.52
	Bark volume proportion	21.969	0.307	<0.001	−0.331	0.011	<0.001				0.783	15.49
	R/S ratio	0.371	0.010	<0.001	−0.379	0.021	<0.001				0.595	0.015
[15]	SOB volume	0.651	0.070	<0.001	1.313	0.037	<0.001	1.845	0.082	<0.001	0.986	30 603
	SUB volume	0.474	0.051	<0.001	1.345	0.036	<0.001	1.895	0.082	<0.001	0.987	24 272
	Bark volume	0.390	0.063	<0.001	1.015	0.068	<0.001	1.469	0.136	<0.001	0.939	923
	SOB density	644.316	42.885	<0.001	0.001	0.032	0.978	−0.136	0.026	<0.001	0.511	6 078
	SUB density	519.312	36.561	<0.001	0.088	0.033	0.099	−0.211	0.028	<0.001	0.525	5 423
	Bark density	964.983	91.240	<0.001	−0.138	0.046	0.003	0.026	0.039	0.506	0.232	15 276
	Bark mass proportion	45.331	4.604	<0.001	−0.313	0.050	<0.001	0.006	0.041	0.876	0.716	16.45
	Bark volume proportion	35.572	3.644	<0.001	−0.234	0.050	<0.001	−0.145	0.041	<0.001	0.805	14.01
	R/S ratio	0.217	0.046	<0.001	0.256	0.099	0.011	−0.581	0.081	<0.001	0.609	0.015

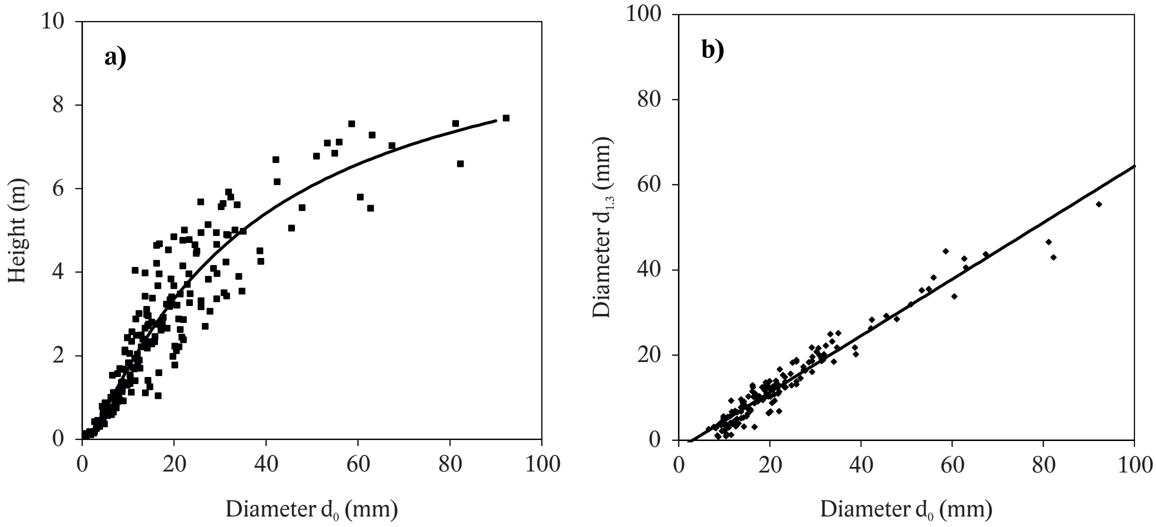

Fig. 9. *Relationship of tree height a) and $d_{1.3}$ diameter b) to stem base diameter d_0 of European hornbeam.*

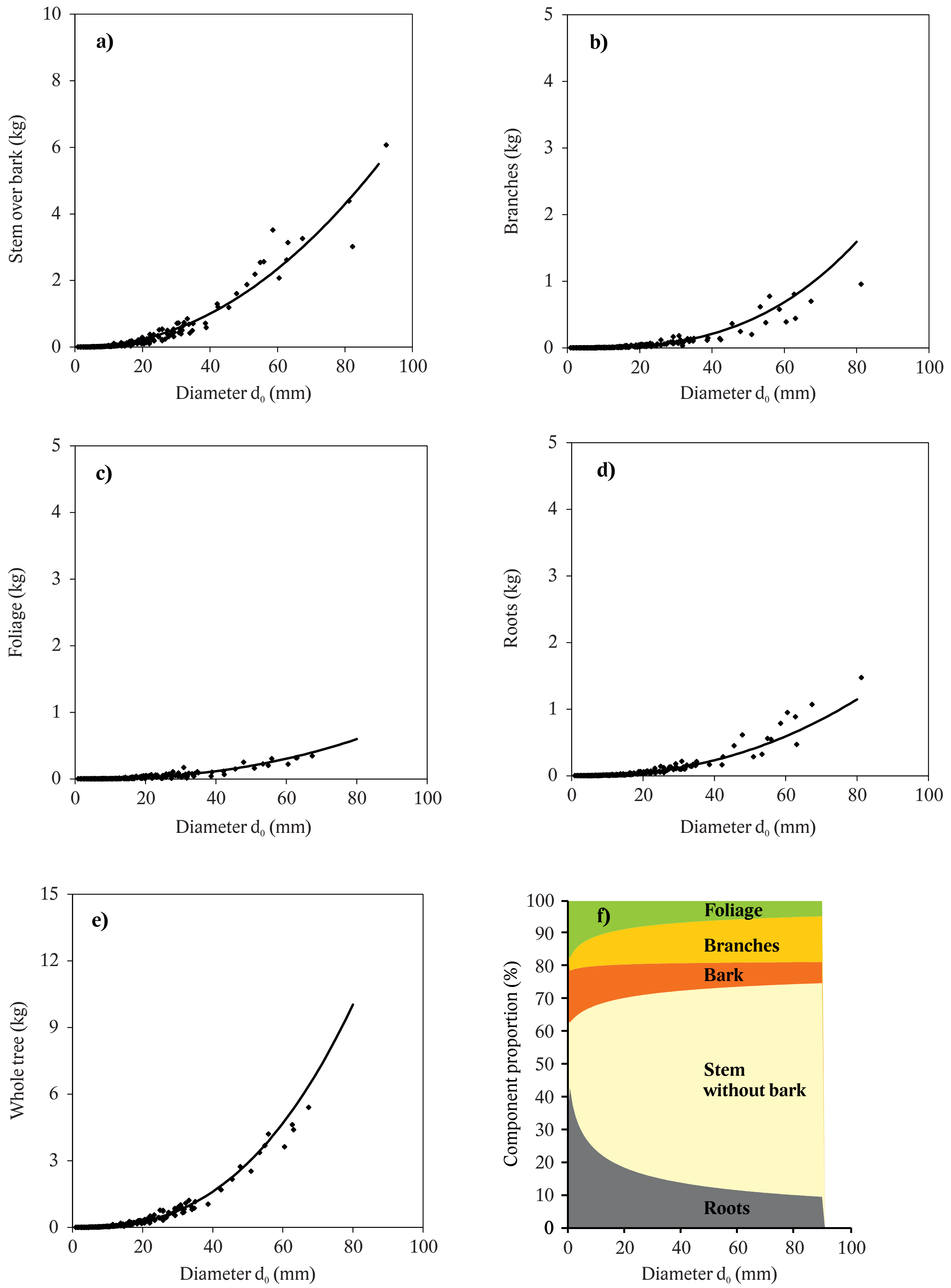

Fig. 10. *Relationship of dry mass of stem over bark a), dry mass of branches b), dry mass of foliage c), dry mass of roots d) and dry mass of the whole tree e) and proportion of individual tree components f) to stem base diameter* d_0 *of European hornbeam.*

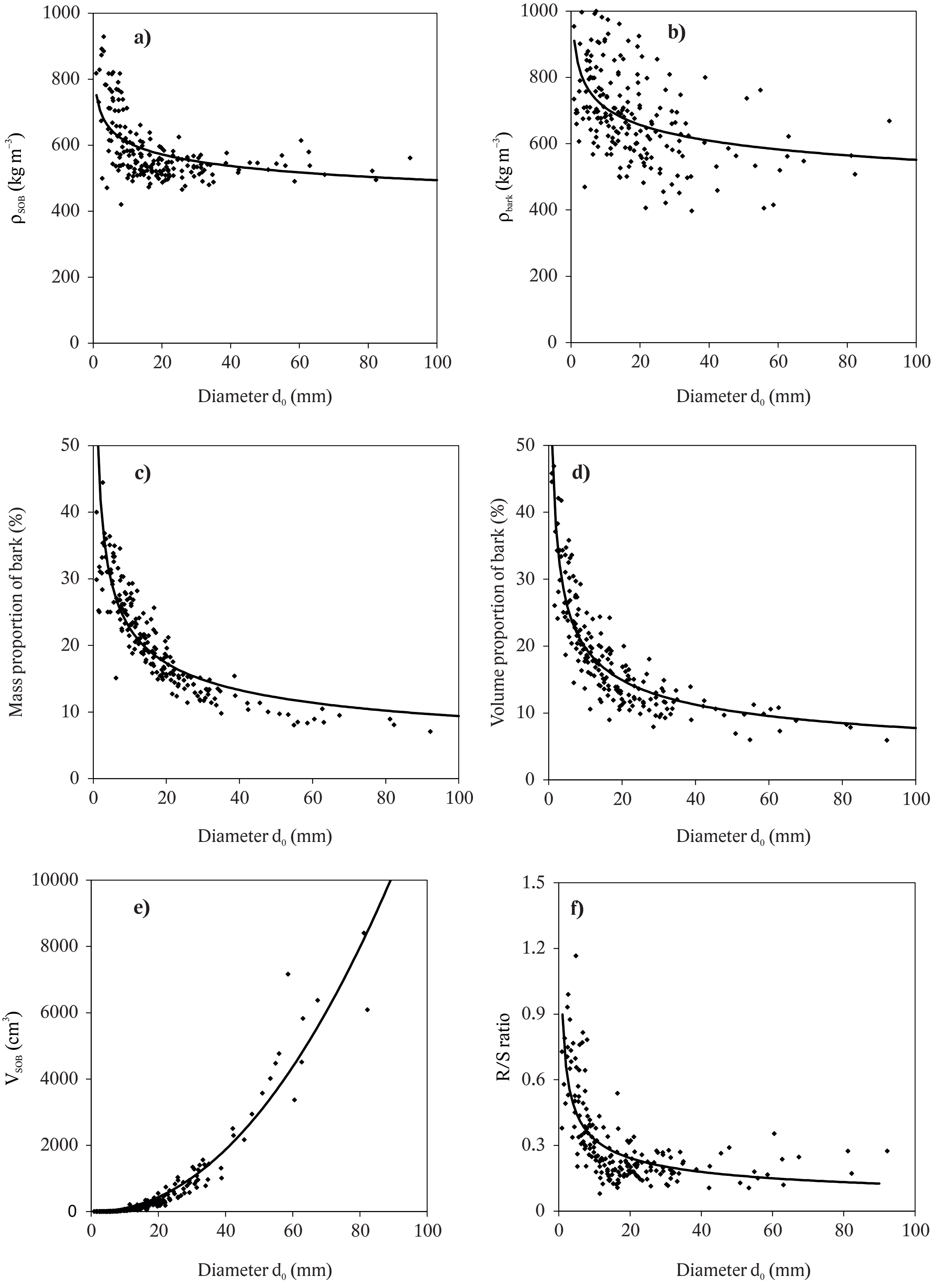

Fig. 11. *Relationship of the basic density of stem over bark a), basic bark density b), mass proportion of bark in SOB mass c), volume proportion of bark in SOB volume d) volume of stem over bark e), and R/S ratio f) to stem base diameter d_0 of European hornbeam.*

4.4. Sessile oak

Sessile oak (*Quercus petraea* [Matt.] Liebl.) is a commercially important tree species of the forests at lower elevations. It predominantly occurs at lower forest vegetation zones from 1st oak to 3rd oak-beech zones, and sporadically also in 4th beech zone, but it does not grow at higher elevations. It is an important tree species in several forest biotopes of European and national significance: Ls2.2 Pannonian oak-hornbeam forests (NATURA 2000*91G0 *Pannonic woods with Quercus petraea and Carpinus betulus*), Ls2.31 Oak-hornbeam forests with lime (9170 Galio-Carpinetum oak-hornbeam forests), Ls2.33 Oak-hornbeam forests with lime, Ls3.2 Thermophillic Pontic-Pannonian oak forests on loess and sand, Ls3.3 Oak cinquefoil forests, Ls3.52 Xerophilous and Acidophilous oak forests (*91I0 *Euro-Siberian steppic woods with Quercus spp.*), Ls3.4 Sessile oak-Turkey oak forests (91M0 *Pannonian-Balkanic turkey oak-sessile oak forests*).

On the base of the processed NFIM2 SR data, the minimum and maximum elevations at which oak occurred were 109 m and 833 m a.s.l., respectively, while most frequently it grew at elevations 300 – 400 m a.s.l. With regard to the stand stock, it is the third most common tree species in the forests of Slovakia, from the point of the occupied area it is 4th, and from the point of occurrence it is 5th in tree species ranking. It grew at a reduced area of 160 ±21 thousand ha, and occurred at 28% of the forested inventory plots.

The biomass regression models of the Sessile oak were derived from 162 individuals. They were taken from eight sites (see Fig. 12), which were located in the orographic units of the Štiavnické vrchy (sites 1 and 2) and Kremnické vrchy (3, 4, 5, 6, 7). The samples represented the individuals with d_0 diameters from 4.45 mm to 88.75 mm, and heights from 0.28 m to 6.64 m (Table 11, Fig. 13a). The dry mass of the whole trees ranged from 5.17 g do 8,790.0 g, and the stem volume ranged from 1.46 cm^3 to 8,300.0 cm^3.

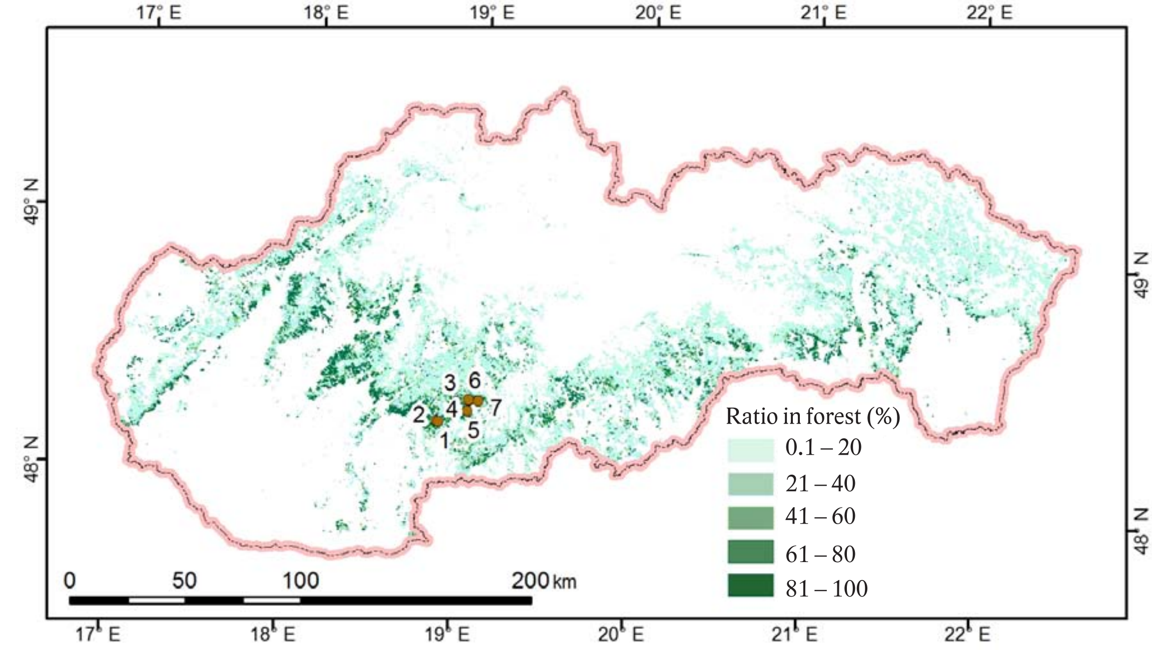

Fig. 12. *Map of sample sites of Sessile oak and its distribution in the forests of Slovakia.*

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 12. Similarly, the volume of stem outside bark, its density, as well as the root-shoot ratio were derived (Table 13).

The regression models, scatter plots, and fitted regression curves were summarised or visualised in a similar way as in the case of Common beech (Chapter 4.1.). Further comments on the biomass of individual components and their proportions of the total tree biomass are presented in Chapter 4.12. (Inter-species comparison of biomass characteristics).

Table 11. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), foliage biomass (foliage), branch biomass (branches), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

				Sessile oak				
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	162	26.85	20.77	4.45	88.75	11.00	40.25	1.22
h (m)	162	2.21	1.80	0.28	6.64	0.69	3.54	0.76
SOB (g)	140	541.07	1 146.41	1.30	5 784.0	11.65	443.50	2.86
Foliage (g)	140	54.36	115.40	0.20	546.0	1.60	38.00	2.76
Branches (g)	140	102.43	227.41	0.09	1 132.0	2.15	65.75	3.03
Roots (g)	162	217.20	328.98	3.03	1 435.0	22.25	252.20	2.22
Aboveground (g)	140	697.86	1 485.43	2.14	7 355.0	14.66	541.25	2.87
Whole tree (g)	140	876.25	1 794.34	5.17	8 790.0	33.75	705.21	2.83
V_{SOB} (cm^3)	162	934.07	1 710.14	1.46	8 300.0	20.28	900.52	2.48

Table 12. *Sessile oak, b_0, b_1, b_2, regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−4.311	0.224	<0.001	2.959	0.071	<0.001				0.942	0.240	1.121	0.544
	Branches	−6.025	0.215	<0.001	2.963	0.068	<0.001				0.947	0.221	1.107	0.496
	Foliage	−5.954	0.221	<0.001	2.768	0.070	<0.001				0.936	0.234	1.106	0.459
	Roots	−1.954	0.150	<0.001	2.066	0.046	<0.001				0.941	0.124	1.065	0.401
	Aboveground part	−3.952	0.206	<0.001	2.931	0.065	<0.001				0.950	0.203	1.099	0.469
	Whole tree	−2.612	0.175	<0.001	2.646	0.005	<0.001				0.956	0.146	1.070	0.382
[10]	Stem over bark	3.471	0.045	<0.001	2.516	0.046	<0.001				0.965	0.147	1.074	0.419
	Branches	1.839	0.086	<0.001	2.388	0.089	<0.001				0.871	0.535	1.271	0.896
	Foliage	1.370	0.074	<0.001	2.269	0.077	<0.001				0.891	0.398	1.190	0.700
	Roots	3.511	0.053	<0.001	1.719	0.051	<0.001				0.898	0.213	1.112	0.553
	Aboveground part	3.769	0.050	<0.001	2.468	0.052	<0.001				0.954	0.186	1.095	0.483
	Whole tree	4.369	0.051	<0.001	2.207	0.053	<0.001				0.942	0.189	1.099	0.503
[11]	Stem over bark	−0.066	0.170	0.698	1.324	0.063	<0.001	1.491	0.053	<0.001	0.993	0.029	1.014	0.171
	Branches	−4.263	0.432	<0.001	2.284	0.161	<0.001	0.619	0.135	<0.001	0.956	0.186	1.092	0.473
	Foliage	−3.577	0.412	<0.001	1.852	0.153	<0.001	0.835	0.129	<0.001	0.954	0.169	1.077	0.399
	Roots	−0.226	0.289	0.436	1.398	0.107	<0.001	0.611	0.091	<0.001	0.956	0.092	1.047	0.333
	Aboveground part	−0.201	0.194	0.303	1.486	0.072	<0.001	1.317	0.061	<0.001	0.991	0.038	1.019	0.199
	Whole tree	0.389	0.201	0.056	1.490	0.075	<0.001	1.054	0.063	<0.001	0.989	0.040	1.020	0.209

Table 13. *Sessile oak, b_0, b_1, b_2, regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.235	0.062	<0.001	2.325	0.062	<0.001				0.955	133 632
	SOB density	896.210	37.848	<0.001	−0.065	0.015	<0.001				0.128	8 334
	R/S ratio	9.135	1.228	<0.001	−0.888	0.059	<0.001				0.698	0.113
[14]	SOB volume	20.139	5.424	<0.001	3.144	0.156	<0.001				0.882	348 588
	SOB density	751.731	8.245	<0.001	−0.038	0.012	0.002				0.070	8 890
	R/S ratio	0.828	0.030	<0.001	−0.772	0.044	<0.001				0.780	0.082
[15]	SOB volume	0.493	0.082	<0.001	1.676	0.052	<0.001	1.205	0.074	<0.001	0.984	46 900
	SOB density	1 208.970	136.502	<0.001	−0.177	0.042	<0.001	0.095	0.034	0.005	0.177	7929
	R/S ratio	1.296	0.377	0.001	−0.167	0.108	0.124	−0.651	0.089	<0.001	0.783	0.082

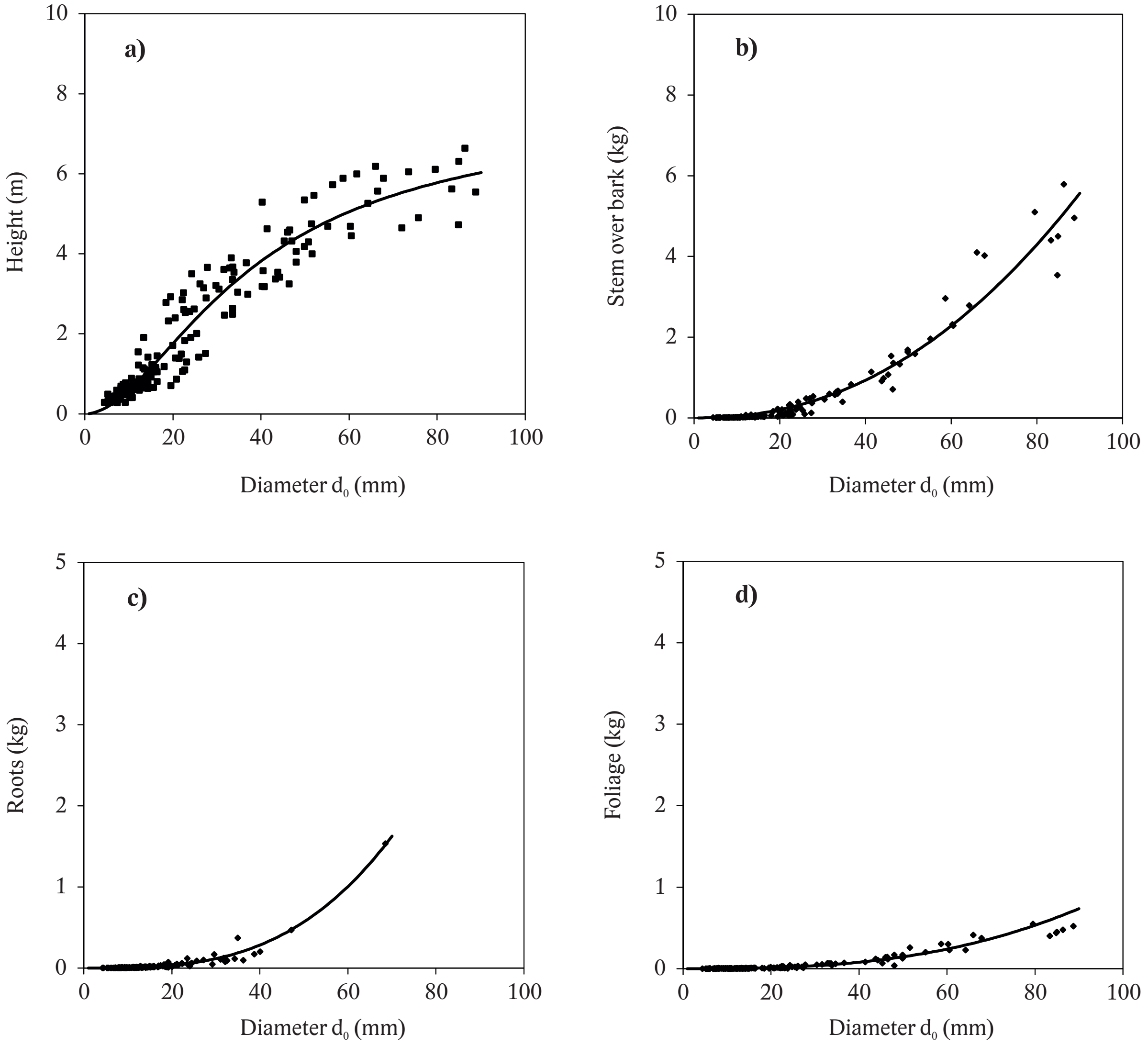

Fig. 13. *Relationship of height a), dry mass of stem outside bark b), dry mass of branches c), dry mass of foliage d) to stem base diameter d_0 of Sessile oak.*

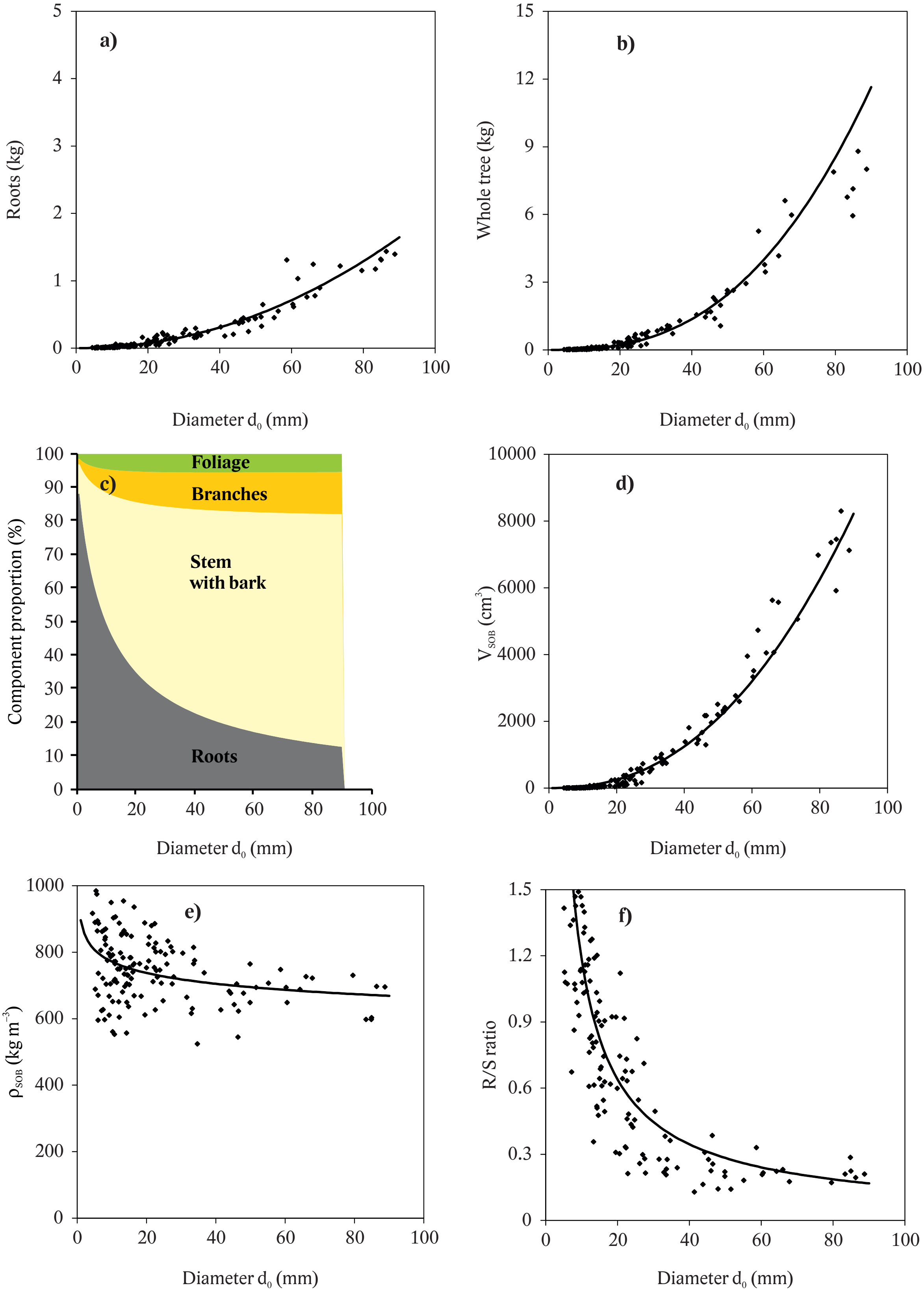

Fig. 14. *Relationship of root dry mass a) total tree dry mass b), proportion of individual components c), volume of stem over bark d), reduced stem density over bark e), and R/S ratio f) to stem base diameter d_0 of Sessile oak.*

4.5. Scots pine

Scots pine (*Pinus sylvestris* L.) is a pioneer and a target tree species growing at a wide range of ecological conditions. It tolerates dry and nutrient-poor rocky soils, but it also grows on wet, waterlogged or even peat sites. It sporadically occurs in all forest vegetation zones, and dominates in the area of the Záhorská nížina (plain). It is particularly important in two biotopes: Ls7.2 Bog pine forests (NATURA 2000 *91D0 *Bog woodland*), and Ls6.2 Relict calcareous pine and larch forests (91Q0 *Western Carpathian calcicolous Pinus sylvestris forests*).

Pine occurred at elevations between 144 m (the lowest occurrence) and 1,285 m a.s.l. (the highest occurrence), most frequently between 200 – 300 m a.s.l. (NFIM2 SR data). From the point of its stand stock, it is the 4th most common tree species in the forests of Slovakia, according to the area it is 5th, and according to its occurrence at the forested inventory plots it was 7th most common tree species. It grew at a reduced area of 106 ±17 thousand ha, and occurred at 17% of the forested inventory plots.

The biomass regression models of the Scots pine were derived from 175 individuals. The trees were taken from seven sites (see Fig. 15). The sites were located in the orographic units of the Biele Karpaty (sites 1 and 2), Vtáčnik (3), Štiavnické vrchy (4 and 5), and Levočské vrchy (6 and 7). The sample trees represented the individuals with d_0 diameters from 3.05 mm to 78.10 mm, and heights from 0.13 m to 4.5 m (Table 14, Fig. 16a). The dry mass of the whole trees ranged from 3.05 g do 4,977.0 g, and the stem volume ranged from 0.72 cm^3 to 5,619.7 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole pine tree are presented in Table 15. The volume of stem over bark, its density, as well as the root-shoot ratio were derived in a similar way (Table 16). The regression models, scatter plots, and fitted regression curves were visualised in a similar way as in the case of previous tree species. The text describing the biomass of individual components and their proportions in the total tree biomass are presented in Chapter 4.12. (Inter-species comparison of biomass characteristics).

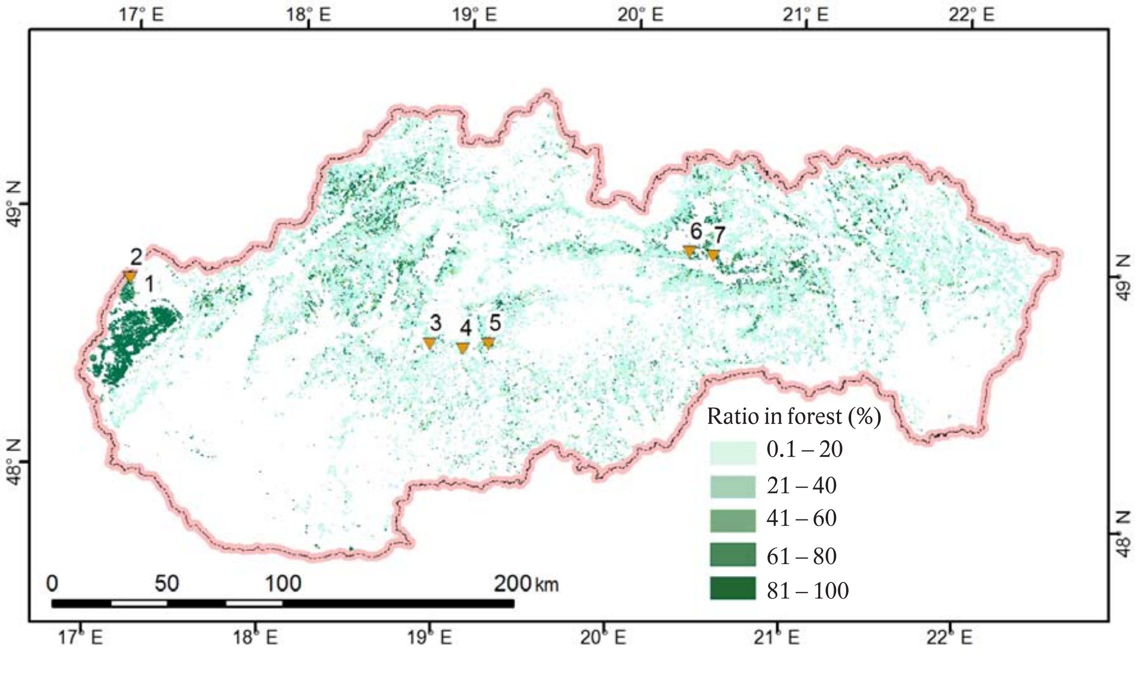

Fig. 15. *Map of sample sites of Scots pine and its distribution in the forests of Slovakia.*

Table 14. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), foliage biomass (foliage), branch biomass (branches), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

	Scots pine							
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	175	28.29	18.35	3.05	78.1	13.45	39.50	0.84
h (m)	175	1.63	1.02	0.13	4.5	0.75	2.27	0.70
SOB (g)	175	315.47	438.97	0.50	2 174.0	25.85	414.00	1.89
Foliage (g)	175	175.43	219.16	1.45	1 283.0	25.60	243.00	2.17
Branches (g)	175	152.42	216.69	0.20	1 077.0	13.00	200.00	2.12
Roots (g)	175	76.55	101.98	0.50	535.0	8.00	100.00	2.15
Aboveground (g)	175	643.31	858.13	2.25	4 442.0	65.35	801.00	1.92
Whole tree (g)	175	719.86	955.25	3.05	4 977.0	72.40	900.50	1.93
V_{SOB} (cm^3)	175	798.17	1 196.04	0.72	5 619.7	50.76	918.51	2.08

Table 15. *Scots pine, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−3.143	0.122	<0.001	2.480	0.038	<0.001				0.960	0.131	1.067	0.395
	Branches	−3.985	0.125	<0.001	2.515	0.039	<0.001				0.960	0.138	1.072	0.435
	Foliage	−1.961	0.144	<0.001	2.014	0.045	<0.001				0.920	0.183	1.089	0.456
	Roots	−3.628	0.130	<0.001	2.236	0.041	<0.001				0.946	0.149	1.079	0.479
	Aboveground part	−1.698	0.097	<0.001	2.290	0.030	<0.001				0.970	0.083	1.041	0.306
	Whole tree	−1.531	0.089	<0.001	2.278	0.028	<0.001				0.975	0.069	1.035	0.282
[10]	Stem over bark	3.958	0.043	<0.001	2.389	0.057	<0.001				0.912	0.293	1.156	0.648
	Branches	3.246	0.062	<0.001	2.304	0.081	<0.001				0.824	0.601	1.323	1.003
	Foliage	3.843	0.060	<0.001	1.805	0.078	<0.001				0.755	0.560	1.273	0.852
	Roots	2.824	0.067	<0.001	1.965	0.087	<0.001				0.745	0.694	1.387	1.173
	Aboveground part	4.880	0.050	<0.001	2.134	0.065	<0.001				0.862	0.388	1.200	0.725
	Whole tree	5.013	0.051	<0.001	2.108	0.066	<0.001				0.854	0.402	1.209	0.752
[11]	Stem over bark	−0.702	0.152	<0.001	1.618	0.052	<0.001	0.944	0.052	<0.001	0.987	0.045	1.023	0.231
	Branches	−3.184	0.257	<0.001	2.232	0.089	<0.001	0.310	0.088	<0.001	0.962	0.129	1.066	0.403
	Foliage	−1.901	0.307	<0.001	1.993	0.106	<0.001	0.024	0.105	0.822	0.920	0.184	1.089	0.457
	Roots	−4.105	0.273	<0.001	2.405	0.094	<0.001	−0.184	0.093	0.050	0.947	0.146	1.078	0.487
	Aboveground part	−0.466	0.177	0.009	1.856	0.061	<0.001	0.476	0.060	<0.001	0.978	0.061	1.031	0.269
	Whole tree	−0.502	0.167	0.003	1.914	0.057	<0.001	0.398	0.057	<0.001	0.980	0.054	1.028	0.253

Table 16. *Scots pine, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [13] – [15].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.235	0.062	<0.001	2.325	0.062	<0.001				0.955	133 632
	SOB density	896.210	37.848	<0.001	−0.065	0.015	<0.001				0.128	8 334
	R/S ratio	9.135	1.228	<0.001	−0.888	0.059	<0.001				0.698	0.113
[14]	SOB volume	20.139	5.424	<0.001	3.144	0.156	<0.001				0.882	348 588
	SOB density	751.731	8.245	<0.001	−0.038	0.012	0.002				0.070	8 890
	R/S ratio	0.828	0.030	<0.001	−0.772	0.044	<0.001				0.780	0.082
[15]	SOB volume	0.421	0.063	<0.001	1.961	0.040	<0.001	0.735	0.034	<0.001	0.983	24 279
	SOB density	1 045.979	86.230	<0.001	−0.251	0.029	<0.001	−0.012	0.028	0.656	0.740	3 196
	R/S ratio	0.029	0.010	0.005	0.550	0.117	<0.001	−0.715	0.115	<0.001	0.201	0.004

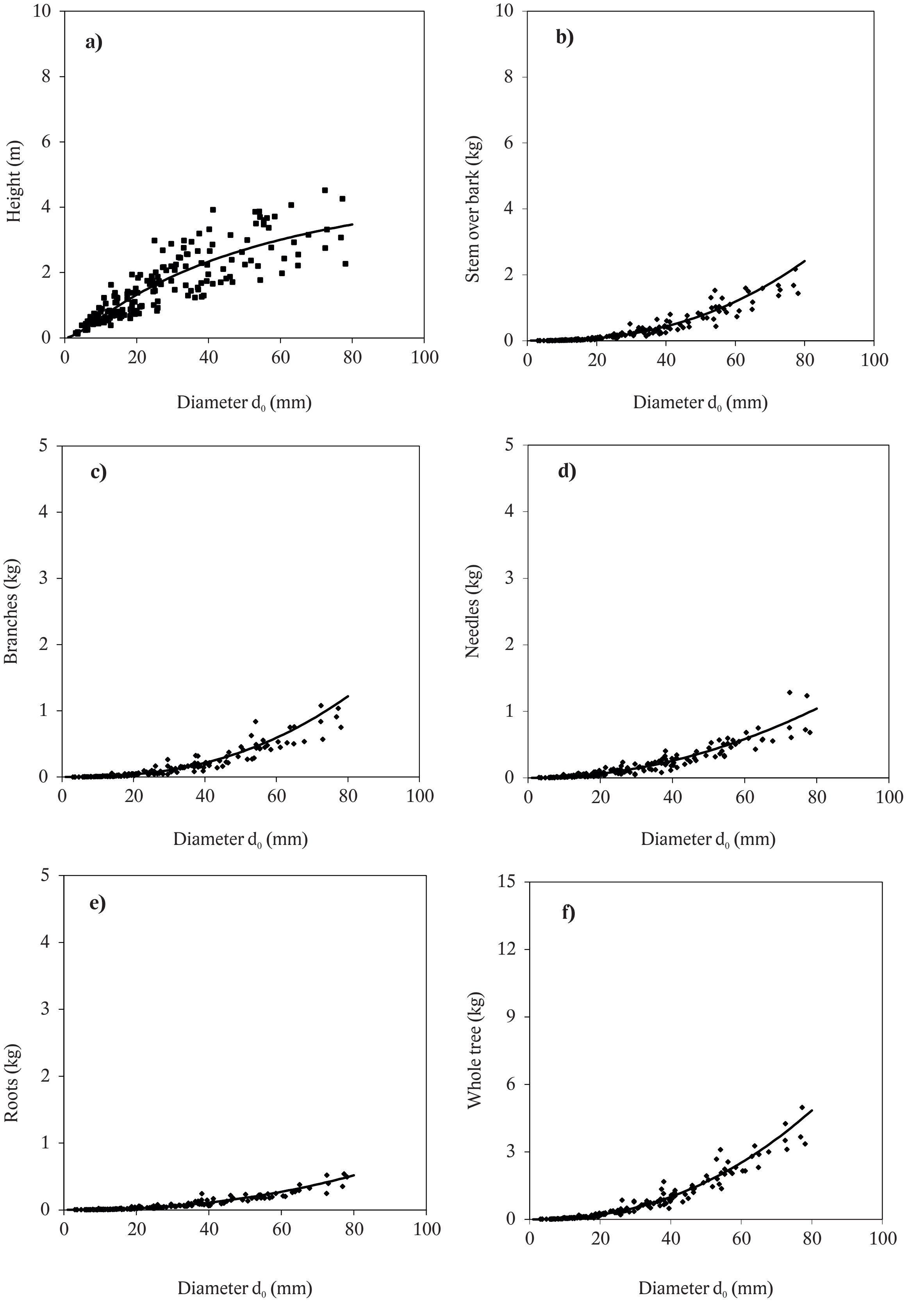

Fig. 16. *Relationship of height a), dry mass of stem over bark b), dry mass of branches c), dry mass of foliage d), dry mass of roots e) and dry mass of the whole tree f) to stem base diameter* d_0 *of Scots pine.*

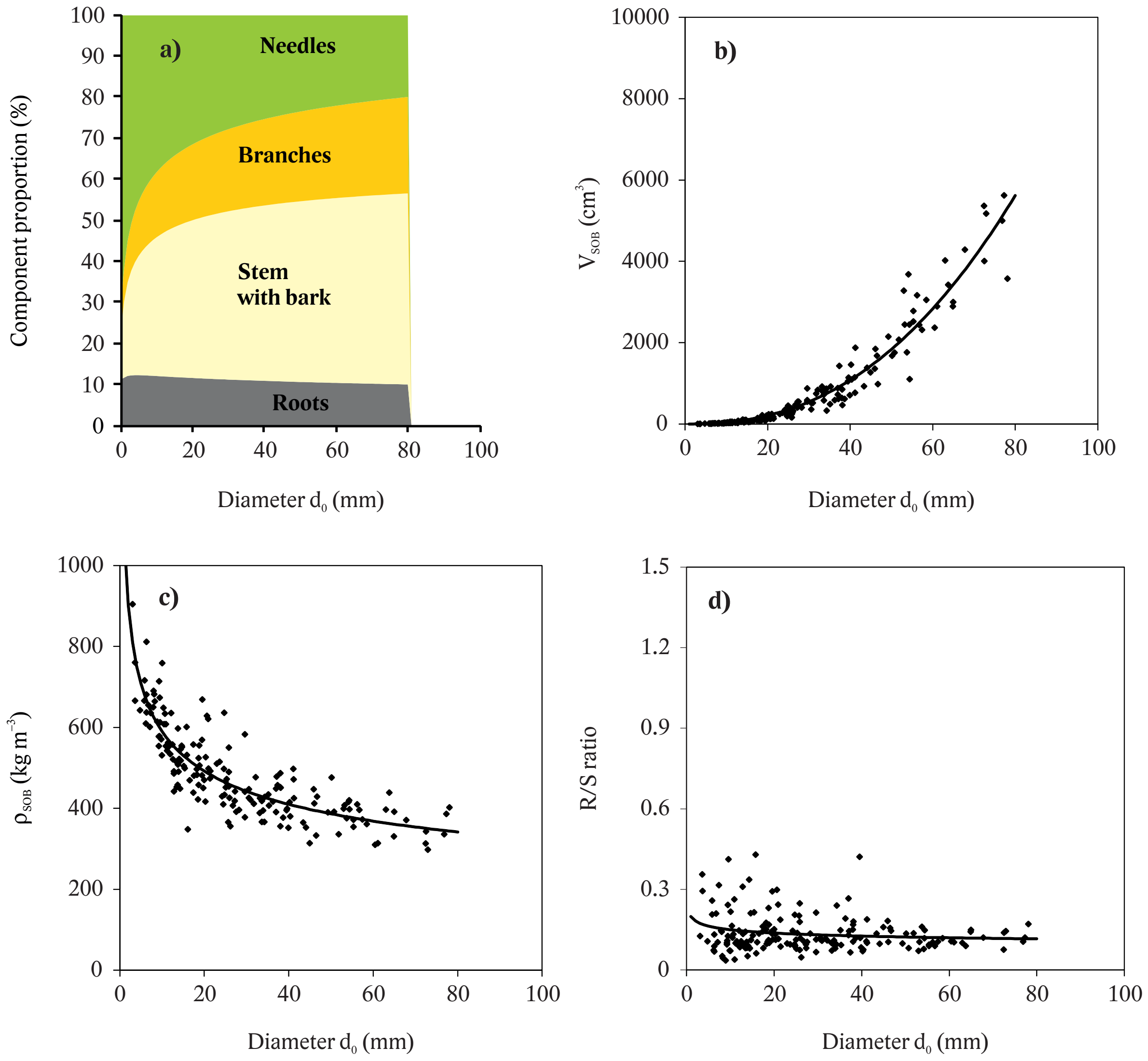

Fig. 17. *Relationship of the component proportion a), volume of stem over bark b), basic density of stem over bark c), R/S ratio d) to stem base diameter d_0 of Scots pine.*

4.6. Sycamore

Sycamore (*Acer pseudoplatanus* L.) is the most common species of Acer genus. Unlike other more frequent tree species, it usually does not create homogeneous stands. The exceptions are the groups of sycamore stands at suitable and favourable sites, where sycamore is most competitive. Sycamore is a demanding tree species from the point of soil moisture and air humidity, as well as from the point of nutrient content in the soil. It usually occurs in small clusters, or as an admixture in stands, often on ridges and in screes, in the ends of valleys, and in ravines. Together with other valuable broadleaved species it increases biodiversity of forest ecosystems and has a positive impact on soil conditions. It is an important tree species in forest biotopes of European significance: Ls5.3 Mountainous sycamore-beech forests (9140 *Medio-European subalpine beech woods with Acer and Rumex arifolius*), and together with the lime tree, ash, and other valuable broadleaved species in Ls4 Lime-maple ravine forests (9180 *Tilio-Acerion forests of slopes, scree and ravines*). It occurs practically in all forest vegetation zones from 1st oak up to 7th spruce zones, and is dominant at scree sites.

According to the processed NFIM2 SR data, its lowest and highest occurrences were recorded at elevations of 112 m and 1,365 m a.s.l., respectively, and its most frequent occurrence between 700 – 800 m a.s.l. From the point of occurrence, it is the third most common tree species in the forests of Slovakia (after beech and spruce), considering its proportion in the area it is the 6th, and the proportion in stand stock it is 8th in the species ranking. It grew at a reduced area of 79 ±15 thousand ha, and occurred at 32% of the forested inventory plots.

The regression models of the sycamore were derived from the data gathered from 150 individuals. Sycamore trees were taken from thirteen sites (see Fig. 18). They were located in the orographic units of Malé Karpaty (sites 1 and 2), Strážovské Vrchy (3), Kysucké Beskydy (4), Javorie (5 and 6), Poľana (7, 8, 9, 10), Nízke Tatry (11) and Slovenské rudohorie (12 and 13). The samples represented the individuals with d_0 diameters from 1.75 mm to 104.50 mm, and heights from 0.11 m to 9.87 m (Table 17, Fig. 19a). The dry mass of the whole trees ranged from 0.23 g do 16,932.93 g, and the stem volume ranged from 1.13 cm^3 to 23,114.93 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 18. The volume of stem over or under bark, its density, as well as the root-shoot ratio were derived in a similar way (Table 19). The regression models, scatter plots, and fitted regression curves were visualised in the graphs as in the case of the previous tree species. The text describing the biomass of individual components and their proportions of the total tree biomass is presented in Chapter 4.12. (Inter-species comparison of biomass characteristics).

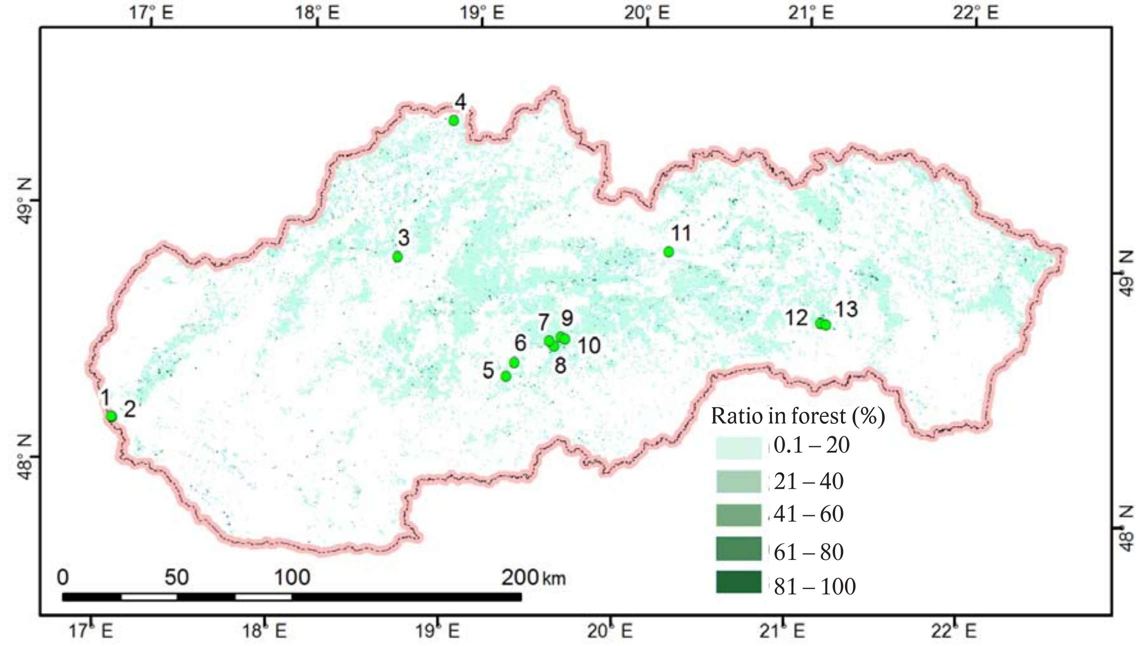

Fig. 18. *Map of sample sites of Sycamore and its distribution in the forests of Slovakia.*

Table 17. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), biomass of stem under bark (SUB), foliage biomass (foliage), branch biomass (branches), bark biomass (bark), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem outside bark (V_{SOB}) of individual trees.*

	Sycamore							
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	150	27.73	22.18	1.75	104.50	11.00	37.45	1.27
h (m)	150	3.00	2.50	0.11	9.87	1.01	4.79	0.87
SOB (g)	150	771.72	1645.16	0.11	12 190.73	19.40	690.49	3.91
SUB (g)	150	666.92	1458.71	0.10	10 948.73	14.40	562.59	4.01
Foliage (g)	150	70.22	105.39	0.18	607.75	8.05	77.24	2.95
Branches (g)	125	92.15	196.18	0.05	1 351.80	6.40	72.65	4.03
Bark (g)	150	104.80	188.64	0.01	1 242.00	110.20	188.64	3.21
Roots (g)	150	243.57	429.48	0.03	2 834.80	16.90	228.00	3.13
Aboveground (g)	150	918.73	1 908.70	0.19	14 098.13	32.25	812.84	3.88
Whole tree (g)	150	1 162.30	2 325.49	0.23	16 932.93	52.35	1 043.11	3.73
V_{SOB} (cm^3)	150	1 569.80	3 317.40	0.13	23 114.93	31.36	1 516.02	3.71

Table 18. *Sycamore, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−3.891	0.090	<0.001	2.842	0.029	<0.001				0.985	0.110	1.047	0.365
	Stem under bark	−4.157	0.095	<0.001	2.857	0.030	<0.001				0.983	0.122	1.051	0.382
	Branches	−6.242	0.315	<0.001	2.844	0.095	<0.001				0.880	0.499	1.223	0.724
	Foliage	−2.468	0.135	<0.001	1.894	0.043	<0.001				0.928	0.247	1.118	0.509
	Bark	−6.119	0.176	<0.001	2.996	0.057	<0.001				0.950	0.420	1.201	0.731
	Roots	−3.998	0.132	<0.001	2.645	0.042	<0.001				0.963	0.236	1.124	0.590
	Aboveground part	−2.931	0.077	<0.001	2.645	0.025	<0.001				0.987	0.080	1.041	0.301
	Whole tree	−2.558	0.073	<0.001	2.627	0.023	<0.001				0.988	0.072	1.037	0.293
[10]	Stem over bark	3.032	0.043	<0.001	2.377	0.034	<0.001				0.971	0.213	1.107	0.553
	Stem under bark	2.803	0.043	<0.001	2.394	0.034	<0.001				0.971	0.208	1.102	0.544
	Branches	0.817	0.138	<0.001	2.240	0.109	<0.001				0.775	0.937	1.478	1.341
	Foliage	2.183	0.068	<0.001	1.524	0.053	<0.001				0.847	0.526	1.254	0.818
	Bark	1.187	0.073	<0.001	2.496	0.057	<0.001				0.928	0.602	1.331	1.263
	Roots	2.481	0.074	<0.001	2.159	0.058	<0.001				0.904	0.619	1.348	1.144
	Aboveground part	3.521	0.046	<0.001	2.201	0.036	<0.001				0.962	0.236	1.123	0.562
	Whole tree	3.857	0.050	<0.001	2.174	0.040	<0.001				0.953	0.289	1.155	0.652
[11]	Stem over bark	−1.223	0.143	<0.001	1.736	0.058	<0.001	0.966	0.049	<0.001	0.996	0.030	1.006	0.186
	Stem under bark	−1.350	0.151	<0.001	1.694	0.061	<0.001	1.016	0.052	<0.001	0.995	0.034	1.006	0.193
	Branches	−5.755	0.640	<0.001	2.638	0.254	<0.001	0.186	0.213	0.383	0.881	0.500	1.222	0.719
	Foliage	−3.107	0.406	<0.001	2.158	0.165	<0.001	−0.231	0.139	0.098	0.929	0.244	1.118	0.516
	Bark	−3.738	0.493	<0.001	2.009	0.200	<0.001	0.861	0.168	<0.001	0.957	0.359	1.176	0.768
	Roots	−3.680	0.400	<0.001	2.514	0.162	<0.001	0.115	0.136	0.401	0.964	0.236	1.123	0.589
	Aboveground part	−0.930	0.156	<0.001	1.816	0.063	<0.001	0.724	0.053	<0.001	0.994	0.036	1.018	0.193
	Whole tree	−1.040	0.177	<0.001	1.998	0.072	<0.001	0.549	0.060	<0.001	0.993	0.047	1.024	0.232

Table 19. *Sycamore, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.028	0.011	0.010	2.917	0.087	<0.001				0.945	604 772
	SUB volume	0.016	0.007	0.018	3.016	0.095	<0.001				0.943	536 429
	Bark volume	0.047	0.015	0.002	2.294	0.073	<0.001				0.935	8 287
	SOB density	790.296	22.815	<0.001	−0.128	0.010	<0.001				0.502	4 457
	SUB density	615.677	24.485	<0.001	−0.064	0.013	<0.001				0.154	3 007
	Bark density	1485.74	96.33	<0.001	−0.262	0.022	<0.001				0.510	14 410
	Bark mass proportion	58.843	1.902	<0.001	−0.347	0.011	<0.001				0.883	3.51
	Bark volume proportion	34.096	2.118	<0.001	−0.233	0.021	<0.001				0.480	9.37
	R/S ratio	1.051	0.143	<0.001	−0.310	0.047	<0.001				0.257	0.028

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
	SOB volume	4.270	1.755	0.016	3.645	0.191	<0.001				0.867	1 468 819
	SUB volume	2.961	1.339	0.029	3.763	0.210	<0.001				0.861	1 312 206
	Bark volume	2.295	0.685	0.001	2.894	0.142	<0.001				0.877	15 784
	SOB density	580.761	5.685	<0.001	−0.112	0.008	<0.001				0.556	3 974
[14]	SUB density	533.178	5.731	<0.001	−0.069	0.009	<0.001				0.281	2 556
	Bark density	774.138	13.626	<0.001	−0.204	0.017	<0.001				0.506	14 552
	Bark mass proportion	24.707	0.254	<0.001	−0.262	0.010	<0.001				0.826	5.22
	Bark volume proportion	19.182	0.321	<0.001	−0.189	0.016	<0.001				0.510	8.84
	R/S ratio	0.497	0.017	<0.001	−0.277	0.034	<0.001				0.343	0.025
	SOB volume	0.172	0.030	<0.001	1.815	0.058	<0.001	1.452	0.072	<0.001	0.987	143 855
	SUB volume	0.107	0.021	<0.001	1.882	0.065	<0.001	1.487	0.080	<0.001	0.986	137 455
	Bark volume	0.188	0.038	<0.001	1.404	0.070	<0.001	1.214	0.087	<0.001	0.974	3 384
	SOB density	532.286	51.026	<0.001	0.036	0.039	0.362	−0.141	0.033	<0.001	0.558	3 979
[15]	SUB density	358.061	30.039	<0.001	0.158	0.033	<0.001	−0.189	0.027	<0.001	0.386	2 198
	Bark density	1 116.778	183.790	<0.001	−0.145	0.065	0.027	−0.096	0.051	0.062	0.523	14 139
	Bark mass proportion	49.967	4.122	<0.001	−0.280	0.033	<0.001	−0.055	0.025	0.033	0.887	3.42
	Bark volume proportion	21.791	3.574	<0.001	−0.051	0.065	0.436	−0.151	0.051	0.004	0.512	8.86
	R/S ratio	0.184	0.065	0.006	0.394	0.139	0.005	−0.575	0.111	<0.001	0.378	0.024

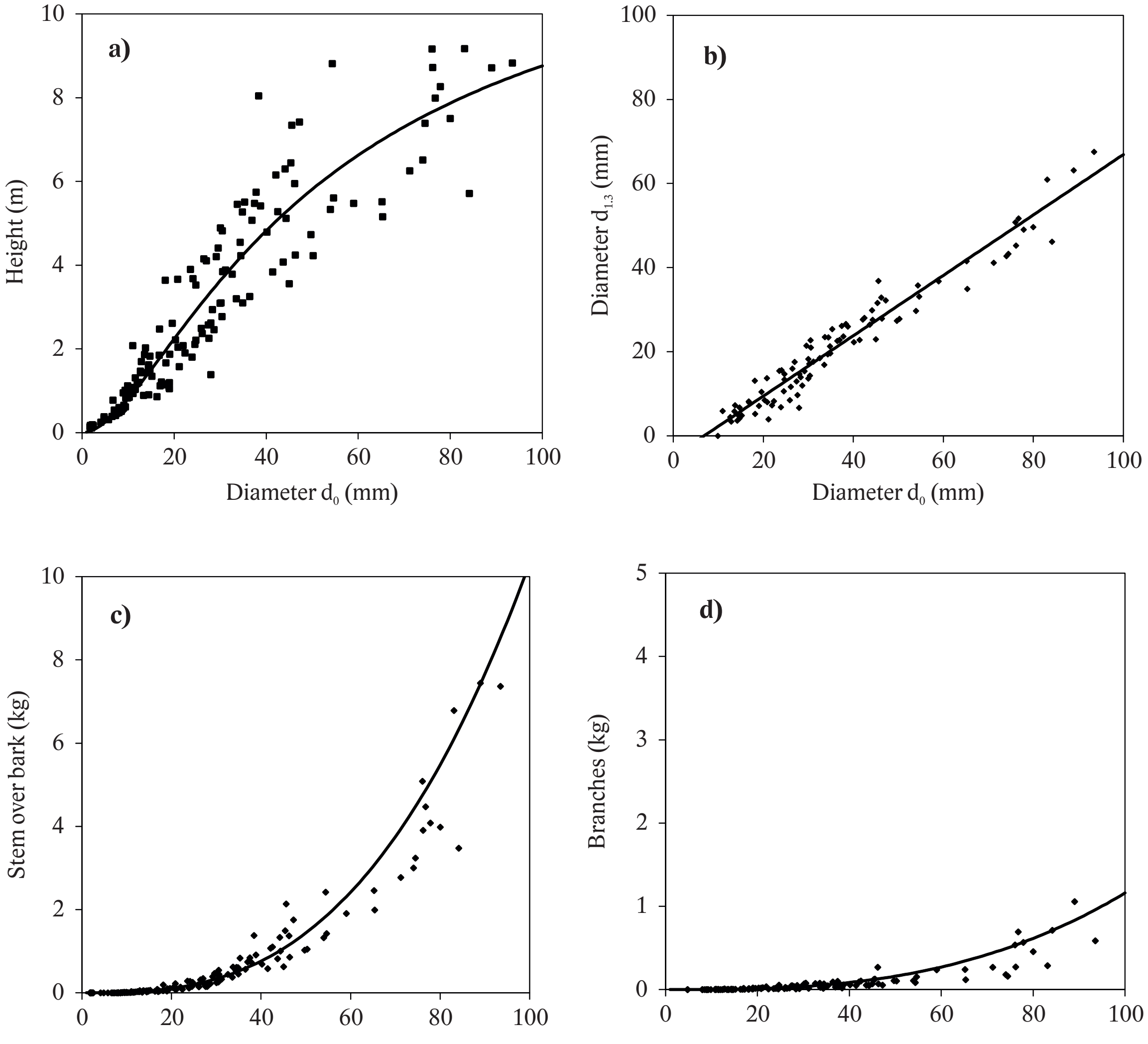

Fig. 19. *Relationship of height a), $d_{1.3}$ diameter b), dry mass of stem over bark c), dry mass of branches d) to stem base diameter d_0 of Sycamore.*

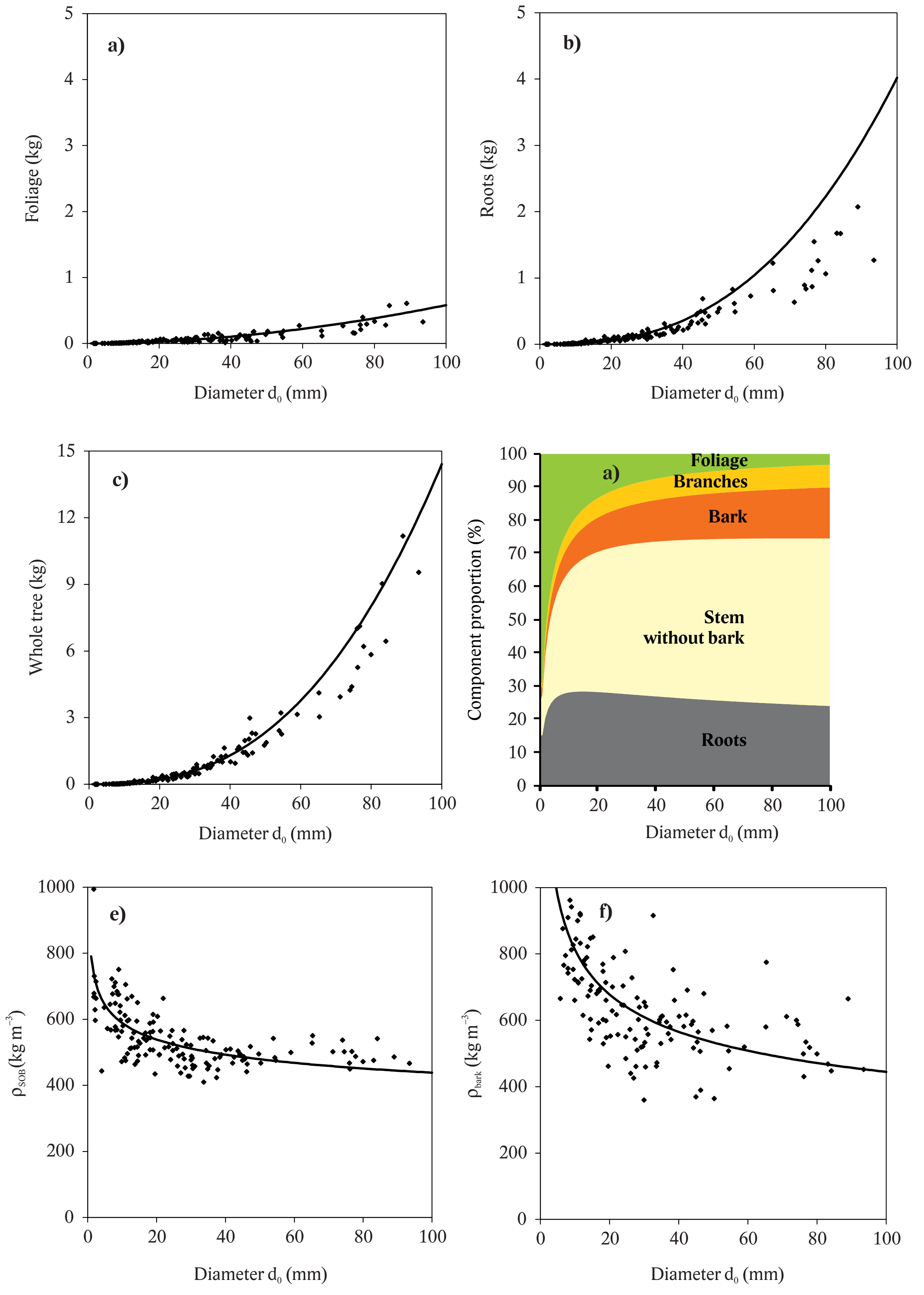

Fig. 20. *Relationship of foliage dry mass a), root dry mass b), dry mass of the whole tree c), proportion of individual tree components d), basic density of stem over bark e), and basic bark density f) to stem base diameter d_0 of Sycamore.*

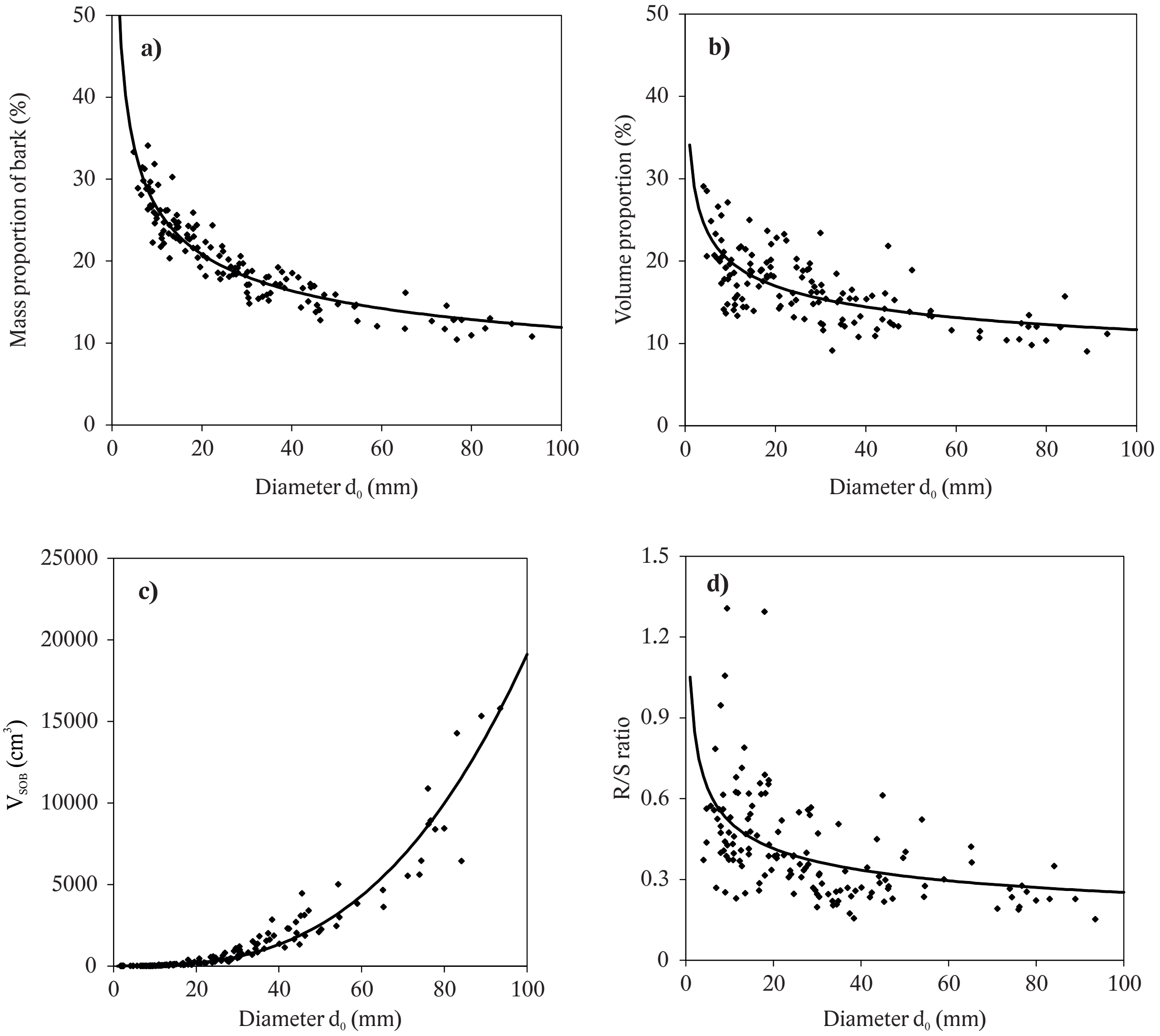

Fig. 21. *Relationship of bark mass proportion of SOB mass a) bark proportion of SOB volume b), volume of stem over bark c) and R/S ratio d) to stem base diameter d_0 of Sycamore.*

4.7. European ash

European ash (*Fraxinus excelsior* L.) belongs together with maple species to the so-called valuable broadleaved species. They represent specific components of stands, which are important for biodiversity, and partially also from the economic point of view. They usually form admixtures to main commercial tree species, and only rarely form small-scale homogeneous stands. Ash is an important admixture practically in all forest vegetation zones from 1st oak up to 7th spruce zones, i.e. it has a wide ecological valency. At specific sites, e.g. at rocky, scree or waterlogged sites, its proportion is greater. In scree and riparian forests it is the main stand-forming tree species. In these forests it grows in the biotopes protected at national and European levels: Ls1.4 Ash-alder sub-montane alluvial forests (NATURA 2000 91E0 *Alluvial forests with Alnus glutinosa and Fraxinus excelsior*), Ls1.2 Oak-elm-ash plain-land alluvial forests (91F0 *Riparian mixed forests of Quercus robur, Ulmus laevis and Ulmus minor, Fraxinus excelsior or Fraxinus angustifolia, along the great rivers*).

The lowest and the highest occurrences of ash (NFIM2 SR) were recorded at elevations of 112 m a.s.l. and 1,151 m a.s.l., respectively, and the most frequent occurrence was recorded between 500 – 600 m a.s.l. From the point of its proportion of the area, stock, and occurrence, it is the 11th most frequent tree species in the forests of Slovakia. It grew at a reduced area of 44 ±11 thousand ha, and occurred at 18% of the forested inventory plots.

The biomass regression models of the European ash were derived using 81 trees. They were taken from six sites (see Fig. 22). The sites were located in two orographic units, namely Javorie (1, 2, 3) and Poľana (4, 5, 6). The diameters d_0 of the trees ranged from 5.35 mm to 51.25 mm, and heights from 0.19 m to 4.24 m (Table 20, Fig. 23a). The dry mass of the whole trees ranged from 5.25 g do 3,064.50 g, and the stem volume ranged from 2.10 cm^3 to 2,239.89 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 21. The regression models for the calculation of the volume of stem over or under bark, its density, as well as the root-shoot ratio are presented in Table 22.

The regression models, scatter plots, and fitted regression curves were visualised in the graphs in a similar way as for the previous tree species. Further comments on the biomass of individual components and their proportions in the total tree biomass are presented in Chapter 4.12. (Inter-species comparison of biomass characteristics).

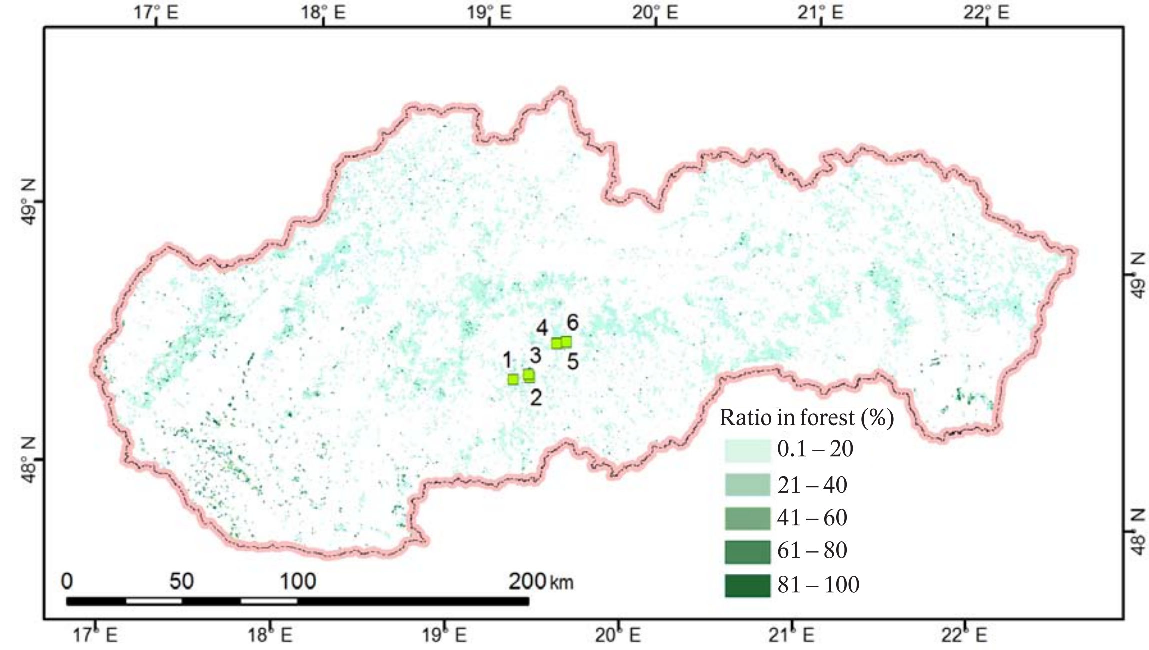

Fig. 22. *Map of sample sites of European ash and its distribution in the forests of Slovakia.*

Table 20. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), biomass of stem under bark (SUB), foliage biomass (foliage), branch biomass (branches), bark biomass (bark), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

				European ash				
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	81	23.44	11.61	5.35	51.25	13.35	31.75	0.42
h (m)	81	2.09	1.18	0.19	4.24	1.02	2.96	0.12
SOB (g)	80	275.90	311.12	1.70	1 235.65	27.70	415.08	1.30
SUB (g)	80	218.27	253.08	1.00	1 009.20	19.65	327.48	1.36
Foliage (g)	81	52.17	57.07	0.75	307.20	8.55	74.65	1.90
Branches (g)	81	40.56	66.07	0.00	322.55	1.95	44.80	2.49
Bark (g)	81	57.40	58.64	0.70	226.45	7.75	87.00	1.10
Roots (g)	80	133.69	179.74	1.60	1 258.00	23.08	169.90	3.63
Aboveground (g)	80	369.10	421.27	2.45	1 806.50	41.43	546.15	1.42
Whole tree (g)	79	508.10	586.19	5.25	3 064.50	64.95	700.00	1.81
V_{SOB} (cm^3)	81	502.06	571.05	2.10	2 239.89	52.31	771.22	1.33

Table 21. *European ash, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−4.374	0.229	<0.001	2.997	0.075	<0.001				0.954	0.140	1.072	0.430
	Stem under bark	−5.129	0.247	<0.001	3.147	0.081	<0.001				0.951	0.163	1.088	0.516
	Branches	−9.108	0.624	<0.001	3.738	0.197	<0.001				0.835	0.562	1.256	0.792
	Foliage	−3.969	0.255	<0.001	2.388	0.083	<0.001				0.912	0.174	1.085	0.435
	Bark	−4.658	0.204	<0.001	2.630	0.066	<0.001				0.952	0.111	1.053	0.331
	Roots	−3.301	0.243	<0.001	2.454	0.079	<0.001				0.925	0.146	1.077	0.452
	Aboveground part	−3.839	0.209	<0.001	2.925	0.068	<0.001				0.959	0.117	1.057	0.360
	Whole tree	−2.999	0.200	<0.001	2.769	0.065	<0.001				0.959	0.099	1.049	0.332
[10]	Stem over bark	3.523	0.056	<0.001	2.206	0.061	<0.001				0.944	0.171	1.096	0.601
	Stem under bark	3.160	0.059	<0.001	2.317	0.065	<0.001				0.942	0.193	1.119	0.773
	Branches	0.698	0.168	<0.001	2.785	0.189	<0.001				0.753	0.841	1.433	1.174
	Foliage	2.345	0.070	<0.001	1.721	0.077	<0.001				0.864	0.270	1.129	0.554
	Bark	2.271	0.047	<0.001	1.942	0.052	<0.001				0.946	0.124	1.060	0.358
	Roots	3.171	0.075	<0.001	1.780	0.084	<0.001				0.853	0.288	1.156	0.719
	Aboveground part	3.874	0.057	<0.001	2.140	0.062	<0.001				0.938	0.178	1.093	0.522
	Whole tree	4.279	0.062	<0.001	2.048	0.069	<0.001				0.920	0.193	1.100	0.525
[11]	Stem over bark	−0.906	0.372	0.017	1.667	0.139	<0.001	1.052	0.103	<0.001	0.980	0.060	1.038	0.399
	Stem under bark	−1.460	0.409	<0.001	1.739	0.153	<0.001	1.113	0.114	<0.001	0.978	0.073	1.052	0.535
	Branches	−6.807	1.152	<0.001	2.830	0.431	<0.001	0.795	0.339	0.022	0.847	0.529	1.244	0.782
	Foliage	−2.219	0.596	<0.001	1.717	0.223	<0.001	0.531	0.165	0.002	0.923	0.156	1.075	0.411
	Bark	−1.502	0.321	<0.001	1.419	0.120	<0.001	0.958	0.089	<0.001	0.981	0.045	1.022	0.222
	Roots	−2.043	0.562	<0.001	1.968	0.211	<0.001	0.394	0.160	0.016	0.931	0.137	1.073	0.450
	Aboveground part	−0.795	0.355	0.028	1.757	0.133	<0.001	0.923	0.099	<0.001	0.981	0.055	1.031	0.315
	Whole tree	−0.589	0.372	0.117	1.838	0.140	<0.001	0.754	0.106	<0.001	0.976	0.060	1.032	0.301

Table 22. *European ash, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.257	0.119	0.034	2.311	0.126	<0.001				0.894	34 847
	SUB volume	0.187	0.091	0.042	2.330	0.131	<0.001				0.889	22 687
	Bark volume	0.072	0.033	0.032	2.245	0.125	<0.001				0.890	1 728
	SOB density	731.954	47.687	<0.001	−0.090	0.022	<0.001				0.173	3 830
	SUB density	563.952	36.847	<0.001	−0.010	0.021	0.659				0.002	3 432
	Bark density	1 316.481	127.782	<0.001	−0.267	0.034	<0.001				0.432	11 372
	Bark mass proportion	80.316	4.586	<0.001	−0.382	0.020	<0.001				0.808	8.30
	Bark volume proportion	46.271	4.048	<0.001	−0.210	0.030	<0.001				0.365	15.19
	R/S ratio	1.647	0.294	<0.001	−0.441	0.064	<0.001				0.366	0.023
[14]	SOB volume	51.973	12.498	<0.001	2.469	0.187	<0.001				0.854	48 182
	SUB volume	37.127	8.820	<0.001	2.542	0.185	<0.001				0.865	27 397
	Bark volume	15.394	4.041	<0.001	2.221	0.207	<0.001				0.792	3 258
	SOB density	581.051	7.840	<0.001	−0.077	0.015	<0.001				0.243	3 508
	SUB density	554.752	7.817	<0.001	−0.024	0.015	0.132				0.028	3 345
	Bark density	649.378	13.624	<0.001	−0.190	0.024	<0.001				0.426	11 479
	Bark mass proportion	29.185	0.385	<0.001	−0.263	0.015	<0.001				0.782	9.41
	Bark volume proportion	26.681	0.468	<0.001	−0.162	0.020	<0.001				0.433	13.56
	R/S ratio	0.525	0.017	<0.001	−0.368	0.039	<0.001				0.500	0.018
[15]	SOB volume	1.501	0.554	0.008	1.397	0.129	<0.001	1.286	0.151	<0.001	0.948	17 360
	SUB volume	1.250	0.451	0.007	1.338	0.125	<0.001	1.407	0.150	<0.001	0.951	10 165
	Bark volume	0.261	0.122	0.035	1.600	0.164	<0.001	0.880	0.183	<0.001	0.917	1 311.8
	SOB density	476.008	76.962	<0.001	0.075	0.060	0.219	−0.129	0.044	0.005	0.258	3 482
	SUB density	366.551	57.336	<0.001	0.156	0.058	0.009	−0.131	0.043	0.003	0.114	3 088
	Bark density	972.677	259.621	<0.001	−0.152	0.100	0.134	−0.088	0.072	0.225	0.442	11 305
	Bark mass proportion	56.377	8.954	<0.001	−0.247	0.060	<0.001	−0.099	0.042	0.021	0.822	7.82
	Bark volume proportion	24.708	5.621	<0.001	0.029	0.085	0.736	−0.181	0.061	0.004	0.434	13.71
	R/S ratio	0.205	0.095	0.033	0.352	0.171	0.043	−0.610	0.123	<0.001	0.527	0.017

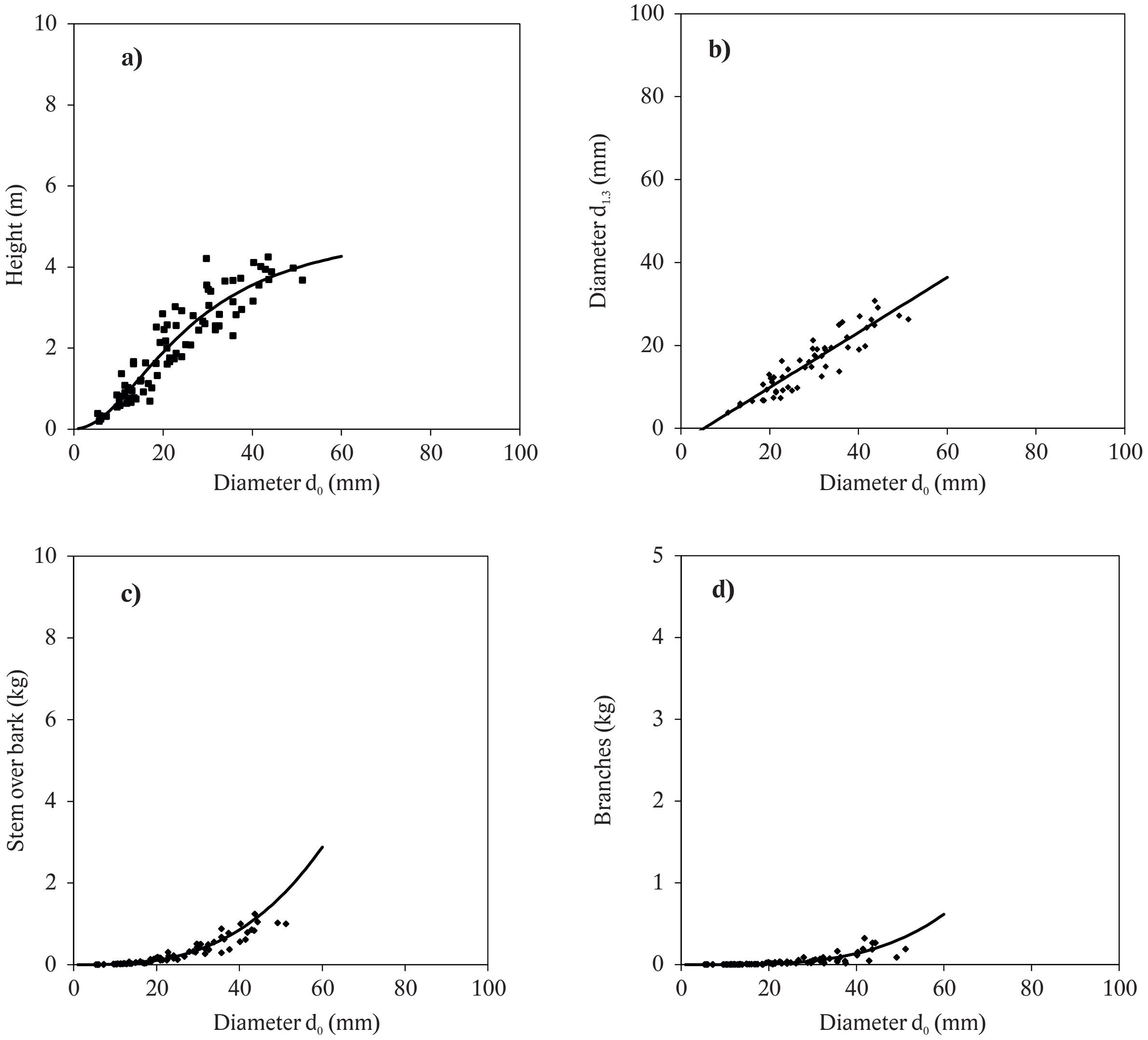

Fig. 23. *Relationship of tree height a), $d_{1.3}$ diameter b), dry mass of stem over bark c), dry mass of branches d) to stem base diameter d_0 of European ash.*

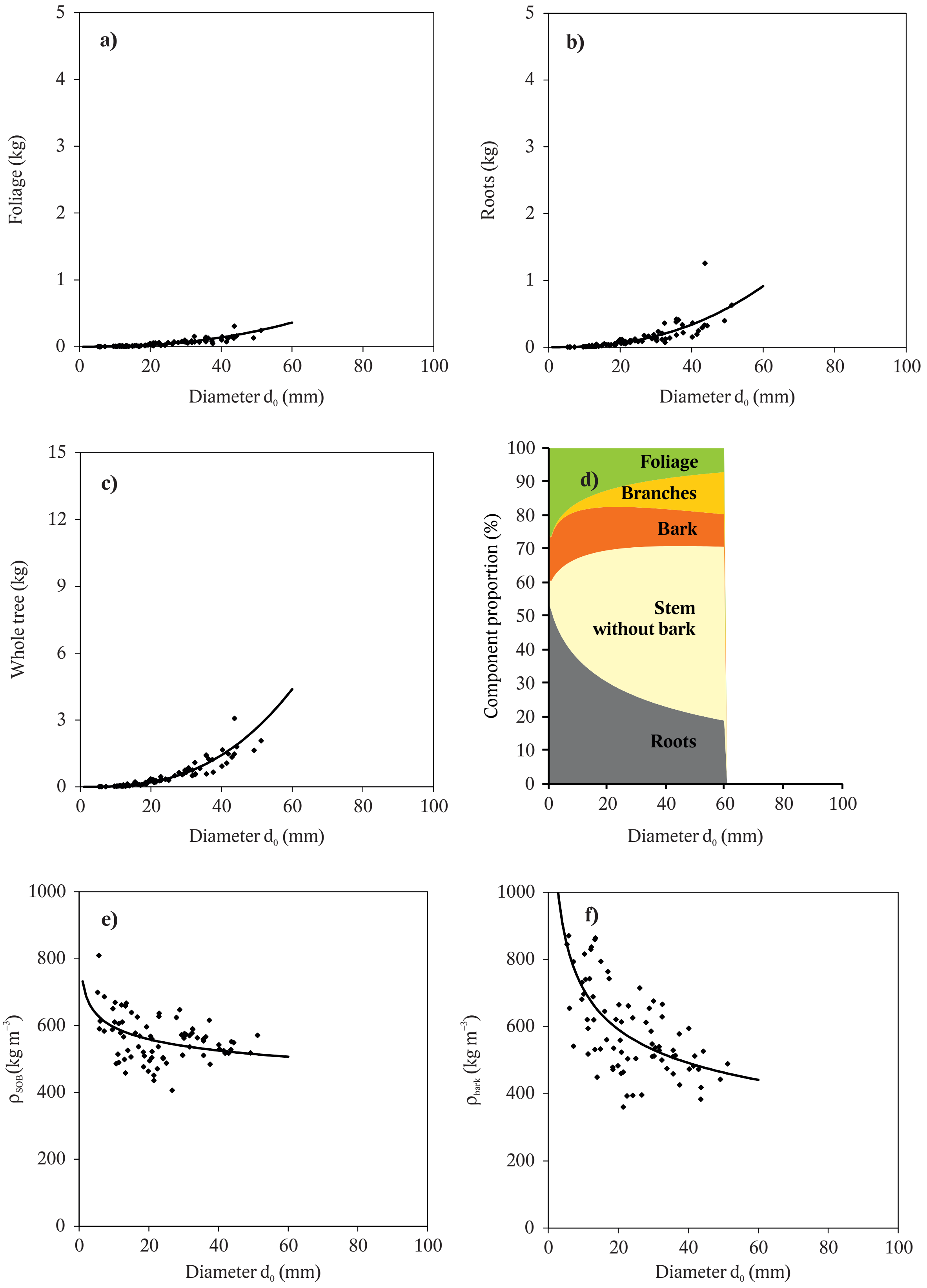

Fig. 24. *Relationship of foliage dry mass a), root dry mass b), dry mass of the whole tree c), proportion of individual tree components d), basic density of stem over bark e), and basic bark density f) to stem base diameter d_0 of European ash.*

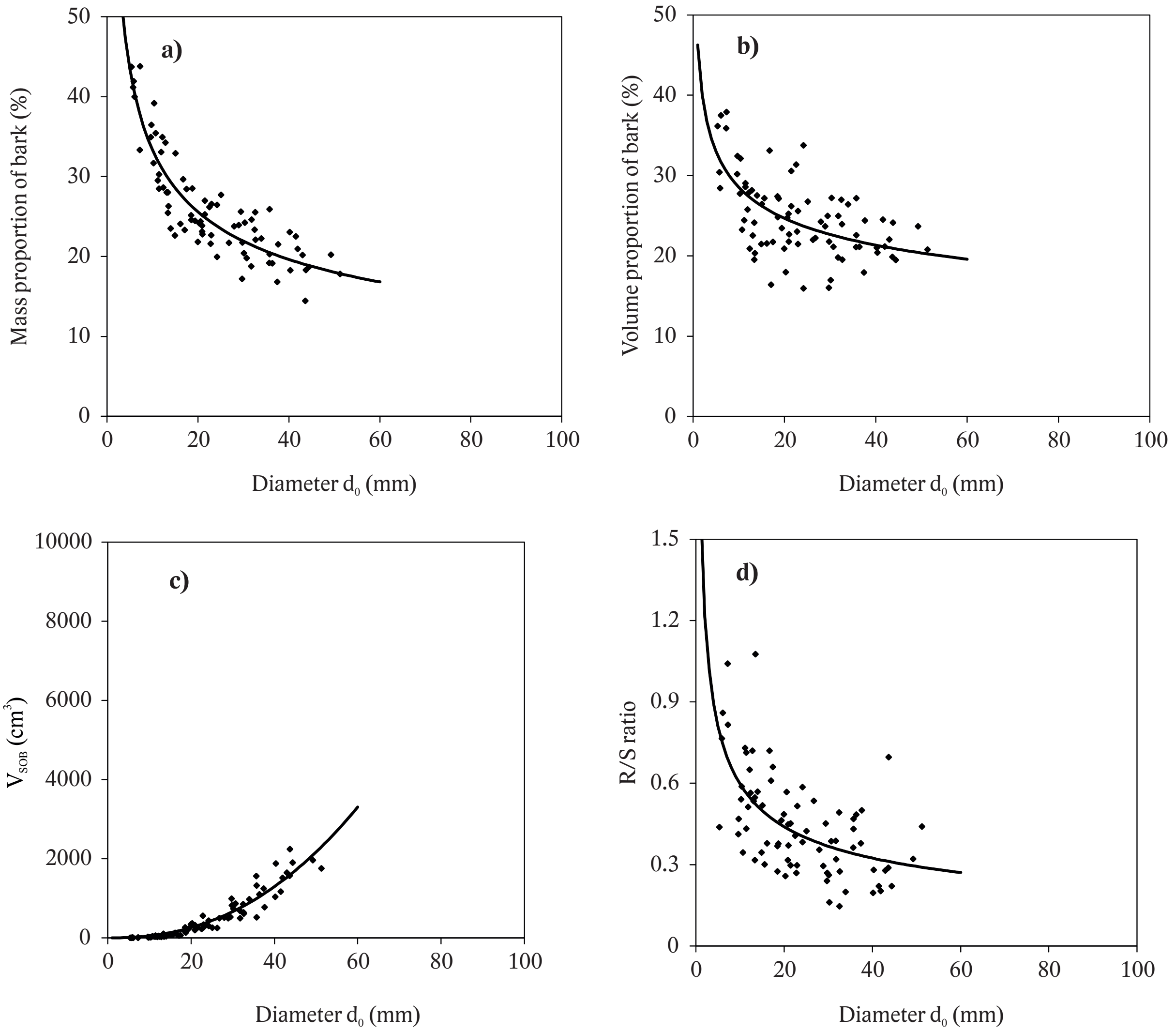

Fig. 25. *Relationship of bark mass proportion of SOB mass a), bark volume proportion of SOB volume b), volume of stem outside bark c), and R/S ratio d) to stem base diameter d_0 of European ash.*

4.8. Goat willow

Goat willow (*Salix caprea* L.) is a pioneer tree species, which occurs mainly after disturbances or as an admixture in all forest vegetation zones from 1st oak zone up to 7th spruce zone. Although it is an abundant tree species, it has a negligible economic importance. Therefore, currently it is not assessed as a stand-forming tree species within the forest survey in Slovakia during the renewal of forest management plans except for noting it down in the site description. Goat willow, similarly to rowan or aspen, provides important nutrition to wildlife, and can lure it away from the commercially important tree species and thus reduce economic losses.

According to the NFIM2 SR data, the lowest and the highest occurrences of this tree species were recorded at elevations of 118 m and 1,485 m a.s.l., respectively, with most frequent occurrence between 600 – 700 m a.s.l. Although it is an abundant tree species ranked 12th from all tree species occurring in the forests of Slovakia on the base of its occurrence and its proportion of the area, according to the proportion of the stock it was ranked 25th. It grew at a reduced area of 33 ±10 thousand ha, and occurred at 15% of the forested inventory plots.

The biomass regression models of the Goat willow were derived using 100 individuals. They were taken from two sites (see Fig. 26) located in the orographic units of Kysucké Beskydy (site 1) and Vysoké Tatry (2). The trees covered the interval of d_0 stem diameters from 3.65 mm to 68.70 mm, and heights from 0.49 m to 4.50 m (Table 23, Fig. 27a). The dry mass of the whole trees ranged from 3.19 g to 3,799.37 g, and the stem volume ranged from 1.83 cm^3 to 3,684.05 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 24. The volume of stem outside or inside bark, its density, as well as the root-shoot ratio were derived in a similar way (Table 25).

The regression models, scatter plots, and fitted regression curves were visualised in a similar way as in the case of the previous tree species. Further text description of the biomass of individual components and their proportions in the total tree biomass is presented in Chapter 4.12. (Inter-species comparison of biomass characteristics)

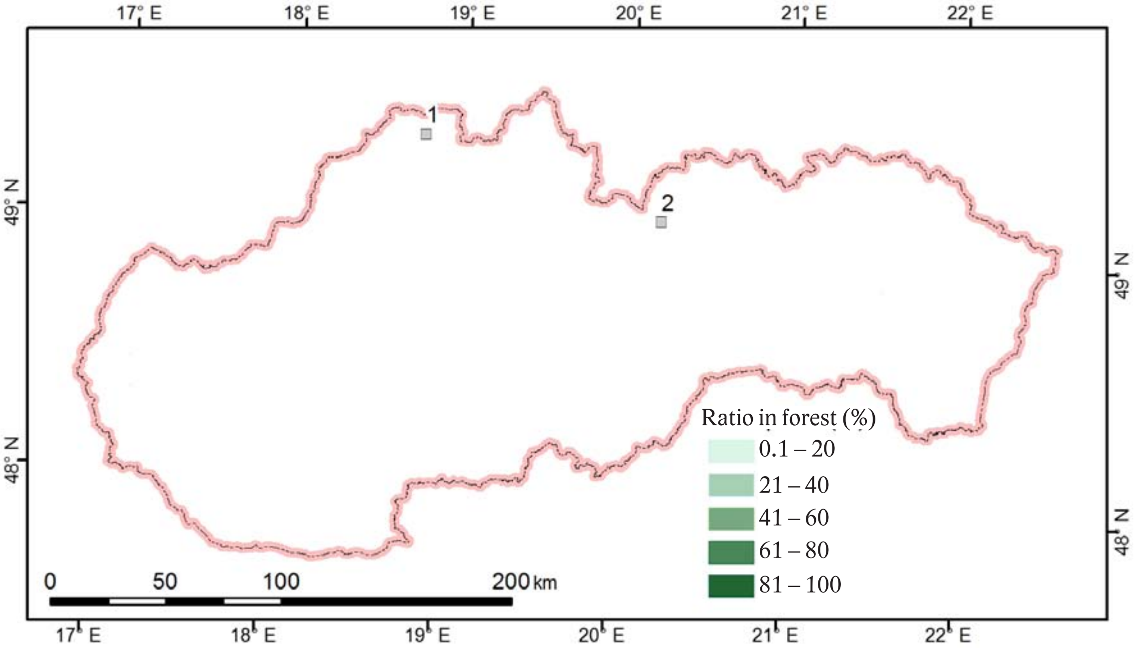

Fig. 26. *Map of sample sites of Goat willow.*

Table 23. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), biomass of stem under bark (SUB), foliage biomass (foliage), branch biomass (branches), bark biomass (bark), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

				Goat willow				
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	100	25.04	13.22	3.65	68.70	14.60	33.25	1.02
h (m)	100	2.04	0.85	0.49	4.50	1.38	2.37	0.81
SOB (g)	100	197.64	293.03	1.15	1 523.23	29.33	218.93	2.97
SUB (g)	100	152.89	239.64	0.70	1 257.93	20.10	160.30	3.10
Foliage (g)	99	78.41	87.02	0.80	467.35	20.30	110.05	2.17
Branches (g)	99	106.06	173.06	0.44	1 185.75	13.00	120.30	3.53
Bark (g)	100	44.75	54.29	0.45	265.30	9.28	54.30	2.37
Roots (g)	100	89.08	136.30	0.80	796.50	15.33	100.43	3.19
Aboveground (g)	100	380.26	539.34	2.39	3 149.17	61.78	411.53	2.94
Whole tree (g)	98	475.06	678.75	3.19	3 799.37	79.55	513.90	2.93
V_{SOB} (cm^3)	100	471.69	686.23	1.83	3 684.05	65.81	539.11	2.99

Table 24. *Goat willow, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−3.178	0.189	<0.001	2.479	0.061	<0.001				0.945	0.107	1.048	0.306
	Stem under bark	−3.886	0.202	<0.001	2.601	0.065	<0.001				0.943	0.122	1.055	0.331
	Branches	−5.018	0.236	<0.001	2.807	0.075	<0.001				0.935	0.166	1.078	0.403
	Foliage	−2.409	0.206	<0.001	2.015	0.066	<0.001				0.906	0.127	1.061	0.360
	Bark	−3.510	0.177	<0.001	2.166	0.057	<0.001				0.937	0.094	1.043	0.290
	Roots	−3.537	0.193	<0.001	2.346	0.062	<0.001				0.937	0.111	1.052	0.330
	Aboveground part	−2.305	0.149	<0.001	2.425	0.047	<0.001				0.965	0.066	1.029	0.232
	Whole tree	−2.035	0.146	<0.001	2.406	0.047	<0.001				0.965	0.064	1.029	0.231
[10]	Stem over bark	2.542	0.066	<0.001	3.063	0.086	<0.001				0.928	0.140	1.069	0.390
	Stem under bark	2.106	0.065	<0.001	3.230	0.086	<0.001				0.935	0.138	1.068	0.386
	Branches	1.613	0.125	<0.001	3.237	0.164	<0.001				0.801	0.505	1.269	0.944
	Foliage	2.335	0.094	<0.001	2.344	0.124	<0.001				0.786	0.289	1.153	0.650
	Bark	1.515	0.070	<0.001	2.636	0.092	<0.001				0.893	0.160	1.080	0.430
	Roots	1.953	0.091	<0.001	2.780	0.120	<0.001				0.846	0.271	1.135	0.573
	Aboveground part	3.360	0.080	<0.001	2.907	0.105	<0.001				0.889	0.206	1.105	0.508
	Whole tree	3.589	0.080	<0.001	2.879	0.105	<0.001				0.886	0.208	1.104	0.501
[11]	Stem over bark	−0.809	0.212	<0.001	1.414	0.088	<0.001	1.457	0.110	<0.001	0.980	0.039	1.019	0.195
	Stem under bark	−1.254	0.207	<0.001	1.417	0.086	<0.001	1.619	0.107	<0.001	0.983	0.037	1.018	0.192
	Branches	−4.569	0.442	<0.001	2.605	0.184	<0.001	0.275	0.229	0.233	0.936	0.165	1.079	0.412
	Foliage	−1.939	0.382	<0.001	1.803	0.159	<0.001	0.290	0.199	0.148	0.908	0.125	1.061	0.363
	Bark	−1.834	0.263	<0.001	1.413	0.109	<0.001	1.031	0.136	<0.001	0.961	0.060	1.029	0.246
	Roots	−2.441	0.336	<0.001	1.854	0.140	<0.001	0.674	0.175	<0.001	0.945	0.097	1.048	0.322
	Aboveground part	−0.912	0.025	<0.001	1.801	0.094	<0.001	0.854	0.117	<0.001	0.977	0.043	1.021	0.206
	Whole tree	−0.705	0.225	0.002	1.810	0.094	<0.001	0.815	0.117	<0.001	0.977	0.043	1.021	0.207

Table 25. *Goat willow, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Dependent variable	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.066	0.018	<0.001	2.598	0.068	<0.001				0.952	22 611
	SUB volume	0.038	0.011	0.001	2.685	0.075	<0.001				0.948	16 280
	Bark volume	0.047	0.013	0.001	2.285	0.072	<0.001				0.931	1 273
	SOB density	512.437	31.057	<0.001	−0.063	0.020	0.002				0.090	2 046
	SUB density	417.407	27.283	<0.001	−0.009	0.021	0.666				0.002	2 120
	Bark density	783.500	64.267	<0.001	−0.168	0.027	<0.001				0.272	5 023
	Bark mass proportion	68.039	4.579	<0.001	−0.292	0.023	<0.001				0.620	13.45
	Bark volume proportion	46.300	3.622	<0.001	−0.198	0.026	<0.001				0.360	13.61
	R/S ratio	0.293	0.038	<0.001	−0.074	0.042	0.079				0.029	0.003
[14]	SOB volume	30.423	4.321	<0.001	3.128	0.105	<0.001				0.926	34 976
	SUB volume	20.487	2.930	<0.001	3.257	0.105	<0.001				0.934	20 493
	Bark volume	10.933	1.763	<0.001	2.681	0.124	<0.001				0.859	2 592
	SOB density	444.766	7.911	<0.001	−0.085	0.024	0.001				0.107	2 008
	SUB density	411.380	8.079	<0.001	−0.021	0.026	0.413				0.006	2 110
	Bark density	529.619	12.696	<0.001	−0.199	0.034	<0.001				0.254	5 148
	Bark mass proportion	35.160	0.548	<0.001	−0.383	0.023	<0.001				0.725	9.75
	Bark volume proportion	30.006	0.573	<0.001	−0.285	0.028	<0.001				0.505	10.53
	R/S ratio	0.250	0.010	<0.001	−0.112	0.052	0.033				0.042	0.003
[15]	SOB volume	1.234	0.224	<0.001	1.364	0.069	<0.001	1.513	0.085	<0.001	0.989	5 518
	SUB volume	0.962	0.170	<0.001	1.309	0.067	<0.001	1.694	0.084	<0.001	0.989	3 309
	Bark volume	0.276	0.102	0.008	1.540	0.140	<0.001	0.903	0.165	<0.001	0.947	975
	SOB density	449.175	51.316	<0.001	−0.004	0.048	0.931	−0.081	0.059	0.176	0.107	2 028
	SUB density	377.944	46.202	<0.001	0.036	0.051	0.485	−0.061	0.063	0.336	0.011	2 121
	Bark density	700.079	111.695	<0.001	−0.117	0.067	0.082	−0.068	0.083	0.413	0.277	5 039
	Bark mass proportion	36.932	4.273	<0.001	−0.021	0.048	0.669	−0.360	0.059	<0.001	0.726	9.83
	Bark volume proportion	24.309	3.255	<0.001	0.088	0.056	0.115	−0.383	0.068	<0.001	0.518	10.37
	R/S ratio	0.233	0.058	<0.001	0.028	0.103	0.783	−0.145	0.128	0.261	0.042	0.003

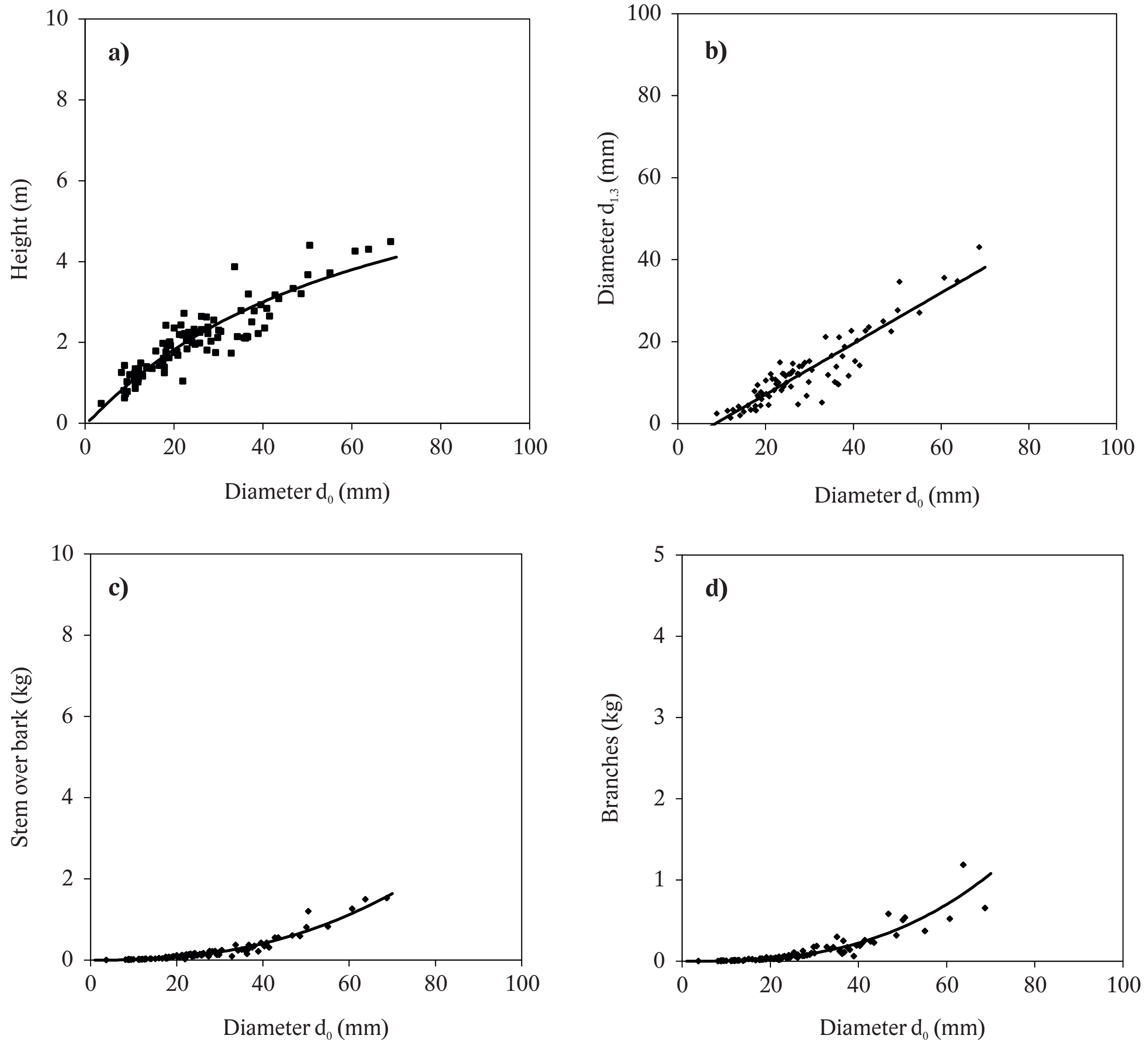

Fig. 27. *Relationship of tree height a), $d_{1.3}$ diameter b), dry mass of stem over bark c), dry mass of branches d) to stem base diameter d_0 of Goat willow.*

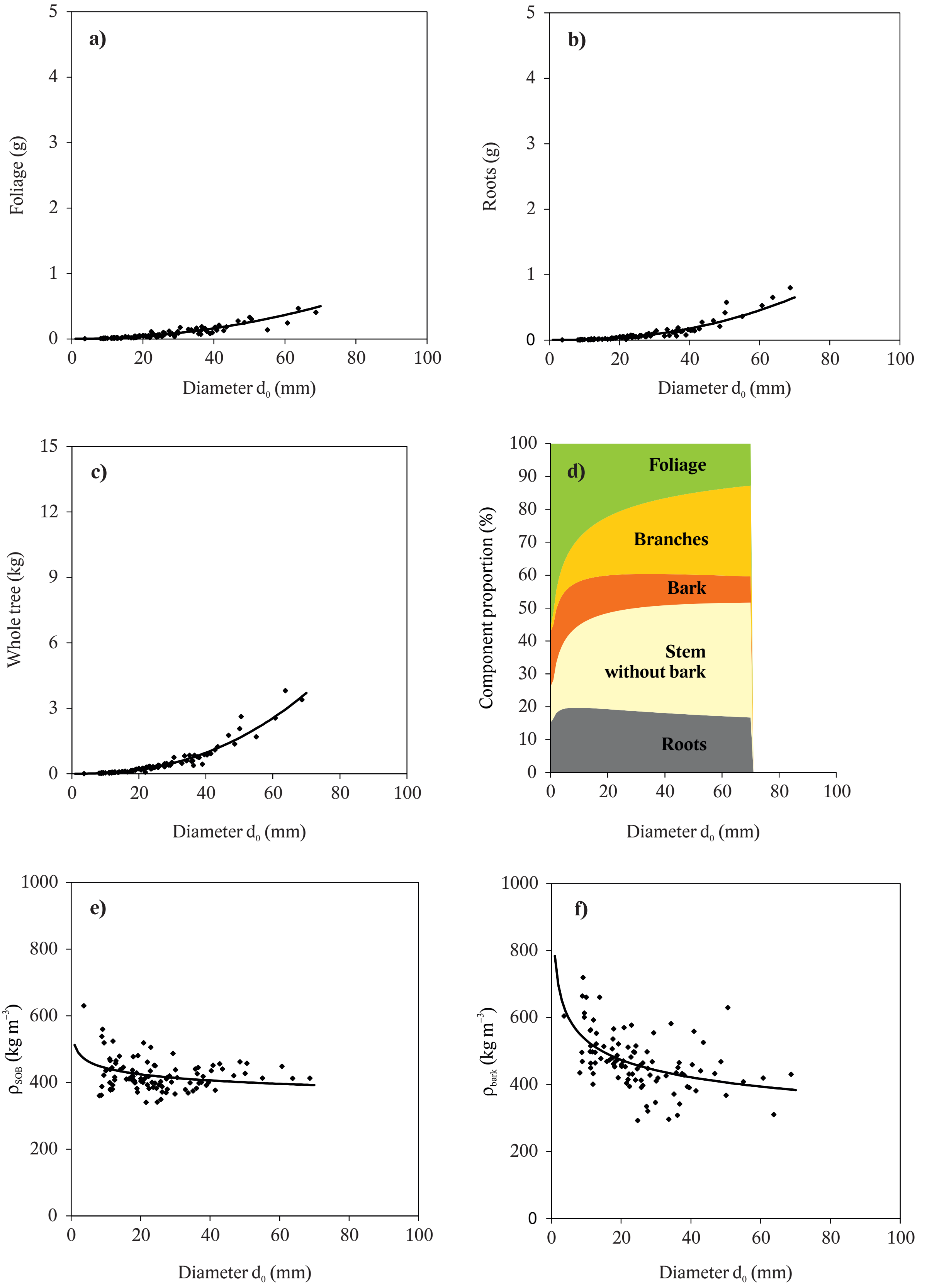

Fig. 28. *Relationship of foliage dry mass a), root dry mass b), dry mass of the whole tree c), proportion of individual tree components d), basic density of stem outside bark e), and basic bark density f) to stem base diameter d_0 of Goat willow.*

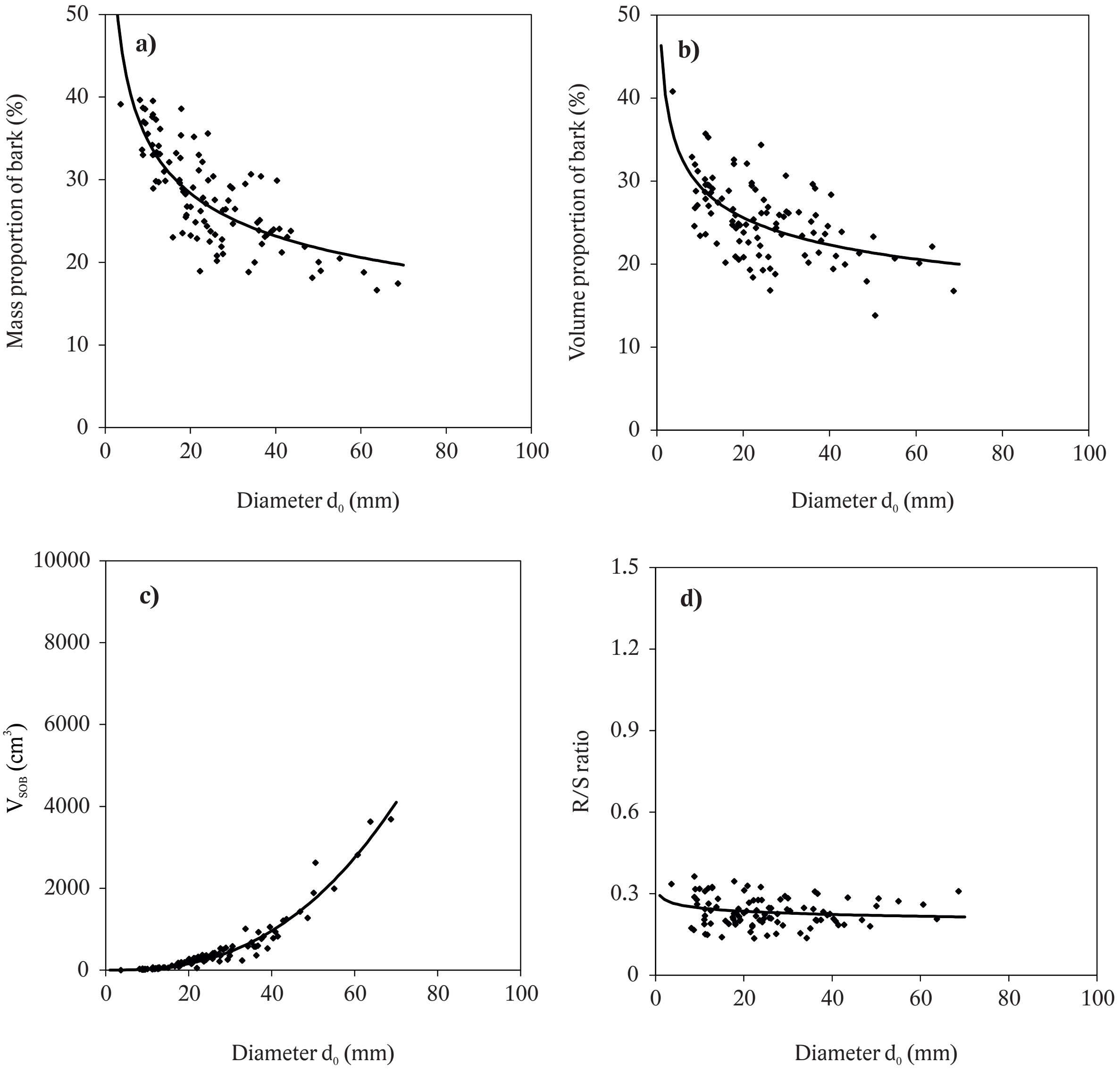

Fig. 29. *Relationship of bark mass proportion of SOB mass a) bark volume proportion of SOB volume b), volume of stem over bark c) and R/S ratio d) to stem base diameter d_0 of Goat willow.*

4.9. European larch

European larch (*Larix decidua* Mill.) is a light demanding tree species, which is with its ecological demands adjusted to rough continental climate. It is an economically important and in industry well utilisable tree species. It is usually planted, and individually occurs in all forest vegetation zones from 1st oak zone up to 8th dwarf pine zone. Naturally, it dominates at rocky mountainous sites. Larch is typical for the most northern parts of Slovakia, usually occurring at elevations from 400 to 1,600 m a.s.l. It is normally an admixture in the stands of other main tree species, and outside *Lariceto-Piceetum* group of forest types (specific for the Vysoké Tatry) larch is not considered to be a native species if its proportion exceeds 5 – 15%. At lower elevations it is regarded as a completely non-native species, but due to its economical importance it is popular to plant it at lower sites, too. Within the scheme of protected biotopes, larch is more abundant only in one biotope, namely Ls9.4 Larch-Stone pine forests (NATURA 2000 9420 *"Alpine Larix decidua and/ or Pinus cembra forests"*).

The lowest and the highest occurrences of larch (according to NFIM2 SR) were recorded at elevations of 138 m and 1,465 m a.s.l., respectively, with most frequent occurrence between 700 and 800 m a.s.l. Its greater economic importance is confirmed by its 9th place in the ranking of tree species according to the stock in the forests of Slovakia, while based on its proportion of the area it was ranked 15th, and from the point of the occurrence it was 16th most frequent tree species. It grew at a reduced area of 32 ±9 thousand ha, and occurred at 9% of the forested inventory plots.

The biomass regression models of European larch were derived from the set of 125 whole tree individuals. The larch trees were taken from six sites all located in the post-disturbance area of Vysoké Tatry (see Fig. 30). The trees covered the interval of d_0 diameters from 3.35 mm to 95.15 mm, and of heights from 0.21 m to 4.89 m (Table 26, Fig. 31a). The dry mass of the whole trees ranged from 3.80 g do 10,133.37 g, and the stem volume ranged from 0.73 cm^3 to 8,203.87 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 27. Similarly, the volume of stem over bark, its density, as well as the root-shoot ratio were derived (Table 28).

The regression models, scatter plots, and fitted regression curves were visualised in a similar way as in the case of the previous tree species. The comment on the biomass of individual components and their proportions in the total tree biomass is presented in Chapter 4.12. (Interspecies comparison of biomass characteristics).

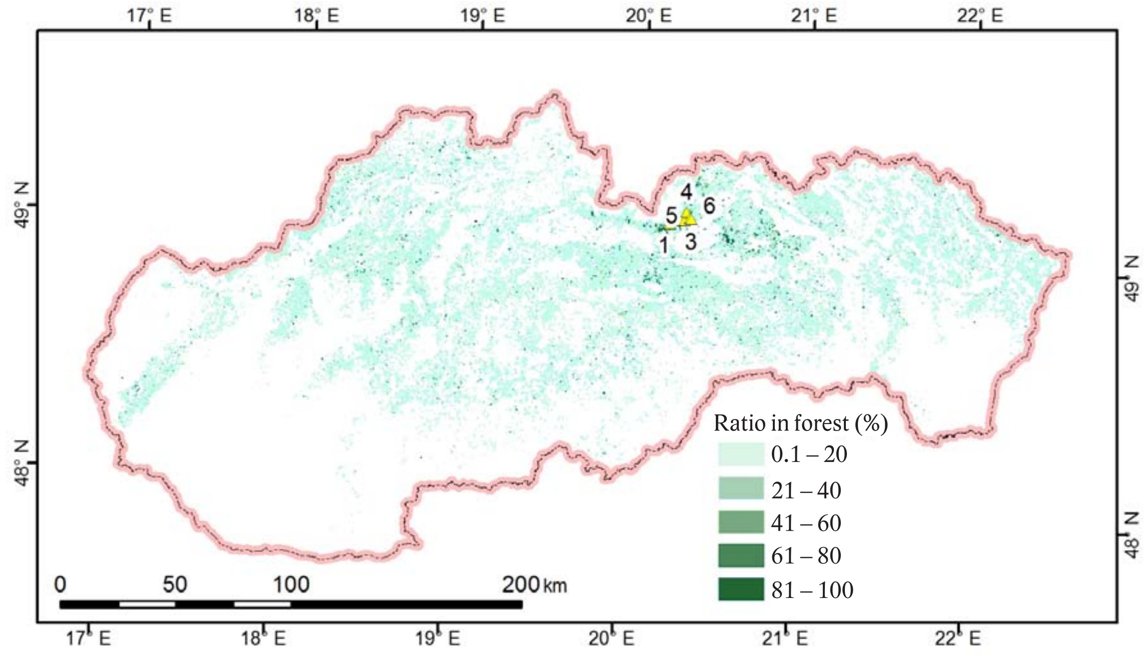

Fig. 30. *Map of sample sites of European larch and its distribution in the forests of Slovakia.*

Table 26. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), foliage biomass (foliage), branch biomass (branches), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

	European larch							
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	125	34.93	25.74	3.35	95.15	11.95	52.55	0.63
h (m)	125	2.05	1.32	0.21	4.89	0.82	3.23	0.31
SOB (g)	125	670.81	944.18	0.95	3 931.86	15.35	986.82	1.73
Foliage (g)	125	250.88	328.92	0.90	1 228.20	14.00	326.85	1.59
Branches (g)	125	684.71	975.55	0.95	4 006.10	14.25	857.05	1.78
Roots (g)	125	263.01	395.35	0.50	1 592.13	7.05	382.31	1.92
Aboveground (g)	125	1 606.40	2 225.30	3.30	8 836.06	41.50	2 232.55	1.70
Whole tree (g)	125	1 869.41	2 609.92	3.80	10 133.37	48.45	2 630.48	1.72
V_{SOB} (cm^3)	125	1 395.86	2 004.30	0.73	8 203.87	24.37	2 028.96	1.75

Table 27. *European larch, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−3.511	0.126	<0.001	2.596	0.038	<0.001				0.974	0.139	1.080	0.521
	Branches	−3.576	0.132	<0.001	2.614	0.040	<0.001				0.973	0.152	1.104	0.770
	Foliage	−2.825	0.133	<0.001	2.191	0.040	<0.001				0.961	0.154	1.098	0.708
	Roots	−3.962	0.131	<0.001	2.453	0.039	<0.001				0.970	0.150	1.105	0.820
	Aboveground part	−2.271	0.115	<0.001	2.508	0.034	<0.001				0.977	0.115	1.077	0.637
	Whole tree	−2.092	0.111	<0.001	2.499	0.033	<0.001				0.979	0.109	1.075	0.648
[10]	Stem over bark	3.671	0.057	<0.001	2.705	0.061	<0.001				0.942	0.319	1.188	1.026
	Branches	3.678	0.075	<0.001	2.667	0.079	<0.001				0.902	0.546	1.288	1.093
	Foliage	3.263	0.070	<0.001	2.218	0.075	<0.001				0.877	0.486	1.261	1.095
	Roots	2.864	0.080	<0.001	2.465	0.085	<0.001				0.871	0.632	1.334	1.145
	Aboveground part	4.683	0.065	<0.001	2.576	0.070	<0.001				0.918	0.418	1.230	1.052
	Whole tree	4.840	0.067	<0.001	2.559	0.071	<0.001				0.913	0.437	1.237	1.043
[11]	Stem over bark	−1.200	0.248	<0.001	1.751	0.088	<0.001	0.945	0.094	<0.001	0.986	0.076	1.051	0.499
	Branches	−2.609	0.338	<0.001	2.260	0.121	<0.001	0.396	0.128	0.002	0.975	0.142	1.097	0.720
	Foliage	−2.448	0.351	<0.001	2.053	0.125	<0.001	0.154	0.133	0.248	0.962	0.153	1.097	0.699
	Roots	−3.993	0.348	<0.001	2.464	0.124	<0.001	−0.013	0.132	0.924	0.970	0.151	1.106	0.822
	Aboveground part	−0.942	0.276	<0.001	2.022	0.099	<0.001	0.543	0.104	<0.001	0.982	0.095	1.067	0.597
	Whole tree	−0.953	0.275	<0.001	2.082	0.098	<0.001	0.466	0.104	<0.001	0.982	0.094	1.067	0.606

Table 28. *European larch, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.389	0.088	<0.001	2.169	0.049	<0.001				0.960	349 183
	SOB density	897.714	36.406	<0.001	−0.153	0.013	<0.001				0.530	4 883
	R/S ratio	0.195	0.019	<0.001	−0.055	0.029	0.058				0.025	0.002
[14]	SOB volume	44.476	11.589	<0.001	3.395	0.172	<0.001				0.868	1 140 699
	SOB density	587.870	6.987	<0.001	−0.161	0.013	<0.001				0.531	4 869
	R/S ratio	0.172	0.005	<0.001	−0.117	0.029	<0.001				0.099	0.002
[15]	SOB volume	1.075	0.151	<0.001	1.520	0.047	<0.001	1.323	0.082	<0.001	0.987	116 292
	SOB density	731.161	76.056	<0.001	−0.078	0.037	0.032	−0.084	0.039	0.032	0.547	4 745
	R/S ratio	0.048	0.012	<0.001	0.453	0.085	<0.001	−0.564	0.087	<0.001	0.272	0.002

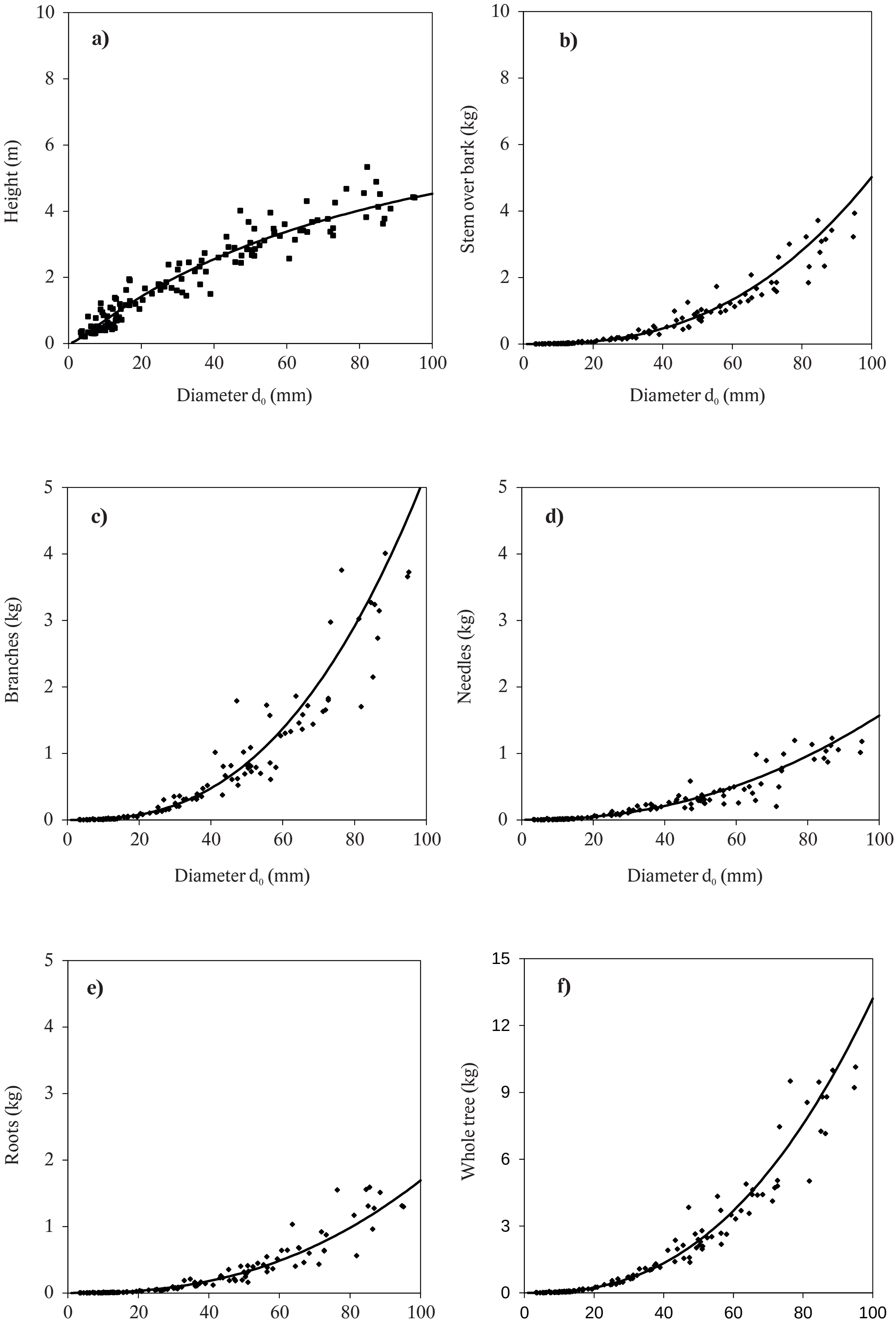

Fig. 31. *Relationship of height a), dry mass of stem over bark b), dry mass of branches c), dry mass of foliage d), dry mass of roots e) and dry mass of the whole tree f) to stem base diameter d_0 of European larch.*

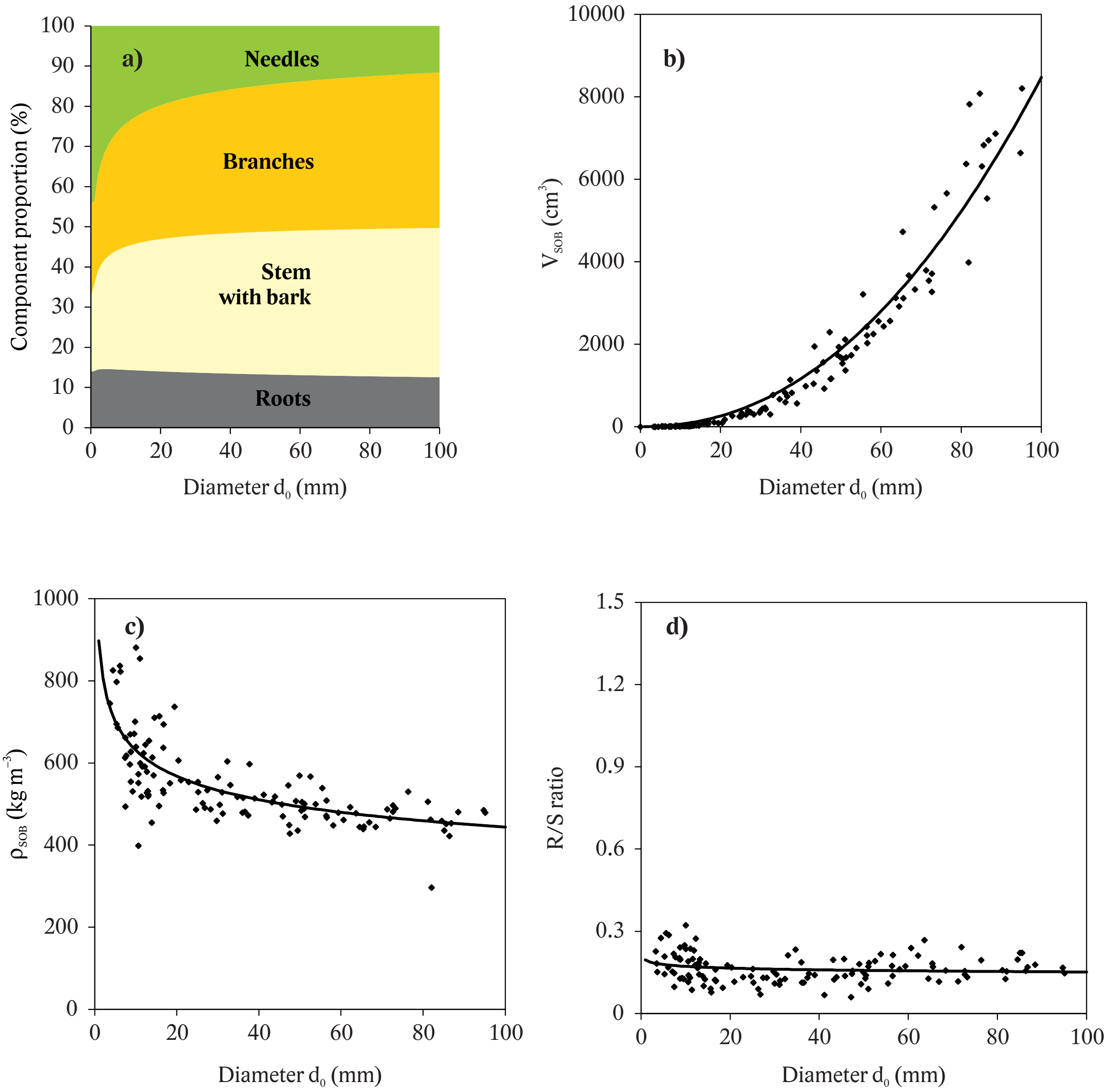

Fig. 32. *Relationship of the proportion of individual tree components a), volume of stem over bark b), basic density of stem over bark c), R/S ratio d) to stem base diameter d_0 of European larch.*

4.10. Rowan

Rowan (*Sorbus aucuparia* L.) is a rare tree species in Slovakia. From the point of its production potential and technical characteristics of the stem it does not belong to the important species for the wood-processing industry. It is a typical pioneer tree species, which increases its abundance after disturbances for a short period. In addition, it is a permanent component of forest communities in mountainous regions of 7th spruce forest vegetation zone in *Sorbeto-Piceetum* group of forest types (predominantly at elevations from 1,250 to 1,550 m a.s.l.). Rowan is an important amelioration tree species, which can enhance soil conditions with its leaf litter. It is a fruit-producing tree species and an attractive species for wildlife (mainly red deer) browsing. This fact was also confirmed with the NFIM2 SR results, which showed that from all tree species rowan was attacked by ruminant ungulates most. Game damaged 17% of rowan individuals (expressed from basal area) by browsing and stripping, while the average damage intensity of all tree species in Slovakia was less than 3%. Young rowan trees in the phase of growth were damaged most frequently, approximately every second individual. It can be assumed that the attractiveness of rowan for game can be used as a biological protection of other tree species, or to increase the carrying capacity of hunting grounds.

According to the NFIM2 SR data, the minimum and maximum elevations at which rowan occurred were 112 m and 1,603 m a.s.l., respectively, while most frequently it grew at elevations 900 – 1,000 m a.s.l. From the point of its occurrence it is 13th most common tree species in the forests of Slovakia, while from the point of its proportion of the stand stock it is ranked 35th. It grew at a reduced area of 32 ±9 thousand ha, and occurred at 15% of the forested inventory plots.

The biomass regression models of rowan were derived from the data about 93 individuals. These trees were taken from five sites all located in the post-disturbance area of Vysoké Tatry (see Fig. 33). The trees covered the intervals of d_0 diameters from 4.95 mm to 80.95 mm, and heights from 0.41 m to 4.86 m (Table 29, Fig. 34a). The dry mass of the whole trees ranged from 7.15 g do 9,154.75 g, and the stem volume ranged from 3.68 cm^3 to 6,661.10 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 30. The volume of stem outside or inside bark, its density, as well as the root-shoot ratio were derived in a similar way (Table 31).

The regression models, scatter plots, and fitted regression curves were visualised in a similar way as in the case of the previous tree species. Further comments on the biomass of individual components and their proportions in the total tree biomass are presented in Chapter 4.12. (Interspecies comparison of biomass characteristics).

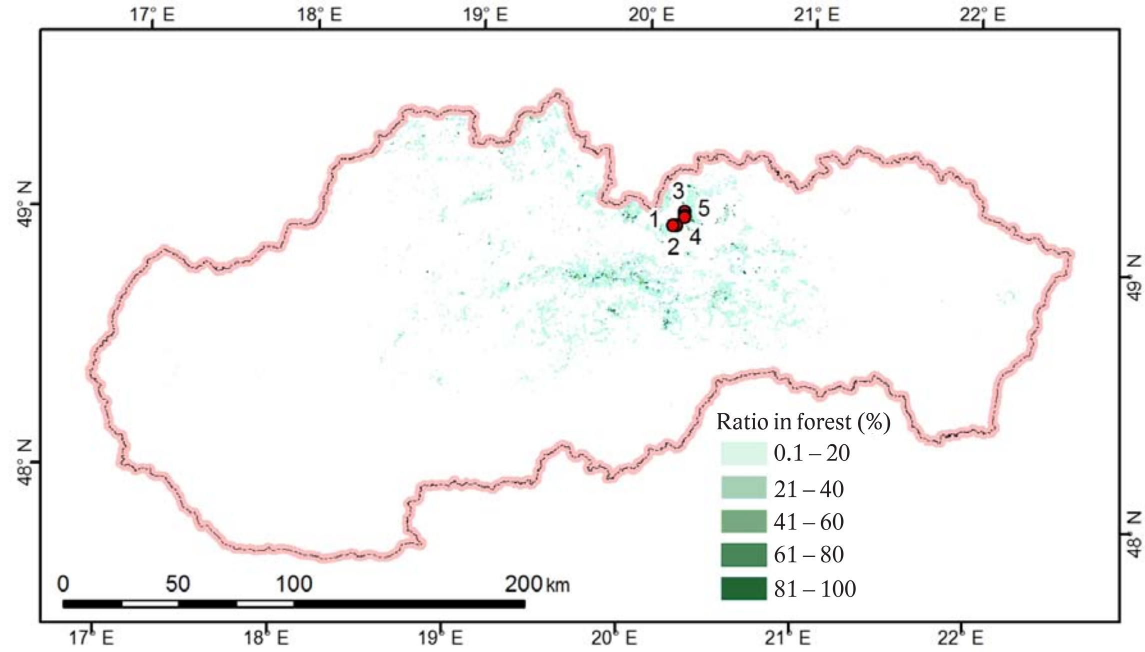

Fig. 33. *Map of sample sites of Rowan and its distribution in the forests of Slovakia.*

Table 29. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), biomass of stem under bark (SUB), foliage biomass (foliage), branch biomass (branches), bark biomass (bark), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

				Rowan				
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0(mm)	93	36.67	21.35	4.95	80.95	17.60	53.65	0.34
h(m)	93	2.82	1.21	0.41	4.86	1.78	3.99	−0.12
SOB (g)	93	742.94	799.21	3.20	3 144.05	83.05	1 199.70	1.09
SUB (g)	93	626.35	690.01	1.90	2 749.40	58.50	1 003.00	1.13
Foliage (g)	93	169.74	202.07	1.55	915.60	18.90	283.10	1.62
Branches (g)	89	283.49	472.64	0.00	2 715.30	8.00	372.60	2.86
Bark (g)	93	116.60	110.73	1.30	418.75	22.50	190.30	0.91
Roots (g)	93	432.57	525.73	2.40	2 379.80	39.40	707.80	1.49
Aboveground (g)	89	1 154.26	1 396.28	4.75	6 774.95	119.75	1 766.35	1.61
Whole tree (g)	89	1 564.29	1 892.83	7.15	9 154.75	167.20	2 407.10	1.61
V_{SOB}(cm^3)	93	1 472.96	1 577.64	3.68	6 661.10	145.16	2 465.56	1.07

Table 30. *Rowan, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p-values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−2.515	0.088	<0.001	2.412	0.025	<0.001				0.990	0.028	1.014	0.171
	Stem under bark	−3.218	0.094	<0.001	2.546	0.027	<0.001				0.990	0.033	1.016	0.183
	Branches	−7.336	0.312	<0.001	3.334	0.090	<0.001				0.943	0.280	1.138	0.596
	Foliage	−3.383	0.161	<0.001	2.237	0.046	<0.001				0.962	0.096	1.047	0.322
	Bark	−2.591	0.092	<0.001	1.966	0.027	<0.001				0.984	0.032	1.016	0.179
	Roots	−3.396	0.169	<0.001	2.476	0.049	<0.001				0.966	0.105	1.056	0.382
	Aboveground part	−2.423	0.099	<0.001	2.499	0.029	<0.001				0.989	0.034	1.017	0.190
	Whole tree	−2.067	0.104	<0.001	2.485	0.030	<0.001				0.987	0.038	1.019	0.198
[10]	Stem over bark	2.861	0.078	<0.001	3.066	0.073	<0.001				0.951	0.142	1.074	0.441
	Stem under bark	2.453	0.080	<0.001	3.242	0.075	<0.001				0.953	0.149	1.078	0.450
	Branches	−0.018	0.193	0.927	4.332	0.182	<0.001				0.871	0.632	1.393	1.443
	Foliage	1.651	0.109	<0.001	2.792	0.103	<0.001				0.890	0.278	1.154	0.704
	Bark	1.790	0.067	<0.001	2.501	0.063	<0.001				0.946	0.104	1.053	0.358
	Roots	2.188	0.122	<0.001	3.076	0.116	<0.001				0.886	0.352	1.196	0.798
	Aboveground part	3.186	0.094	<0.001	3.135	0.090	<0.001				0.934	0.202	1.112	0.584
	Whole tree	3.522	0.100	<0.001	3.104	0.095	<0.001				0.924	0.227	1.125	0.615
[11]	Stem over bark	−1.317	0.161	<0.001	1.857	0.071	<0.001	0.749	0.092	<0.001	0.994	0.017	1.008	0.129
	Stem under bark	−1.843	0.164	<0.001	1.909	0.072	<0.001	0.859	0.093	<0.001	0.995	0.017	1.008	0.130
	Branches	−6.976	0.690	<0.001	3.162	0.308	<0.001	0.244	0.416	0.560	0.943	0.282	1.137	0.592
	Foliage	−3.389	0.390	<0.001	2.240	0.171	<0.001	−0.004	0.222	0.987	0.962	0.097	1.047	0.322
	Bark	−1.575	0.191	<0.001	1.495	0.084	<0.001	0.635	0.109	<0.001	0.988	0.023	1.011	0.153
	Roots	−3.684	0.408	<0.001	2.610	0.179	<0.001	−0.181	0.232	0.438	0.966	0.106	1.056	0.379
	Aboveground part	−1.666	0.220	<0.001	2.149	0.096	<0.001	0.470	0.124	<0.001	0.990	0.030	1.015	0.178
	Whole tree	−1.586	0.243	<0.001	2.262	0.106	<0.001	0.299	0.137	0.032	0.988	0.036	1.018	0.196

Table 31. *Rowan, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Dependent variable	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0,557	0,189	0,004	2,101	0,082	<0,001				0,951	123 665
	SUB volume	0,356	0,127	0,006	2,163	0,085	<0,001				0,950	88 720
	Bark volume	0,299	0,102	0,004	1,827	0,082	<0,001				0,932	4 742
	SOB density	821,786	33,646	<0,001	−0,130	0,012	<0,001				0,527	2 028
	SUB density	719,209	28,331	<0,001	−0,087	0,012	<0,001				0,364	1 819
	Bark density	1 271,188	78,324	<0,001	−0,275	0,019	<0,001				0,668	4 913
	Bark mass proportion	90,963	3,515	<0,001	−0,438	0,013	<0,001				0,925	4,06
	Bark volume proportion	63,813	3,617	<0,001	−0,316	0,018	<0,001				0,762	8,39
	R/S ratio	0,453	0,082	<0,001	−0,064	0,053	0,234				0,015	0,016
[14]	SOB volume	32,970	11,634	0,006	3,205	0,246	<0,001				0,855	363 668
	SUB volume	23,916	8,915	0,009	3,296	0,260	<0,001				0,850	263 797
	Bark volume	10,107	2,971	0,001	2,808	0,207	<0,001				0,860	9 840
	SOB density	622,663	8,229	<0,001	−0,178	0,013	<0,001				0,629	1 592
	SUB density	599,732	8,057	<0,001	−0,126	0,013	<0,001				0,469	1 518
	Bark density	681,152	13,846	<0,001	−0,336	0,022	<0,001				0,683	4 686
	Bark mass proportion	32,650	0,529	<0,001	−0,491	0,019	<0,001				0,866	7,29
	Bark volume proportion	30,893	0,601	<0,001	−0,373	0,021	<0,001				0,746	8,96
	R/S ratio	0,408	0,027	<0,001	−0,125	0,065	0,057				0,038	0,016
[15]	SOB volume	0,880	0,286	0,003	1,697	0,112	<0,001	0,862	0,188	<0,001	0,960	101 061
	SUB volume	0,555	0,189	0,004	1,759	0,116	<0,001	0,870	0,196	<0,001	0,959	73 310
	Bark volume	0,512	0,176	0,005	1,413	0,125	<0,001	0,836	0,209	<0,001	0,943	4 049
	SOB density	520,806	47,552	<0,001	0,078	0,039	0,050	−0,272	0,049	<0,001	0,644	1 544
	SUB density	477,880	41,915	<0,001	0,100	0,038	0,010	−0,247	0,048	<0,001	0,507	1 427
	Bark density	864,156	138,766	<0,001	−0,103	0,069	0,140	−0,217	0,083	0,010	0,690	4 627
	Bark mass proportion	82,974	9,027	<0,001	−0,398	0,047	<0,001	−0,048	0,054	0,370	0,926	4,07
	Bark volume proportion	49,369	7,498	<0,001	−0,201	0,065	0,003	−0,142	0,078	0,072	0,770	8,18
	R/S ratio	0,172	0,075	0,024	0,375	0,186	0,004	−0,572	0,231	0,015	0,084	0,016

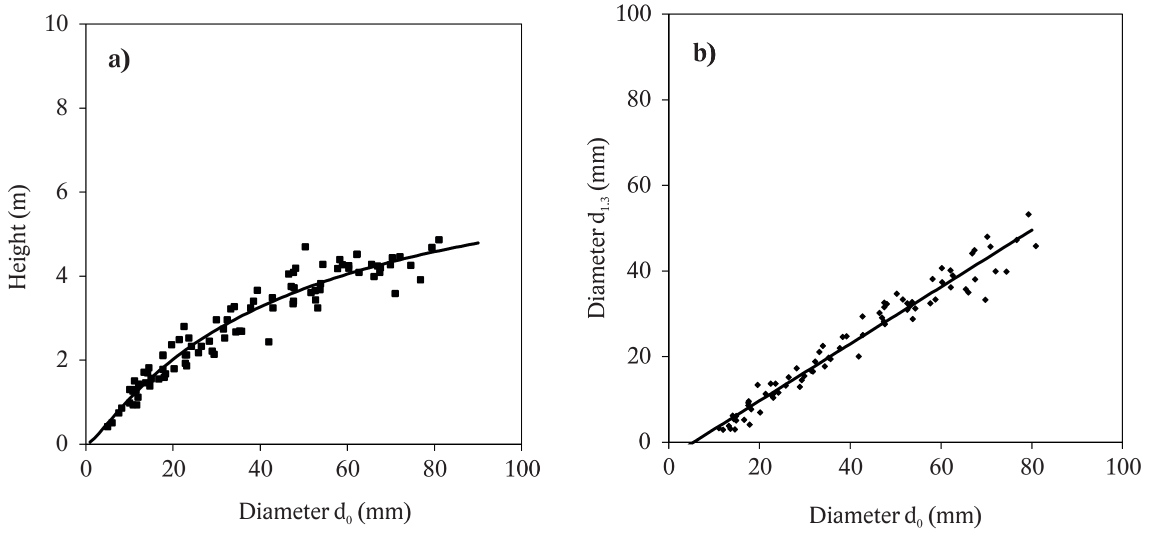

Fig. 34. *Relationship of tree height a) and $d_{1.3}$ diameter b) to d_0 stem base diameter of Rowan.*

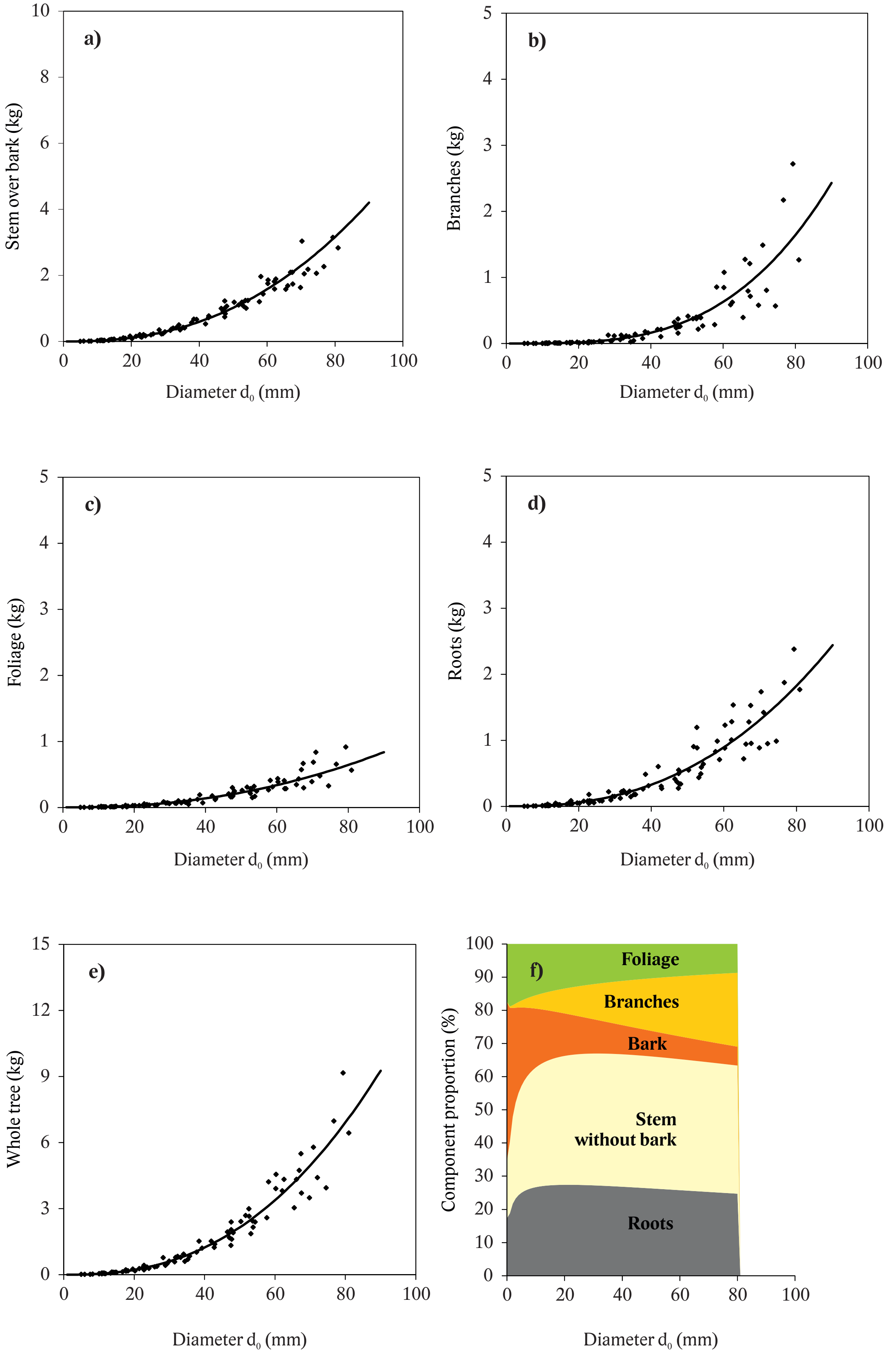

Fig. 35. *Relationship of dry mass of stem over bark a), dry mass of branches b), dry mass of foliage c), dry mass of roots d) and dry mass of the whole tree e) and proportion of individual tree components f) to stem base diameter d_0 of Rowan.*

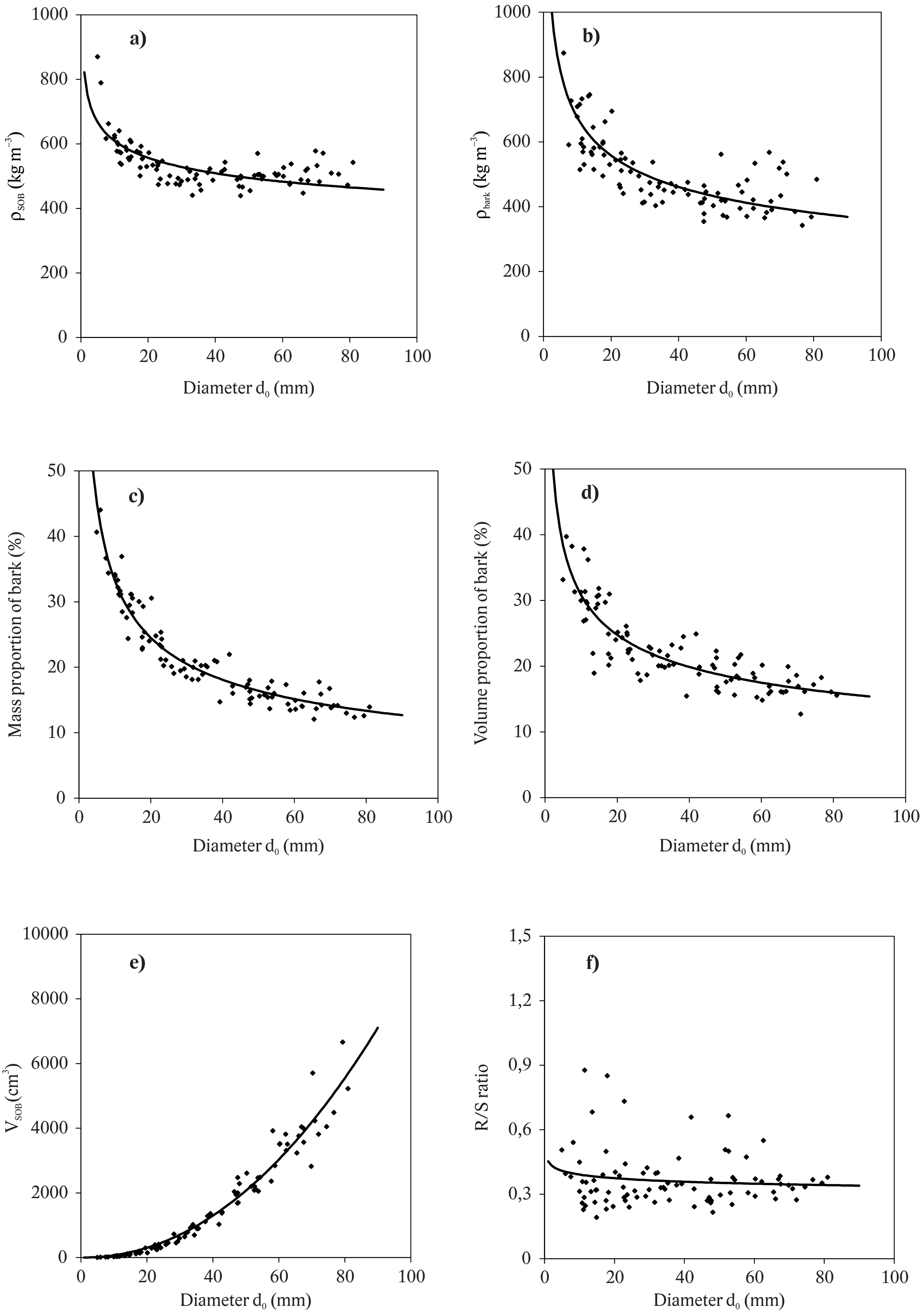

Fig. 36. *Relationship of the basic density of stem over bark a), basic bark density b), bark mass proportion of SOB mass c), bark volume proportion of SOB volume d) volume of stem over bark e), and R/S ratio f) to stem base diameter d_0 of Rowan.*

4.11. Common aspen

Common aspen (*Populus tremula* L.) is a pioneer tree species with an important economic significance. Its proportion in the forests of Slovakia is small, based on its occurrence it is ranked 17th, from the point of the stock and area it was ranked 18th and 16th, respectively. It usually occurs in middle forest vegetation zones from 2nd beech-oak zone up to 6th spruce-beech-fir zone, most frequently at lower elevations. It is not an important tree species in the biotopes of European and national significance, and it is not the main tree species in any biotope. Aspen is an attractive tree species for the nutrition of red deer, hence it increases the carrying capacity of hunting grounds and can ensure biological protection of economically important tree species.

According to the NFIM2 SR data, the minimum and maximum elevations at which aspen occurred were 199 m and 1,466 m a.s.l., respectively, while most frequently it occurred at elevations 450 – 550 m a.s.l. It grew at a reduced area of 17 ±7 thousand ha, and occurred at 8% of the forested inventory plots.

The biomass regression models for the Common aspen were derived from the data measured at 185 individuals. The trees were taken from seven sites (see Fig. 37) located in orographic units of Kremnické vrchy (1 and 2), Štiavnické vrchy (3 and 4), Krupinská planina (5), Malá Fatra (6) and Nízke Tatry (7). The trees covered the intervals of d_0 diameters from 3.30 mm to 100.90 mm, and heights from 0.40 m to 10.54 m (Table 32, Fig. 38a). The dry mass of the whole trees ranged from 6.25 g do 15,650.85 g, and the stem volume ranged from 2.76 cm^3 to 24,500.28 cm^3.

The regression models (i.e. the coefficients and basic statistical characteristics) for the calculation of the biomass in individual tree components, as well as of the whole tree are presented in Table 33. The volume of stem outside or inside bark, its density, as well as the root-shoot ratio were derived using the same approach (Table 34).

The regression models, scatter plots, and fitted regression curves were visualised in a similar way as in the case of the other tree species. The text describing the biomass of individual components and their proportions in the total tree biomass is presented in Chapter 4.12. (Inter-species comparison of biomass characteristics).

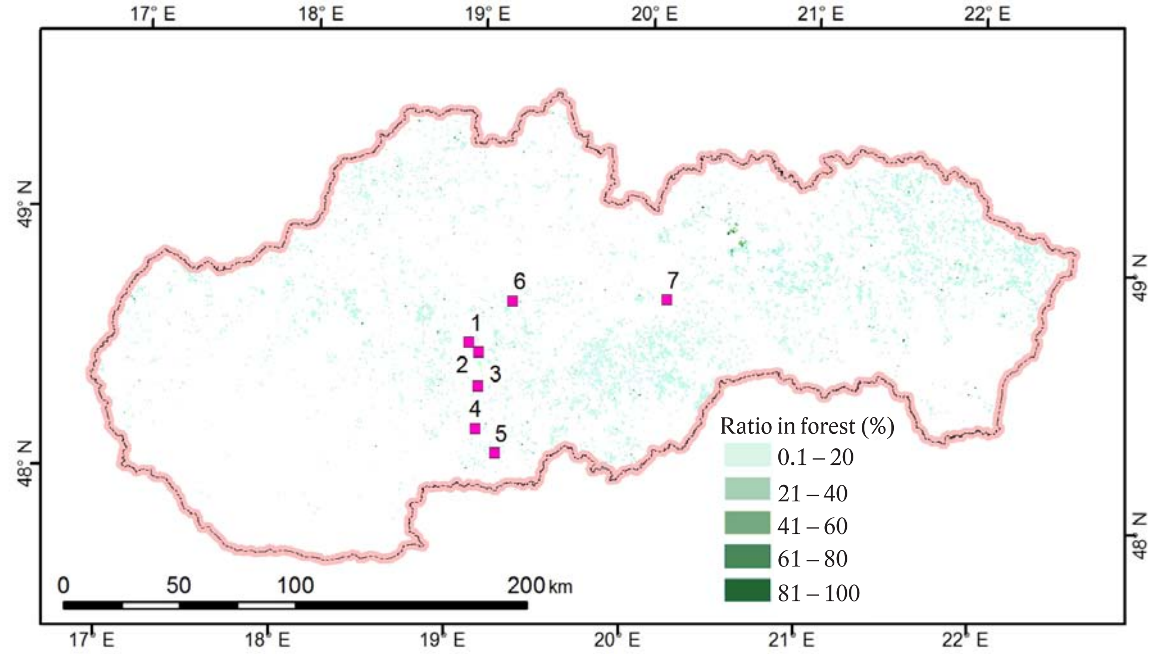

Fig. 37. *Map of sample sites of Common aspen and its distribution in the forests of Slovakia.*

Table 32. *Number (N), mean, standard deviation (SD), minimum, maximum, 25-percentile (25. p), 75-percentile (75. p) and skewness of diameter (d_0), tree height (h), biomass of stem over bark (SOB), biomass of stem under bark (SUB), foliage biomass (foliage), branch biomass (branches), bark biomass (bark), root biomass (roots), aboveground biomass (aboveground), total tree biomass (tree), and volume of stem over bark (V_{SOB}) of individual trees.*

	Common aspen							
	N	Mean	SD	Min	Max	25. p	75. p	Skewness
d_0 (mm)	185	31.39	20.00	3.30	100.90	15.50	43.10	0.89
h (m)	185	3.81	2.42	0.40	10.54	1.87	4.96	0.75
SOB (g)	182	935.07	1 654.58	1.23	10 474.65	48.29	899.89	3.10
SUB (g)	182	699.67	1 293.38	0.76	8 351.95	29.95	673.93	3.26
Foliage (g)	181	93.54	130.82	0.75	736.85	10.92	128.86	2.57
Branches (g)	179	251.49	460.01	0.00	2 770.00	11.89	283.65	3.45
Bark (g)	185	235.29	364.10	0.47	2 122.70	18.34	275.70	2.57
Roots (g)	183	262.48	375.57	1.20	2 190.00	23.25	310.26	2.57
Aboveground (g)	174	1 193.43	2 151.36	3.15	13 460.85	69.25	1 235.58	3.38
Whole tree (g)	172	1 455.66	2 530.23	6.25	15 650.85	82.88	1 538.25	3.27
V_{SOB} (cm^3)	185	2 232.89	3 979.88	2.76	24 500.28	106.71	2 139.86	3.22

Table 33. *Common aspen, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE), logarithmic transformation bias λ and its standard deviation (S.D.) for equations [9] – [11].*

Eq.	Tree component	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE	λ	S.D.
[9]	Stem over bark	−3.612	0.107	<0.001	2.795	0.033	<0.001				0.976	0.098	1.048	0.323
	Stem under bark	−4.454	0.120	<0.001	2.932	0.036	<0.001				0.973	0.123	1.061	0.367
	Branches	−5.683	0.196	<0.001	3.010	0.060	<0.001				0.935	0.306	1.116	0.710
	Foliage	−2.907	0.225	<0.001	2.020	0.069	<0.001				0.829	0.429	1.191	0.634
	Bark	−3.906	0.104	<0.001	2.528	0.031	<0.001				0.973	0.092	1.045	0.313
	Roots	−3.315	0.130	<0.001	2.410	0.039	<0.001				0.954	0.145	1.078	0.474
	Aboveground part	−2.853	0.103	<0.001	2.687	0.032	<0.001				0.977	0.088	1.042	0.296
	Whole tree	−2.379	0.092	<0.001	2.618	0.028	<0.001				0.981	0.070	1.036	0.293
[10)	Stem over bark	2.541	0.055	<0.001	2.602	0.042	<0.001				0.956	0.182	1.090	0.450
	Stem under bark	1.986	0.054	<0.001	2.743	0.040	<0.001				0.962	0.172	1.085	0.439
	Branches	1.114	0.117	<0.001	2.653	0.089	<0.001				0.834	0.786	1.402	1.154
	Foliage	1.676	0.111	<0.001	1.755	0.085	<0.001				0.706	0.736	1.350	1.009
	Bark	1.680	0.060	<0.001	2.336	0.045	<0.001				0.937	0.211	1.107	0.502
	Roots	2.034	0.076	<0.001	2.198	0.057	<0.001				0.893	0.336	1.166	0.641
	Aboveground part	3.108	0.069	<0.001	2.451	0.053	<0.001				0.924	0.283	1.145	0.611
	Whole tree	3.425	0.069	<0.001	2.386	0.053	<0.001				0.923	0.275	1.137	0.576
[11]	Stem over bark	−1.354	0.162	<0.001	1.741	0.071	<0.001	1.040	0.067	<0.001	0.990	0.042	1.021	0.210
	Stem under bark	−1.759	0.163	<0.001	1.674	0.072	<0.001	1.240	0.067	<0.001	0.991	0.043	1.021	0.211
	Branches	−6.312	0.449	<0.001	3.303	0.197	<0.001	−0.286	0.184	0.122	0.936	0.304	1.162	0.689
	Foliage	−4.306	0.505	<0.001	2.674	0.223	<0.001	−0.645	0.210	0.002	0.837	0.409	1.184	0.637
	Bark	−2.319	0.199	<0.001	1.787	0.088	<0.001	0.732	0.082	<0.001	0.981	0.065	1.033	0.271
	Roots	−2.593	0.295	<0.001	2.072	0.130	<0.001	0.334	0.123	0.007	0.956	0.140	1.074	0.448
	Aboveground part	−1.692	0.219	<0.001	2.145	0.096	<0.001	0.533	0.090	<0.001	0.981	0.073	1.036	0.281
	Whole tree	−1.434	0.200	<0.001	2.177	0.088	<0.001	0.434	0.083	<0.001	0.983	0.060	1.031	0.269

Table 34. *Common aspen, b_0, b_1, b_2 regression coefficients, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), mean square errors (MSE) for equations [13] – [15].*

Eq.	Dependent variable	b_0	S.E.	P	b_1	S.E.	P	b_2	S.E.	P	R^2	MSE
[13]	SOB volume	0.066	0.015	<0.001	2.792	0.051	<0.001				0.962	553 328
	SUB volume	0.038	0.009	<0.001	2.865	0.056	<0.001				0.954	405 034
	Bark volume	0.043	0.009	<0.001	2.528	0.049	<0.001				0.956	25 170
	SOB density	603.039	23.540	<0.001	-0.093	0.012	<0.001				0.232	2 908
	SUB density	442.437	16.643	<0.001	-0.022	0.012	0.058				0.019	2111
	Bark density	953.096	49.181	<0.001	-0.180	0.017	<0.001				0.371	8153
	Bark mass proportion	73.579	3.251	<0.001	-0.260	0.015	<0.001				0.628	23.73
	Bark volume proportion	49.011	2.586	<0.001	-0.186	0.017	<0.001				0.390	21.90
	R/S ratio	0.823	0.114	<0.001	-0.338	0.048	<0.001				0.211	0.019
(14]	SOB volume	10.943	2.555	<0.001	3.176	0.107	<0.001				0.914	1 200 225
	SUB volume	6.331	1.540	<0.001	3.322	0.111	<0.001				0.917	735 196
	Bark volume	6.315	1.424	<0.001	2.699	0.105	<0.001				0.878	70 190
	SOB density	499.005	6.590	<0.001	−0.103	0.011	<0.001				0.323	2 564
	SUB density	426.242	5.893	<0.001	−0.031	0.011	0.004				0.043	2 060
	Bark density	651.553	10.928	<0.001	−0.185	0.014	<0.001				0.454	7 085
	Bark mass proportion	42.352	0.518	<0.001	−0.262	0.011	<0.001				0.748	16.1
	Bark volume proportion	33.069	0.567	<0.001	−0.189	0.015	<0.001				0.469	19.07
	R/S ratio	0.395	0.018	<0.001	−0.323	0.043	<0.001				0.233	0.019
[15]	SOB volume	0.385	0.065	<0.001	1.809	0.067	<0.001	1.157	0.078	<0.001	0.983	235 109
	SUB volume	0.262	0.048	<0.001	1.775	0.073	<0.001	1.295	0.087	<0.001	0.981	170 898
	Bark volume	0.141	0.031	<0.001	1.894	0.087	<0.001	0.725	0.094	<0.001	0.968	18 440
	SOB density	381.359	32.960	<0.001	0.119	0.038	0.002	−0.208	0.035	<0.001	0.359	2 441
	SUB density	339.056	29.066	<0.001	0.102	0.038	0.007	−0.122	0.035	<0.001	0.080	1 990
	Bark density	534.357	63.217	<0.001	0.088	0.052	0.092	−0.262	0.048	<0.001	0.462	7 010
	Bark mass proportion	33.678	3.068	<0.001	0.101	0.040	0.012	−0.351	0.036	<0.001	0.757	15.62
	Bark volume proportion	26.944	3.272	<0.001	0.091	0.053	0.089	−0.270	0.049	<0.001	0.478	18.87
	R/S ratio	0.402	0.141	0.005	−0.007	0.155	0.964	−0.317	0.141	0.026	0.233	0.019

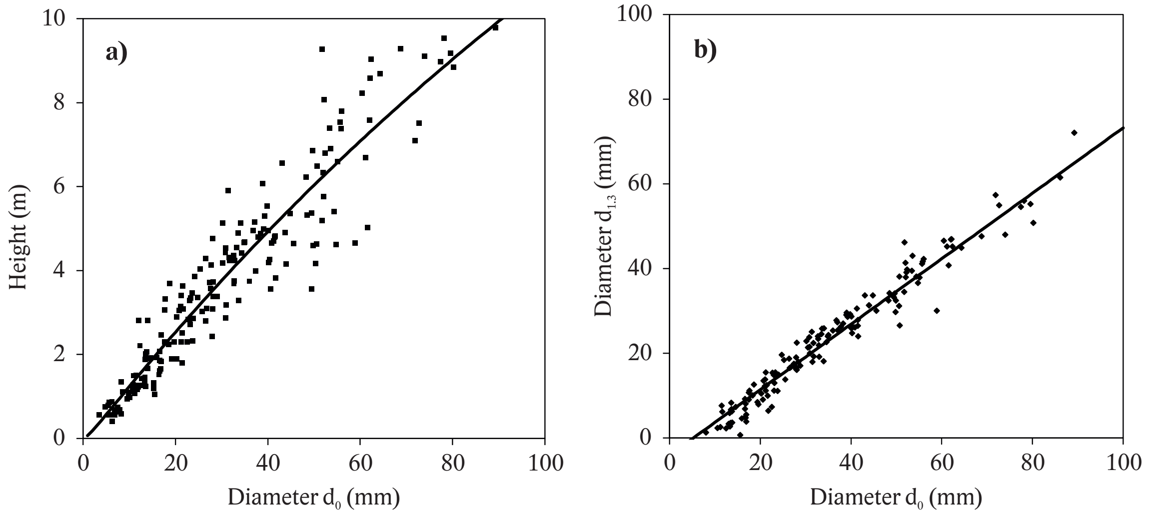

Fig. 38. *Relationship of tree height a) and $d_{1.3}$ diameter b) to stem base diameter d_0 of Common aspen.*

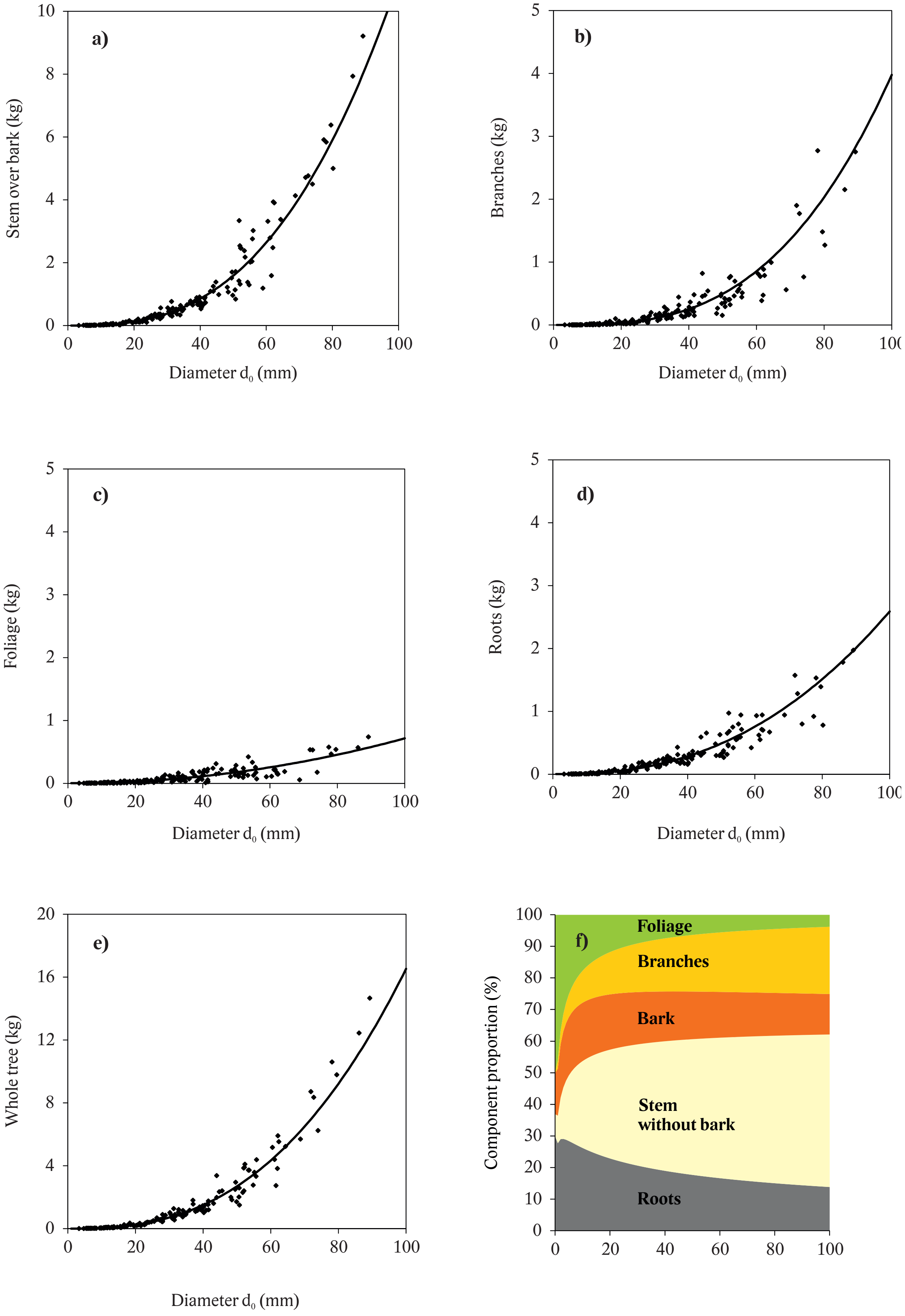

Fig. 39. *Relationship of dry mass of stem over bark a), dry mass of branches b), dry mass of foliage c), dry mass of roots d) and dry mass of the whole tree e) and proportion of individual tree components f) to stem base diameter d_0 of Common aspen.*

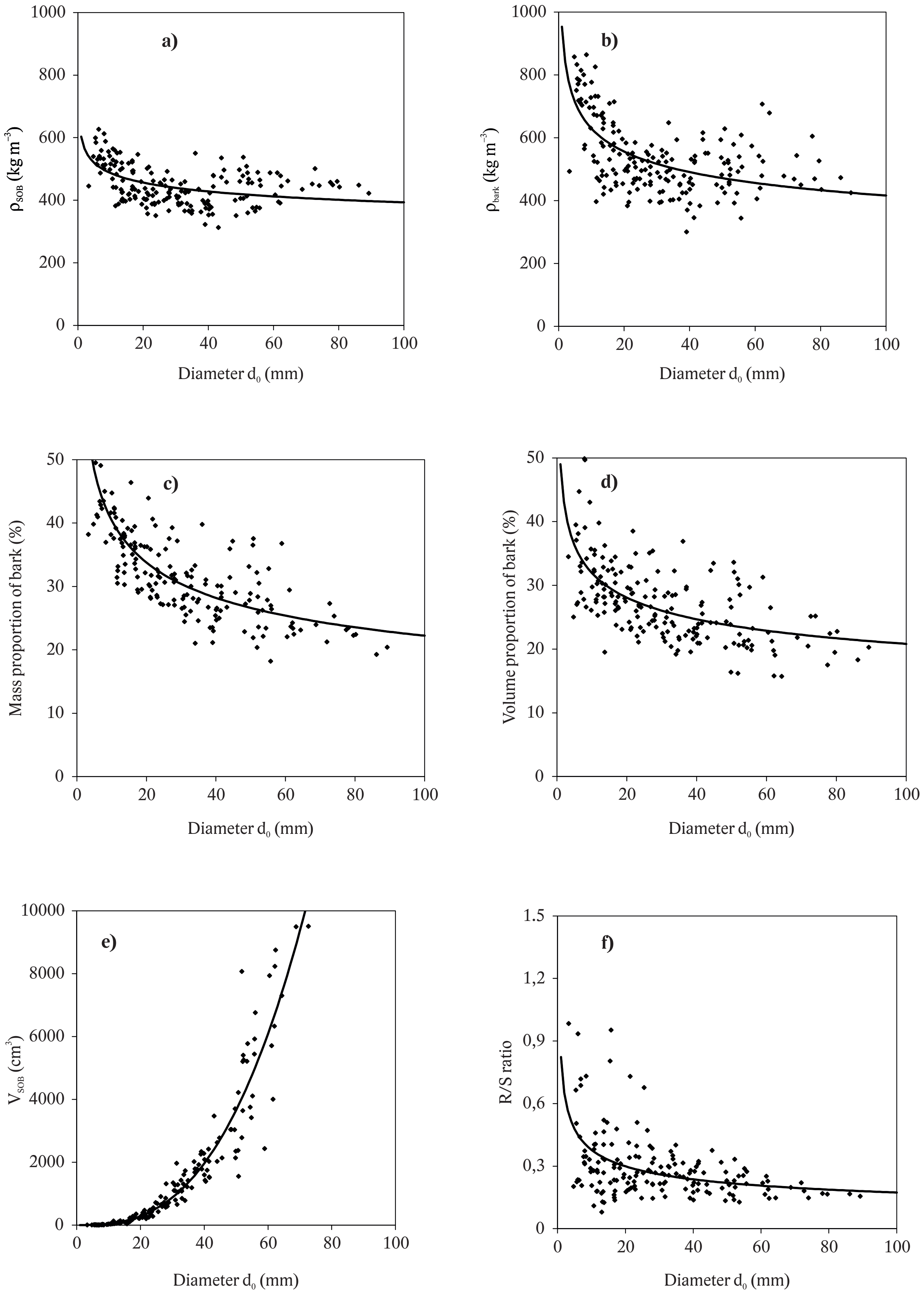

Fig. 40. *Relationship of the basic density of stem over bark a), basic bark density b), mass proportion of bark in SOB mass c), volume proportion of bark in SOB volume d), volume of stem over bark e), and R/S ratio f) to stem base diameter d_0 of Common aspen.*

4.12. Inter-species comparison of biomass characteristics

Since our results on tree species biomass dealt with eleven species, we had a possibility to compare their inter-species differences. We assumed that the differences in biomass allocation can exist between individual tree species, as well as between groups of tree species. At a tree species group level, we expected differences due to the differences in the leaf-fall cycle (i.e. evergreen versus deciduous) or due to their ecological demands (mainly light demanding versus shade tolerant). Hence, in the following text we will focus on graphical visualisation of potential inter-species differences and their subsequent interpretation.

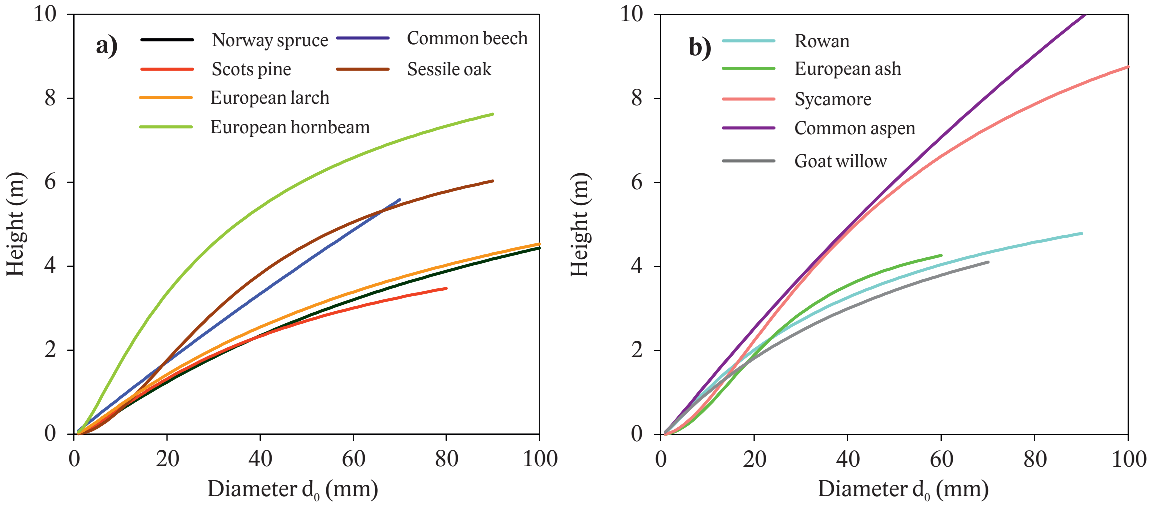

Fig. 41. *Inter-tree species comparison of the relationships of tree height to stem base diameter d_0.*

The height curves based on d_0 diameter as an independent variable showed substantial inter-species differences. We graphically divided the most important tree species (spruce, pine, beech, oak, larch, hornbeam; Fig. 41a) from the valuable (ash and sycamore) and pioneer tree species (rowan, aspen, and goat willow; Fig. 41b). If we consider equal diameters for all analysed tree species, we see that aspen was the highest tree species followed by sycamore, hornbeam, and oak. Beech was shorter, and the group of shortest trees (very similar in height) comprised ash, rowan, larch, spruce, goat willow, and pine. The relationship of height to d_0 diameter was described using the regression function [18]. The statistical characteristics of this function for individual tree species are in Table 35.

Table 35. *Regression coefficients b_0, b_1, b_2, their standard errors (S.E.), p–values (P), coefficients of determination (R^2), and mean square errors (MSE) of regression functions describing the relationship of tree height to d_0 diameter.*

Tree species	b_0	S.E.	p	b_1	S.E.	p	b_2	S.E.	p	R^2	MSE
Beech	0.493	12.795	0.969	11.204	1.279	<0.001	0.019	0.747	0.456	0.779	117.311
Spruce	44.751	19.323	0.022	11.816	1.316	<0.001	0.103	0.17	<0.001	0.937	150.708
Hornbeam	16.924	6.036	0.006	3.254	0.527	<0.001	0.093	0.009	<0.001	0.864	701.942
Oak	137.581	25.176	<0.001	1.971	1.385	0.157	0.127	0.017	<0.001	0.920	424.214
Pine	52.966	38.272	0.168	9.260	2.694	<0.001	0.164	0.039	<0.001	0.741	198.814
Sycamore	84.237	25.897	0.001	3.273	1.311	0.014	0.073	0.014	<0.001	0.882	723.968
Ash	125.858	45.116	0.007	0.395	3.445	0.909	0.193	0.061	0.002	0.861	150.077
Goat willow	6.921	4.691	0.143	8.127	0.542	<0.001	0.126	0.016	<0.001	0.812	237.939
Larch	26.626	18.865	0.161	10.506	1.126	<0.001	0.113	0.013	<0.001	0.929	281.182
Rowan	14.640	13.260	0.273	6.486	0.969	<0.001	0.135	0.014	<0.001	0.933	287.626
Aspen	8.221	11.812	0.487	7.077	0.693	<0.001	0.021	0.009	0.017	0.897	1 218.609

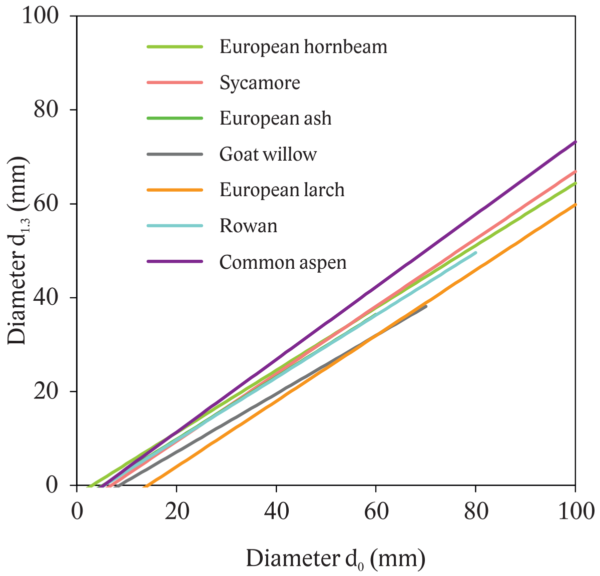

Fig. 42. *Inter-tree species comparison of the relationships of* $d_{1.3}$ *diameter to stem base diameter* d_0.

Next, we compared the regression relationships of d_0 diameter to $d_{1.3}$ diameter between the individual tree species (in the case of the main tree species, i.e. beech, oak, spruce, and pine, which we started our project with, the data on $d_{1.3}$ diameter were missing; see Fig. 42), and the relationships were fitted with linear function [17]. This relationship reflects the stem taper in its bottom part, the greater the values of $d_{1.3}$ diameter in relation to d_0 diameter are, the less taper the stem is. Based on this relationship, aspen had the least tapered stem, while larch and goat willow had the most tapered stems. The stem tapers of the other tree species (i.e. sycamore, hornbeam, ash, and rowan) were in the middle of the analysed group. The statistical characteristics of the linear functions for individual tree species are in Table 36.

Table 36. *Regression coefficients* b_0, b_1, b_2, *their standard errors (S.E.), p–values (P), coefficients of determination* (R^2), *and mean square errors (MSE) of regression functions describing the relationship of* $d_{1.3}$ *diameter to* d_0 *diameter.*

Tree species	b_0	S,E,	P	b_1	S,E,	P	R^2	MSE
Hornbeam	−2.023	0.378	<0.001	0.664	0.013	<0.001	0.946	6.10
Sycamore	−4.948	0.732	<0.001	0.718	0.017	<0.001	0.950	12.38
Ash	−3.446	1.275	0.009	0.664	0.042	<0.001	0.827	8.57
Goat willow	−5.285	0.971	<0.001	0.620	0.031	<0.001	0.838	11.60
Larch	−9.967	1.434	<0.001	0.698	0.023	<0.001	0.925	25.66
Rowan	−3.629	0.711	<0.001	0.665	0.016	<0.001	0.958	7.83
Aspen	−3.422	0.911	<0.001	0.763	0.022	<0.001	0.890	29.46

The observations of inter-species differences in the total tree biomass in relation to d_0 diameter revealed interesting information. We divided the tree species to two groups, one group comprising the species with greater quantities (with dry mass exceeding 10 kg at d_0 diameter equal to 100 mm; Fig. 43A), namely beech, hornbeam, oak, sycamore, larch, and aspen, and the other group containing the species with lower quantities (below 10 kg; Fig. 43B), which comprised spruce, pine, ash, goat willow, and rowan. This inter-species comparison indicated that at a specific d_0 diameter the greatest tree biomass was found for hornbeam and aspen, and the lowest biomass was found for goat willow and pine. However, the reasons for these differences are not clear, and hence, their interpretation is not simple, either. We cannot unambiguously state that at a particular d_0 diameter a specific group of tree species had a substantially different biomass amount than the other group (e.g. light demanding versus shade tolerant, or coniferous versus broadleaved). We use d_0 diameter equal to 50 mm as a basis for further interpretation of inter-species differences. Using our models, we estimated the following amounts of tree biomass at this diameter (tree species were ranked bottom-up on the base of their mass): goat willow – 1.65 kg, pine – 1.66 kg, rowan – 2.15 kg, spruce – 2.27 kg, sycamore – 2.33 kg, larch – 2.34 kg, oak – 2.46 kg, beech – 2.58 kg, ash – 2,65 kg, aspen – 2.69 kg, hornbeam – 2.90 kg.

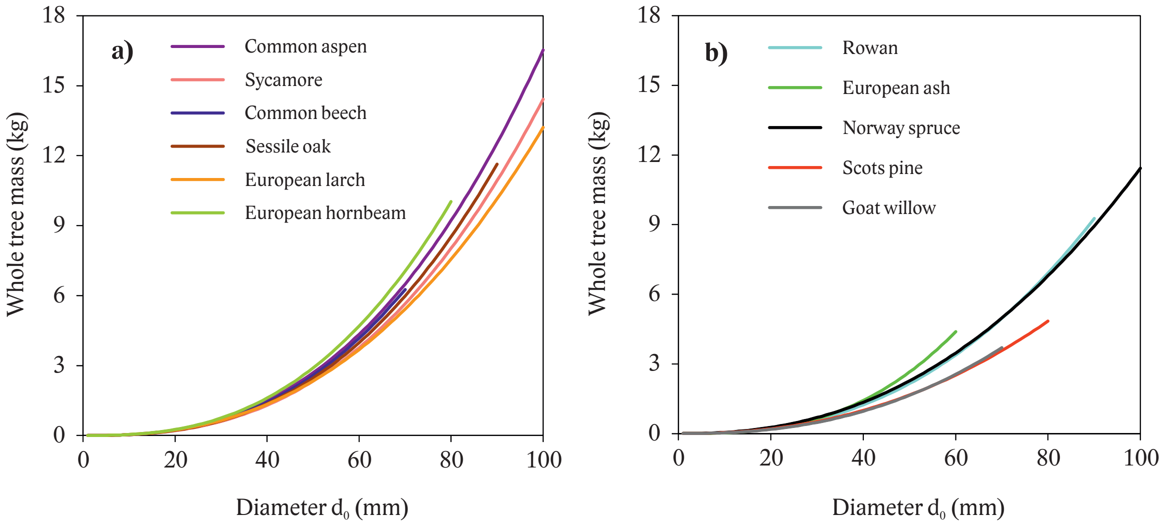

Fig. 43. *Inter-tree species comparison of the relationships of tree dry mass to stem base diameter d_0.*

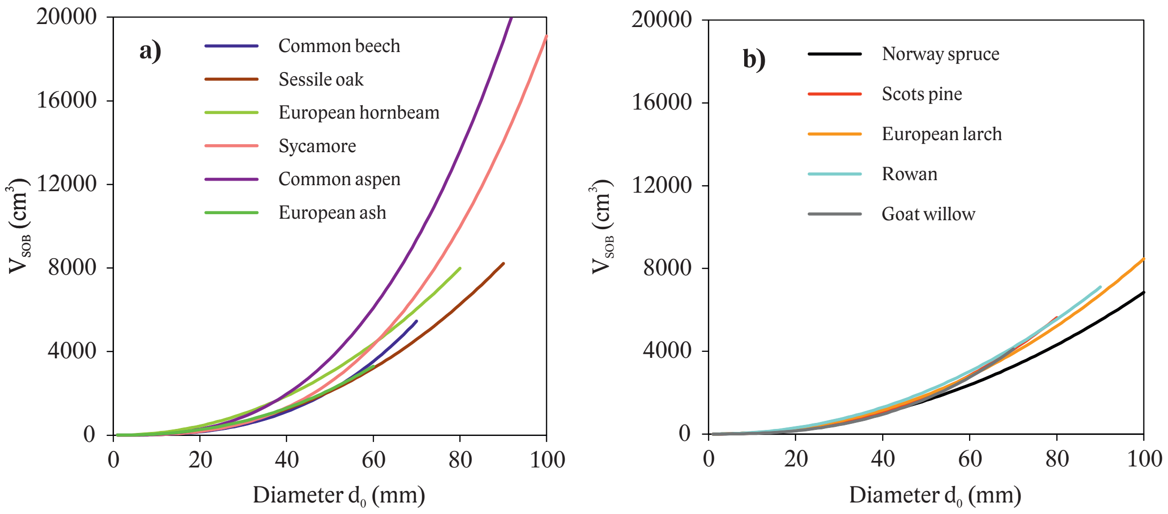

Fig. 44. *Inter-tree species comparison of the relationships of volume of stem over bark to stem base diameter d_0.*

Similarly we compared the inter-species differences in the volume of stem over bark (Fig. 44a, 44b). Also in this case we divided the tree species to two groups, one comprising the tree species with the volume of stem over bark exceeding 8,000 cm^3 at d_0 diameter equal to 100 mm (beech, hornbeam, oak, sycamore, ash, and aspen), and the other with the volume below 8,000 cm^3 (spruce, pine, goat willow, larch, rowan). Next, we compared the dry mass of stem over bark. At d_0 diameter equal to 50 mm, we estimated the following quantities of stem over bark for the individual tree species: goat willow – 0.71 kg, spruce – 0.72 kg, pine – 0.74 kg, larch – 0.83 kg, rowan – 1.03 kg, beech – 1.34 kg, sycamore – 1.44 kg, aspen – 1.59 kg, oak – 1.60 kg, ash – 1.67 kg, hornbeam – 2.10 kg.

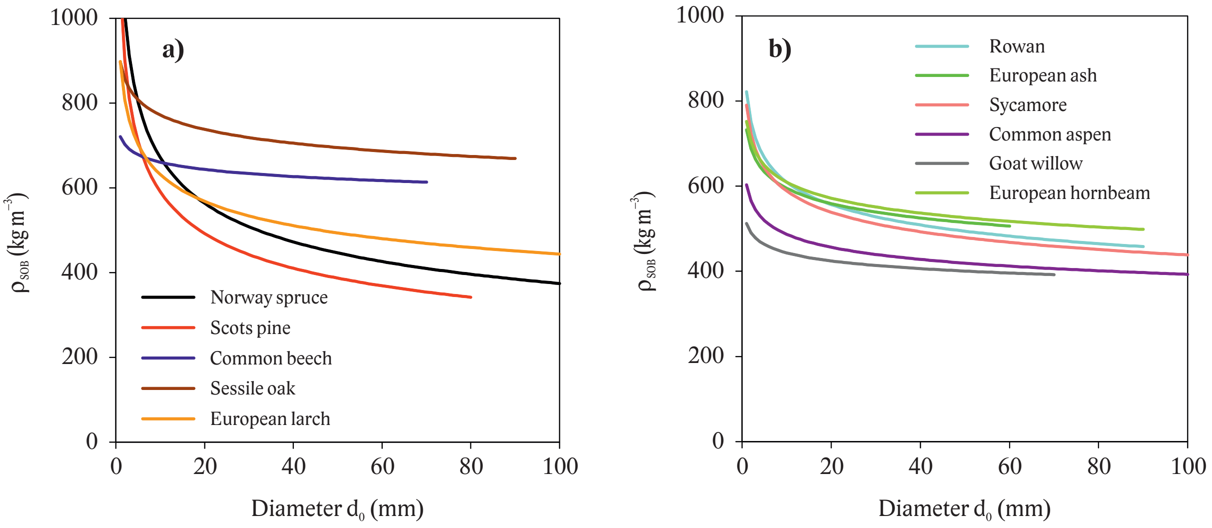

Fig. 45. *Inter-tree species comparison of the relationships of the basic density of stem over bark to stem base diameter* d_0.

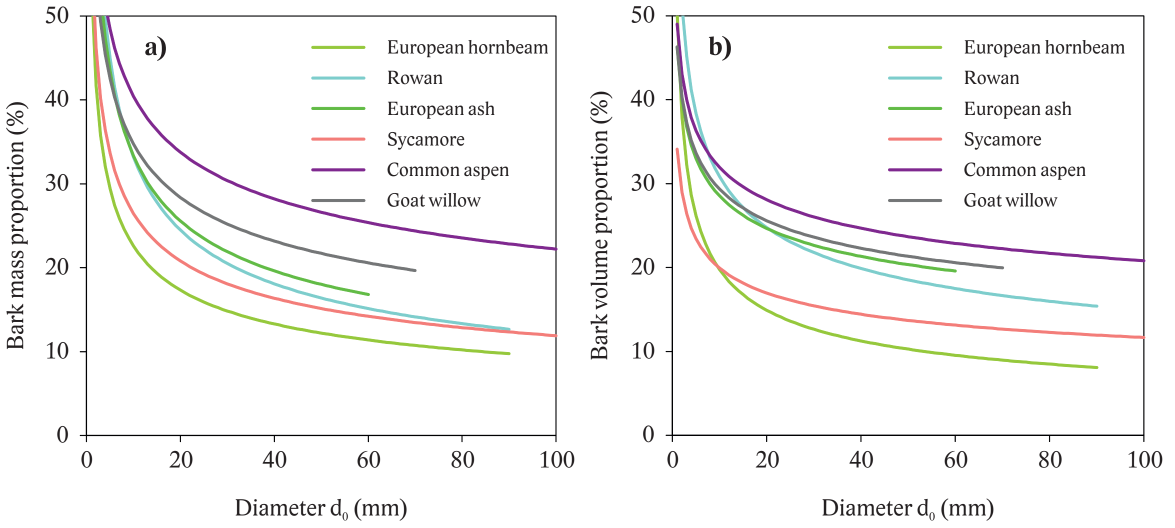

Fig. 46. *Inter-tree species comparison of the relationships of bark mass a) and bark volume proportion b) of SOB to stem base diameter* d_0.

Next, we graphically compared the basic density of stem over bark (Fig. 45a, 45b). Basic density of stem over bark is a variable with a great variation of values that depends on a number of factors. The most important factors are site conditions, climatic conditions, and silvicultural treatments. The greatest density was found for the smallest individuals irrespective of tree species. The value of the basic density of stem over bark decreased with the increasing tree size for the majority of the observed tree species, while the reduction was first rapid, then slow. After reaching diameter $d_0 = 40$ mm, their values changed only a little, and did not depend on d_0 diameter. This did not hold for spruce, pine, and larch, for which we observed the dependence on d_0 diameter in the whole range of diameters. Oak and beech had the greatest density, while aspen and goat willow had the lowest density of stem over bark. The bark mass (Fig. 46a) and volume (Fig. 46b) proportion of stem over bark (SOB) were derived similarly. The highest bark proportion was found for aspen and goat willow, and the lowest for hornbeam and sycamore.

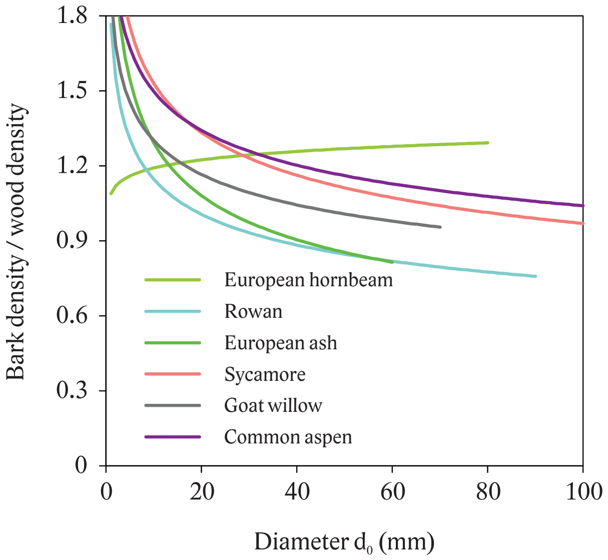

Fig. 47. *Inter-species comparison of the relationship of the ratios between bark density and wood density to stem base diameter d_0.*

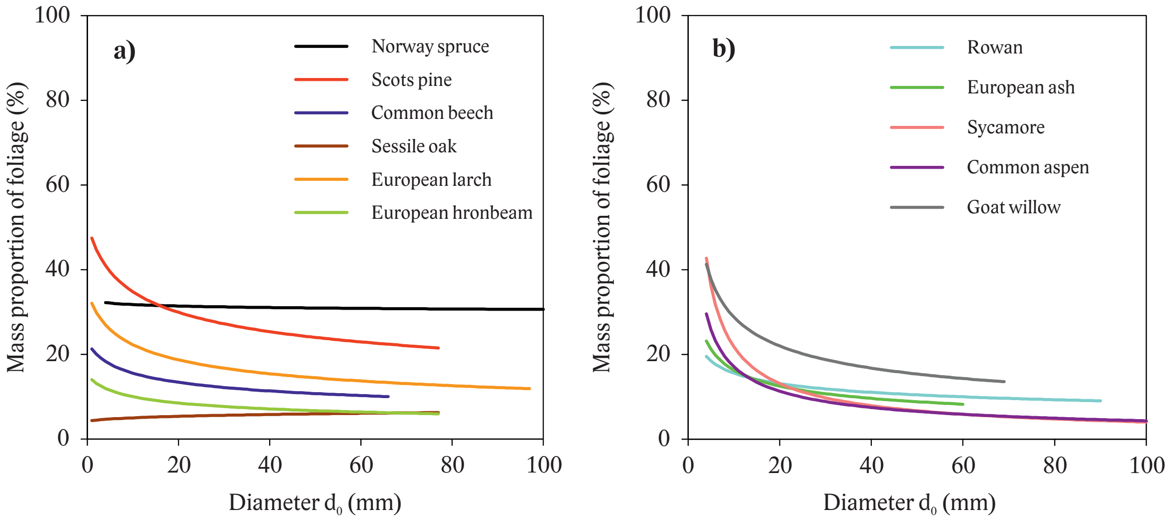

Fig. 48. *Inter-tree species comparison of the relationships between the foliage proportion of the whole tree biomass to stem base diameter d_0.*

We were also interested in the difference between bark density and density of stem wood (Fig. 47). If the density of both components is the same, the ratio between them is 1.0. The ratio of almost all tree species decreased with the increasing tree size represented by d_0 diameter. It means that bark density of small trees was greater than the density of their stem wood. A surprisingly opposite tendency was observed for hornbeam, for which bark density increased with the tree size and was always greater than wood density. Here we have to note that in small trees the bark proportion of the stem is very high, and hence, the data on bark density are relevant.

Next, we focused on inter-species differences in biomass allocation, i.e. on the component proportion of the total tree biomass. We found that the proportion of the total tree biomass in foliage biomass (Fig. 48a, 48b) decreased with the increasing d_0 stem diameter or remained stable. The stable foliage proportion was revealed for oak and spruce. Pine had the highest foliage proportion (50% in the case of small individuals) followed by spruce. On the contrary, oak had the lowest foliage proportion (below 10%). Hence, the results indicate that ever-green tree species (i.e. pine and spruce) have a higher foliage proportion than deciduous species. Here we present the foliage proportion of the whole tree biomass at d_0 diameter equal to 50 mm for individual tree species. The values were as follows: oak – 5.7%, hornbeam – 6.3%, sycamore – 6.4%, aspen – 6.4%, ash – 8.2%, beech – 10.1%, rowan – 10.4%, larch – 14.7%, goat willow – 15.0%, pine – 23.6%, spruce – 30.0%.

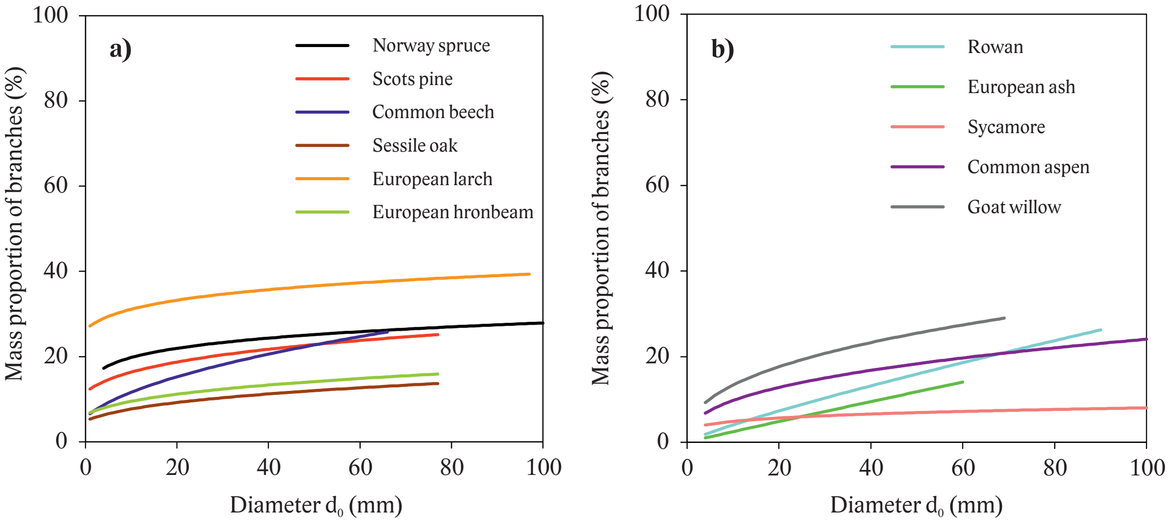

Fig. 49. *Inter-tree species comparison of the relationships of branch biomass proportion of whole tree biomass to stem base diameter d_0.*

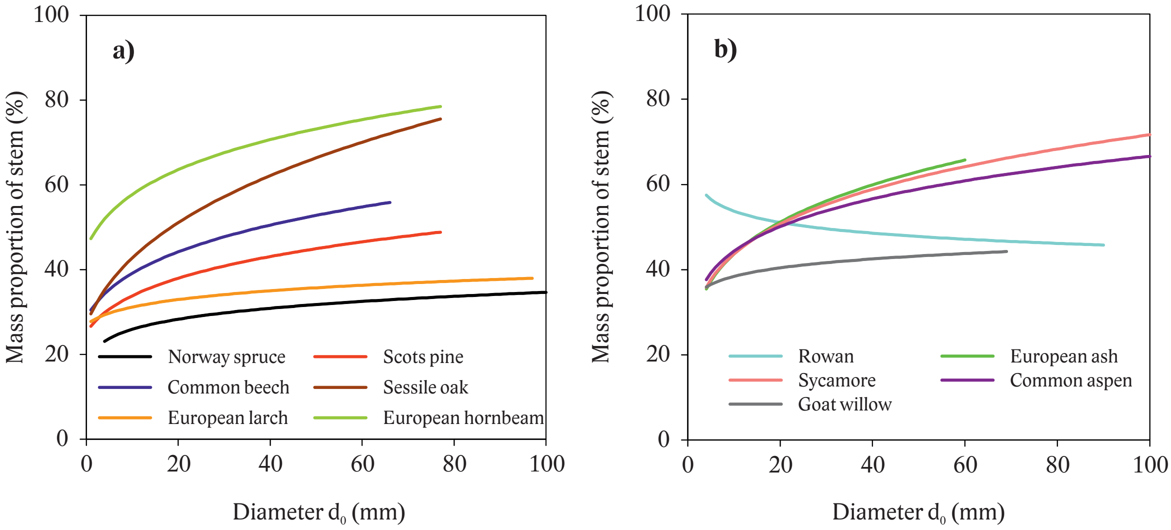

Fig. 50. *Inter-tree species comparison of the relationships between the biomass proportion of whole tree biomass in stem over bark to stem base diameter d_0.*

Large inter-species differences existed also in the case of the branch proportion of the whole tree biomass (Fig. 49a, 49b). Here we observed an opposite tendency as in the case of foliage for the majority of tree species, i.e. the increase of branch proportion with the increasing d_0 stem diameter. High branch proportion (approximately 30 – 40%) was found for larch, followed by goat willow. In contrast, sycamore had the lowest branch proportion (below 10%). For example, at a diameter d_0 equal to 50 mm the following proportions of the total tree biomass in branches were estimated: sycamore – 6.6%, ash – 10.9%, oak – 11.5%, hornbeam – 12.8%, rowan – 15.8%, aspen – 17.9%, beech – 20.5%, pine – 21.8%, spruce – 24.4%, goat willow – 24.9%, larch – 36.5%.

Stem over bark was the most important component of mass of all tree species in the greatest part of the diameter range (Fig. 50a, 50b). Nevertheless, also in this case we revealed significant inter-species differences. The proportion increased with the increasing d_0 stem diameter in the case of all tree species except for rowan (for which we observed a slight decrease). The highest proportion in the stem over bark was found for oak and hornbeam (exceeding 70% in the case of larger individuals), while spruce and larch had the lowest proportions (around 30 %). If d_0 diameter was set to 50 mm, the following stem proportions of the total tree biomass were estimated: spruce – 30.8%, larch – 35.5%, goat willow – 42.6%, pine – 44.0%, rowan – 47.5%, beech – 48.4%, aspen – 58.0%, ash – 60.4%, sycamore – 61.0%, oak – 63.5%, hornbeam – 68.5%.

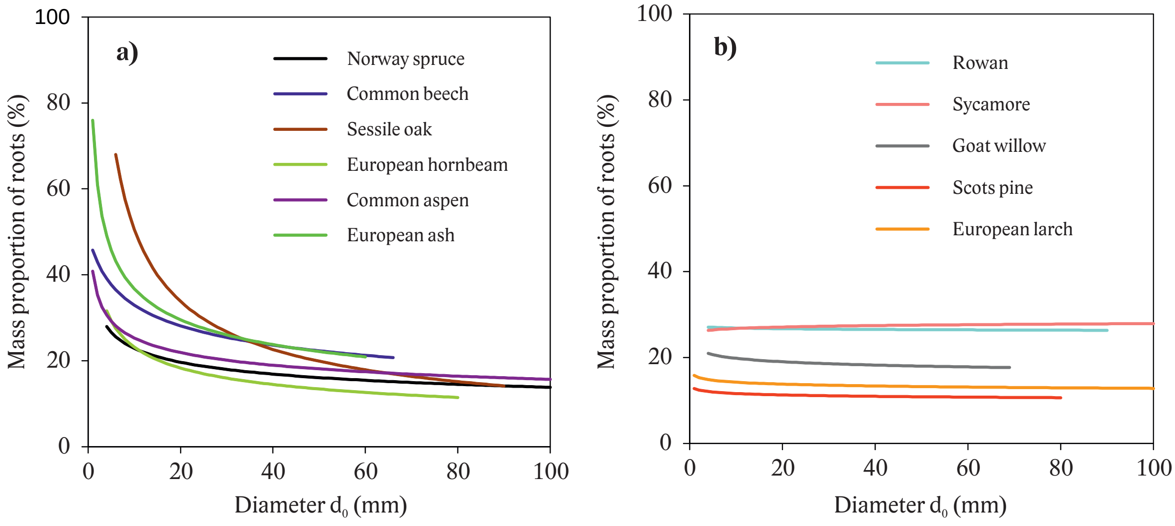

Fig. 51. *Inter-tree species comparison of the relationships between the root proportion of the whole tree biomass to stem base diameter d_0.*

Last, we examined the inter-species differences in the root proportion of the total tree biomass (Fig. 51a, 51b). For the majority of tree species, the root proportion decreased with the increasing d_0 stem diameter, but in the case of pine, larch, sycamore, rowan and goat willow, the proportion was almost stable. The greatest inter-species differences were found for smaller individuals (for diameters d_0 around 30 mm), while for larger individuals the differences decreased. In the smallest individuals of oak and ash, the roots accounted for more than 50% of the whole tree biomass, while in the case of pine and larch it was only around 15%. If we compared the modelled values of the root biomass proportion to the total tree biomass at d_0 diameter equal to 50 mm, the tree species were ranked as follows: pine – 10.5%, hornbeam – 12.4%, larch – 13.2%, spruce – 14.9%, goat willow – 17.6%, aspen – 17.7%, oak – 19.3%, ash – 20.5%, beech – 21.0%, sycamore – 26.1%, rowan – 26.3%.

5. Knowledge synthesis and conclusion

The quantification of the whole tree biomass (or above-ground biomass and biomass of individual components) from easily measurable tree characteristics, i.e. d_0 diameter and tree height, is the most important outcome of our work. We found great inter-species differences. However, the results did not reveal substantial differences between the groups of coniferous and broadleaved tree species. We mentioned this because some authors tried to develop models of the tree biomass or the biomass of individual components using generalised relationships separately for coniferous and broadleaved tree species (e.g. Teobaldelli et al. 2009; Annighofer et al. 2016). For example, the generalised model of Annighofer et al. (2016) for coniferous tree species estimated the above-ground biomass of a tree with d_0 diameter to be equal to 1.8 kg. The model for broadleaved species estimated the above-ground biomass of the tree with the same dimension to be 2.3 kg. Our models estimated the amount of the above-ground biomass of a coniferous tree with diameter d_0 equal to 50 mm in the interval from 1.48 kg (pine) to 2.03 kg (larch). The biomass of spruce, which is the most common coniferous tree species in Slovakia, was 1.96 kg. In the case of broadleaved tree species, the biomass fluctuated from 1.35 kg (goat willow) up to 2.60 kg (hornbeam). The biomass of beech, i.e. our most common tree species in Slovakia, was 2.07 kg.

The results of this work revealed substantial inter-species differences in the biomass allocation of young individuals between the analysed tree species. The tree species had different proportions of the whole tree biomass in foliage, branches, stem over bark, and roots. We confirmed that ever-green tree species (i.e. pine and spruce) had a greater foliage proportion of the whole tree biomass than deciduous tree species (i.e. broadleaved species, and larch).

From all components, the greatest proportion of the tree biomass of the analysed tree species (except for the smallest individuals) was in the stem. The majority of the tree species had surprisingly high root and foliage proportions, which is different from older individuals (outside our interval of observations). This fact was confirmed by comparing our results with the knowledge of other authors (see e.g. Zhou et al. 2006; Kleinn 2007; Skovsgaard et al. et al. 2011; Krejza et al. 2017), who presented models for bigger trees than those included in our set. We also found that the proportions in individual components changed with the tree size, which results from uneven relative increments of individual tree components. For example, we can observe that the biomass proportion in stem, or in branches increases with the tree size at the expense of foliage and roots. This suggests that tree species have a specific growth strategy. More specifically, smaller trees prefer storing carbohydrates in physiologically most active organs. These organs are responsible for photosynthesis (thanks to the active surface of foliage), or for water and nutrient absorption (using root tips). Later, the differences between the relative increments of roots and foliage and the relative increments of stem and branches diminish. As trees develop further, the ratios change in the favour of above-ground "woody" organs. Subsequent preference of stem and branch growth is most probably linked to the need to ensure construction or support tree organs, or to occupy the space under competitive conditions (mainly a struggle for light) in a closed stand canopy.

The knowledge about biomass allocation, its inter-species differences, or its changes related to stand characteristics (e.g. density and vertical structure) and the development of an individual is interesting from several aspects. For example, it can tell us a lot about various growth strategies of individual tree species, i.e. the process of occupying soil by roots and the above-ground area by foliage. This question is particularly up-to-date from the point of management of mixed stands composed of the tree species that differ in their growth characteristics. Next, such knowledge clarifies the periods of carbon storage (or the opposite phenomenon, i.e. the rate of carbon flow) in the biomass of living trees. The duration of carbon storage obviously depends on the life span of a tree organ. While foliage has a life span from one growing season (deciduous tree species) up to a period of several years (ever-green tree species), stem and coarse roots and branches have a life span of several decades up to the maximum equal to a life time of a tree.

Here we have to note that allometric relationships should not be a goal, but only certain means or a tool to secure further scientific or practical intentions (see Čermák et al. 2015). We can demonstrate this with our previous works (see Chapter 7, i.e. List of papers of the authors relevant to the topics), where we used the allometric relationships to derive the component biomass for different scientific aims. They included the assessment of growth or production of tree species and stands (papers No. 5, 10, and 15), tree ontogenesis (papers No. 2 and 8), and physiological indicators of tree species (papers No. 2, 4, and 11), or development of biomass in old disintegrated or young post-disturbance forest stands (10, 12, 19). Other papers dealt with carbon stock and sequestration (papers 12, 19, and 20), as well as with the quantification of biomass consumed by red deer and the amount of forage potential of young stands (papers No. 7, 16, and 17).

Our original ambition with our allometric relationships for the estimation of tree biomass and its individual components was to derive models applicable in the western part of the Carpathians, or in the area of the Slovak Republic. The whole tree samples taken from the majority of the Slovak territory occupied by a particular species were thought to be the basis to meet this goal. For objective reasons (mainly problems to find young forest stands originating from natural regeneration and dominated by the particular species, i.e. its proportion had to exceed 90% in stand species composition), this could not be achieved in the case of goat willow, European larch, and Rowan. The samples of these three tree species were taken from the post-disturbance areas of the northern Slovakia (Vysoké Tatry, or Kysucké Beskydy). Hence, the models of these tree species may not be suitable for the rest of Slovakia, and should serve as framework information.

Another unsolved problem of a wider implementation of our models is the fact that they did not include the trees originating from artificial plantations, where lower numbers of individuals occur per unit area, nor they included the individuals developed under parent stands. In both cases, we can assume different light conditions as in our modelled case (i.e. young forest stands originating from natural regeneration developed without a parent stand), i.e. and probably also different allocation of biomass. The impact of a tree position inside a stand (availability of resources, mainly light) on biomass allocation remains an open question, particularly under the conditions of closed stands. For this purpose, the models for individual bio-sociological positions of trees should be developed. The models for some other tree species, mainly Silver fir and birch, are still missing. The birch samples were collected in the year 2017, but we have not managed to process the data and include it in this publication.

At the end, we need to point out at two most important methodological problems, which occurred while developing these models. One is the selection of the sample trees and the other logarithmisation of the data. When selecting the sample trees, we applied the principle of the equal numbers of sample trees representing individual bio-sociological positions, which were taken from the stands of different ages (usually 1 – 10 years). This sampling design caused that the trees representing subdominant and suppressed individuals had lower ranges of diameters and heights in our dataset. At the same time, it resulted in the considerably left-skewed distributions of diameters and heights. Regarding the logarithmic transformation of allometric equations, our opinion is that it is more suitable to use an allometric equation in its power form. Logarithmic transformation deforms original data, which can cause considerable differences between the models derived with and without the logarithmic transformation, particularly at greater values of an independent variable. We present such an example in Fig. 52 and 53, which shows the power model (b) and the linearised model after its reverse re-transformation (a). The differences in the predicted values of the spruce branch dry mass for the trees with diameter d_0 equal to 100 mm are substantial (3,000 g versus 2,000 g).

Fig. 53 shows the fitting of the scatter plot after the linear transformation, from which 11 thickest trees marked red should be noted first. The same trees are marked red also in Fig. 52a. In both figures we can see that in nine cases the predicted values were greater than the measured ones, while in two cases the values were almost equal. While in Fig. 53 everything seems to be OK and the values of the residuals are not substantially greater, Fig. 52a shows that the values of the residuals after the reverse re-transformation of the linear model are great. This is caused by the fact that the same differences between the predicted and logarithmically transformed measured values, i.e. the same values of residuals, do not represent the same differences in the predicted and measured values of dry mass, but become greater with the increasing d_0 diameter (see Fig. 53). The deformation of the measured values can also be seen when comparing the widths of the diameter intervals comprising 11 thickest trees. In Fig. 52a the interval is from 60 to 100 mm, which is 40% of the whole range of diameters, while in Fig. 53 the interval is from 4.1 to 4.6 mm, which is 10% of the whole range of diameters. It means that if Fig. 53 shows that the linear function overestimates the values at ten per cent of the interval width, in reality it overestimates the values at forty per cent of the interval. The correctness of the logarithmically transformed model expressed by the variability of the predicted values around the observed values (Fabrika & Pretzsch 2011) mainly depends on how the linear function fits the scatter plot at greater values of the independent variable. In Fig. 54 we can see the residuals of the linear and non-linear models. In the case of the residuals of the linear model, heteroscedasticity is eliminated, but there is a clear trend of overestimation at the smallest and greatest values, which is also visible in Fig. 53. The values of the non-linear model are heteroscedastic, but no signs of underestimation or overestimation in any parts of the interval are visible.

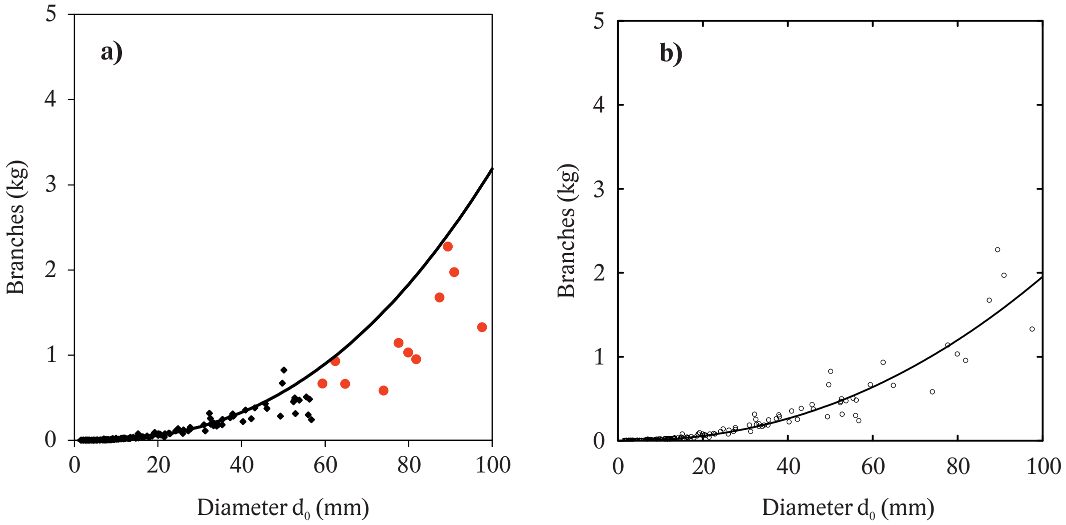

Fig. 52. *Scatter plot of measured values of spruce branch dry mass fitted with logarithmic transformation of allometric equation [8] a) and with allometric equation in a non-linear power form [13] b).*

We would like to emphasise that in the works of this character it is important to ensure the standardisation of the applied approaches, i.e. to choose one of the available approaches (either logarithmic or other transformation, or non-linear regression), and to apply this approach systematically to all data. In our work we used the method that is most frequently applied in the international scientific literature. This method was appropriate for the majority of the cases. In several (rather rare) cases, other approaches of fitting the scatter plot would be more suitable. However, in order to meet one of our main goals, i.e. to compare inter-species differences in biomass allocation, we did not combine the methods.

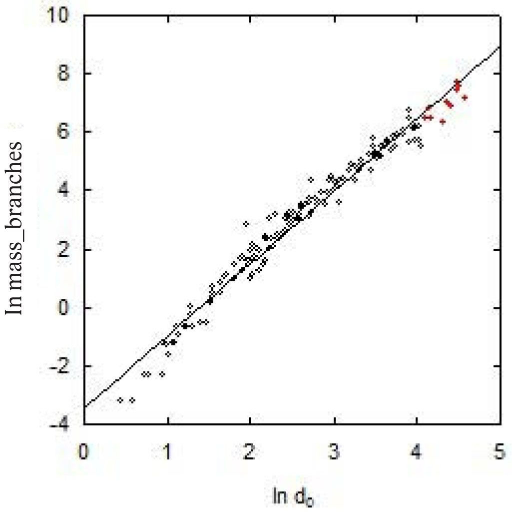

Fig. 53. *Scatter plot of logarithmically transformed values of spruce branch dry mass fitted with linear function [3].*

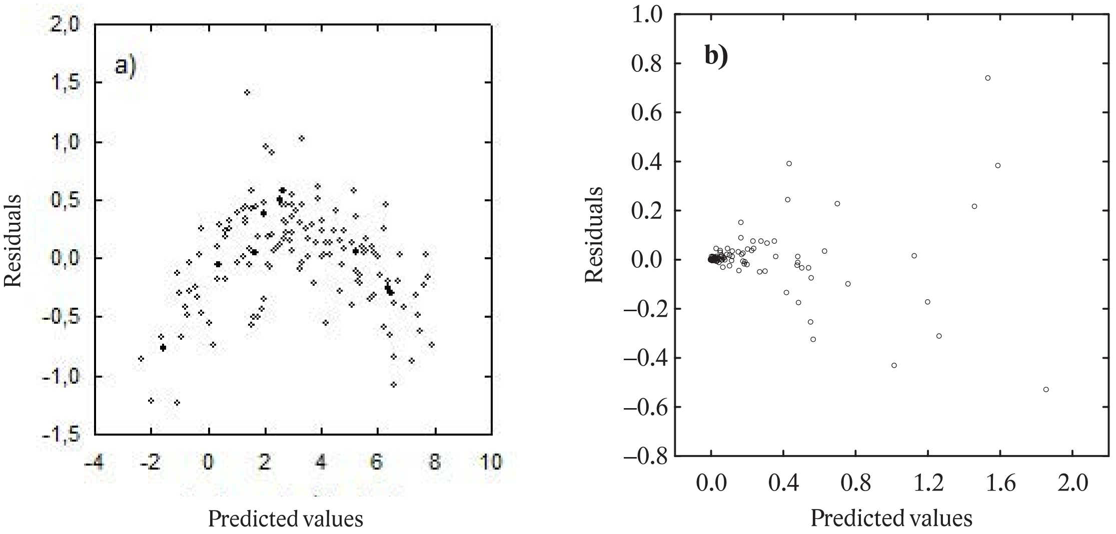

Fig. 54. *Scatter plots of the residuals of the model derived using the logarithmic transformation of data fitted with the linear function a) and of the model derived using the non-linear function.*

We intend to address the issue of developing mathematical models for the calculation of biomass of tree species (including the optimal selection of sample trees, and the most appropriate way of fitting the scatter plot) also in the future, and hence, we will fill in the gaps in the knowledge. In spite of some unsolved questions we believe that we have made considerable progress in this area. We are encouraged to continue in the work by a large number of our already published original scientific papers that dealt with this issue (see Chapter 7). We are also pleased with the intense citations of our papers, especially abroad. For example the paper of Pajtík et al. (2008) was cited more than 60 times (according to SCOPUS database).

We hope that the newly developed mathematical biomass models for eleven tree species, or the knowledge on biomass allocation to tree components, will serve as a basis for scientific purposes of many of our colleagues - research workers. The newly acquired knowledge could be applied not only in Slovakia, but also in other European countries, particularly in the regions of the Carpathian Mts., namely in the Czech Republic, Poland, Ukraine, and Romania.

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Acknowledgments

This publication was prepared mainly when solving the tasks of the following scientific projects: “Modelling biomass allocation in young stands of the selected broadleaf tree species” (APVV-0584-12) and “Ecological production of tree and ground vegetation after large-scale disturbances” (APVV-14-0086) financed by the Slovak Research and Development Agency.

SLOVAK RESEARCH
AND DEVELOPMENT
AGENCY

Jozef Pajtík, Bohdan Konôpka, Vladimír Šeben

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ISBN 978-80-8093-241-1