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BIOMASS ESTIMATION OF EUROPEAN BEECH STANDS

Diploma Thesis

2016/2017 Bc. Marek Veselský

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Abstract

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Biomass estimation of European beech stands

Forest ecosystems plays an important role in the global carbon cycle of carbon sinks of terrestrial ecosystem. Carbon sequestered or stored in forest trees is mostly referred to as the biomass of tree, site or forest. This diploma thesis deals with biomass estimation of European beech stands at the Holíkov (the Drahanská vrchovina Highlands) and Štítná nad Vláří (the Bílé Karpaty Mts.) study sites in the Czech Republic. Study was conducted in the period of 2010 to 2015. 65 allometric equations were tested for the purpose of determining the most suitable candidate for the estimation of aboveground and belowground biomass of stands and of all the major tree compartments. It is obvious from the results that the allometric equations performed very differently from each other. It was also found, based on the obtained results, that the most suitable allometric equations for the study sites are by Vejpustková *et al.* 2013 and Wutzler *et al*. 2008.

Key words: allometric equations, biomass, compartments, Holíkov, European beech, study site, Štítná nad Vláří

Abstrakt

Bc. Marek Veselský

Odhad biomasy bukových porostů

Lesní ekosystémy mají v globálním měřítku důležitý podíl na koloběhu a ukládání uhlíku do suchozemských ekosystémů. Uložený uhlík v lesních porostech je většinou označovaný jako biomasa. Diplomová práce se zabývá odhadem biomasy v bukových porostech na výzkumných plochách Holíkov (Drahanská vrchovina) a Štítná nad Vláří (Bílé Karpaty) v České republice. Studie byla provedena v období od 2010 do 2015. Bylo použito 65 alometrických rovnic za účelem stanovení nejvhodnější alometrické rovnice pro odhad nadzemní a podzemní biomasy porostu a všech hlavních frakcí stromu. Z výsledků je zřejmé, že některé alometrické rovnice se od sebe velmi lišily. Dále, na základě výsledků bylo také zjištěno, že pro experimentální plochy je nejvhodnější alometrická rovnice podle Vejpustkové *et al.* 2013 a podle Wutzlera *et al.* 2008.

Klíčová slova: alometrické rovnice, biomasa, buk lesní, frakce, Holíkov, experimentální plocha, Štítná nad Vláří

LIST OF FIGURES AND TABLES

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

BCEF – Biomass conversion and expansion factors

BEF – Biomass expansion factor

C – Carbon

CO_2 – Carbon dioxide

DBH – Diameter at breast height (1,3 m)

GHG – Greenhouse gas

GWh – Gigawatt Hour

H – Height

IPCC – Intergovernmental Panel on Climate Change

LIDAR – Light detection and ranging

R/S – ratio of root biomass to shoot biomass, or ratio of belowground to aboveground biomass

RES – Renewable energy systems

TJ – Terajoule

UNFCCC – the United Nations Framework Convention on Climate Change

1 INTRODUCTION

From a global perspective forest ecosystems account for 80% of carbon biomass of terrestrial vegetation and play an important role in carbon cycling of terrestrial ecosystems (Liu *et al*. 2000). Forest carbon biomass is significantly affected by timber harvesting, land use, climate change and other natural and human-induced disturbances (Canadell *et al*. 2007). Given that forest ecosystems are the major carbon sinks in the Czech Republic, accurate estimation of forest carbon storage and its change is critical for understanding their budgets with respect to CO_2 emissions. It is also important for scientific evaluation of the effects of forest management on the capacity of forests to act as carbon sinks. Forests deserve special attention in assessing the consequences of global change because they cover approximately 31 % of the world's total land area – about 4 033 million hectares (FAO 2010).

In the last decades, the attention on biomass issues has risen as a consequence of the need for assessing the carbon stored in the forests as required by the United Nation Framework Convention on Climate Change (UNFCCC) and the following obligations under the Kyoto Protocol (UNFCCC 1997).

Forest woody biomass and its carbon content estimation are significant for several reasons. From the forestry point of view, estimation of forest woody biomass is important for planning its exploitation (production of forest wood assortments). Forest biomass estimation for the scales larger than stand (from management units to all state forests scale) has a strategic and political meaning which is important for knowing the stock of these natural resources, e.g.: the purpose of mandatory annual reports to certain international institutions and treaties (Kyoto Protocol, Intergovernmental Panel on Climate Change (IPCC), etc.), for strategic planning of the use of renewable energy sources from woody biomass or for the focusing on precise information concerning the availability of nutrients in the biomass of forest trees (Augusto *et al*. 2000, Aksellson *et al*. 2007, Šrámek *et al*. 2009).

The most accurate way to determine woody biomass is to cut down trees under investigation and perform appropriate measurements. However, destructive harvesting of forest biomass in sample plots is a time-consuming procedure and generates considerable uncertainty when the obtained results are extrapolated to larger areas (McWilliam *et al.* 1993). Undoubtedly, the most common approach to obtain biomass estimates at stand level is through allometric equations that are fitted to morphometric measurements taken from destructive sampling of individual trees. Subsequently, these allometric equations are used to estimate the biomass of sample plots within which the diameters and heights for all the trees have been measured (Wutzler *et al*. 2008). They may be applied as a component of biomass expansion factors, which operate on aggregated data at the stand-level but in this study they were applied directly at the stand level. There are numerous studies on biomass equations of different species for different regions. This thesis mainly focuses on the application of allometric equations created by various authors for the pusposes of determining the the biomass of European Beech (*Fagus sylvatica L*.) grown in central Europian conditions.

2 AIMS AND OBJECTIVES

The objective of this study is to estimate biomass of European beech stands at Holíkov (the Drahanská vrchovina Highlands) and Štítná nad Vláří (the Bílé Karpaty Mts.) study sites, Czech Republic. This study presents an application of 65 reviewed allometric equations used for the estimation of the total biomass of beech as well as its individual compartments (branches, brushwood, crown biomass, foliage, stem wood biomass, biomass of stem bark, total stem biomass, timber, roots). Dataset is based on dendrometric characteristics of measured trees that were collected every year in the period from 2010 to 2015. Allometric equations were evaluated according to their performance. Resulting model values were compared to find the most suitable equations for individual compartments. Obtained results allow for better predictions about biomass estimation of beech stands on chosen study sites or similar sites in Central Europe.

3 GENERAL OVERVIEW

3.1 The Importance of Forest Biomass Estimation

Studies on estimation of forest biomass have gained greater importance in the last decades because of the rise of the general interest in the subject of climate change, particularly regarding the increase of carbon dioxide (CO_2) concentration in the atmosphere (Gasparini *et al*. 2006). Forest biomass is a key biophysical property that describes the carbon (C) content of vegetation. Quantification at various scales, from root system (Montagnoli *et al*. 2012, 2014) to above-ground organs, is critical for understanding the stocks and fluxes associated with forest clearance, degradation, and regeneration, particularly given current concerns regarding global climate change (Barrett *et al*. 2001, Palombo *et al*. 2014). Knowledge of C dynamics is crucial when addressing issues relating to C accounting (Montagnoli *et al*. 2012), including quantifying C for credit schemes (Patenaude *et al*. 2004, Kim *et al*. 2009). Carbon credit is a certificate showing that a government or a company has paid to have a certain amount of carbon dioxide removed from the environment (Collins Sons *et al.* 1986). National reporting of C sources and sinks is also required to fulfill obligations to international agreements such as the United Nations Framework Convention on Climate Change (UNFCCC) (Rosenqvist *et al.* 2003). Despite these requirements, there is still much uncertainty in biomass estimation at a range of scales and in particular on how much C is cycled through the Earth's forests. Scenario development to assess whether this cycling might change as a result of forest alteration (e.g. degradation induced by climate change) is also needed and is becoming increasingly important as a research field (Brack *et al.* 2006, Lucas *et al.* 2008). Tree biomass plays a key role in sustainable management and in estimating forest C stocks (Zianis and Mencuccini 2004). In addition to making estimates of C pools in forests, estimation of biomass is relevant for studying biogeochemical cycles, because the content of nutrient elements in forests is also related to the quantity of biomass present (Nihlgård 1972, Santa Regina and Tarazona 2001, Whittaker *et al*. 1974).

Climate change is expected to significantly alter the state of the natural environment and to negatively impact on the quality of human existence. The main reason for this change is considered to be the industrial emission of greenhouse gases

(GHG) into the atmosphere, together with deforestation and deterioration of the C balance of natural ecosystems (Pan *et al*. 2011). Forests constitute the most important terrestrial ecosystem contributing to the global C cycle and to C sequestration (Dixon 1994). Thus, forest ecosystems are not just passive objects of climate change, but through several positive and negative feedbacks alter the global C cycle (Janssens *et al*. 2005). Brunner and Godbold (2007) indicated that European forests hold approximately 110 tons of C per hectare in tree biomass, about 27 tons of which is stored belowground as living roots. Crucially, forest soils store a further 65 tons of C per hectare in their mineral fraction, and C pool with long residence time. The importance of C sequestration in forest ecosystems as a complex measure to mitigate climate change is an established concept (Vogt 1991, Dixon 1994). In Europe, forests are estimated to be taking up 7–12 % of European C emissions (Goodale *et al*. 2002, Janssens *et al*. 2003). Further reforestation and improvements in management could increase C sequestration in the short term (Jandl *et al*. 2007). European forests are also significant soil C stores highlighting their importance for C stores in the future (Janssens *et al*. 2003, Karjalainen *et al*. 2003). In Central Europe, the amount of C stored in tree biomass exceeds soil C storage (Brunner and Godbold 2007). At the same time, the quantity of C fixed in forest biomass is more dynamic than in the forest soils. Thus, accurate estimates of forest tree biomass are important to develop a clear understanding of biomass C storage and changes in time.

The estimation of biomass at the tree level and the subsequent step of scaling up biomass to the stand and eventually the regional level using forest inventory data is an essential component of monitoring C storage in forests (Kauppi *et al*. 1992, Nabuurs *et al*. 2003, Liski *et al*. 2006). Advances in the quality and the efficiency of C monitoring will affect decisions on climate politics and energy politics (Raupach *et al.* 2005). Estimation of C content in forest woody biomass is important with regard to greenhouse effect mitigation, and regarding mandatory reporting about CO_2 emissions and removals in forestry sector for countries, which signed the Kyoto Protocol. (Paladinic *et al.* 2009) Herbs, primarily wooden perennials that in their growth process use photosynthesis to absorb CO_2 from the air and in such a manner sequestrate C in biomass, decrease the concentration of quantitatively most significant GHG in the air. For this reason, forest stands are called C pools or C sinks. The C sequestration function of forests has been well researched during the last 20 years, and forest ecosystems, depending on their capacity, have been found to be the biggest C sinks among all other terrestrial ecosystems (Paladinic *et al*. 2009). Mandatory annual reports to certain international institutions and treaties are the key to strategic planning of the use of renewable energy sources from woody biomass (Kyoto Protocol, Intergovernmental Panel on Climate Change (IPCC). In addition, the UNFCCC and in particular the Kyoto Protocol recognise the importance of forest C sink and the need to monitor, preserve and enhance terrestrial C stocks, since changes in the forest C stock influence the atmospheric CO2 concentration. (Paladinic *et al*. 2009) Terrestrial biotic C stocks and stock changes are difficult to assess IPCC (2003) and most current estimates are subject to considerable uncertainty (Löwe *et al*. 2000, Clark *et al*. 2001, Jenkins *et al*. 2003).

3.2 Description of European beech

European beech (*Fagus sylvatica L.*) is one of the most common and dominant broadleaved tree species in Central European forests (Ellenberg 2009, BMEL 2014). European beech normally grows 30 – 35 m tall. Beech trees can live for 250 years or more but are normally harvested at 80 – 120 years of age. Thin, smooth and silver-grey bark is highly characteristic for this species. The leaves are elliptical without any lobes or peaks and have a short stalk. Beech is a good species for soil conservation as it produces a large amount of leaf litter and has extensive shallow and intermediate roots. Beech is also relatively resistant to most diseases. It does not suffer from massive predations by pests that lead to a total dieback of stands. Late spring frosts often damage young trees or flowers, which emerge simultaneously with leaf flush. Intense sunlight may damage the stemsurface. Aphids may attack the bark and *Nectria ditissima* fungus may inflict bark necrosis. Beech is highly shade tolerant. It can be regenerated naturally in continuous cover silvicultural systems (Wuehlisch 2008). Beech is widely distributed in Central and Western Europe, growing naturally from seeds under the canopy of oak-dominated abandoned coppiced forests. Natural regeneration of beech trees in oak coppiced forests is more prominent in ecotones where oak coppiced forests and beech dominated forests overlap on hillslopes (Sayer 2000, Kohler *et al*. 2006, Gärtner *et al*. 2008). Beech is the most diversely used tree species in Europe. Beech wood is mainly used for furniture. It is also excellent for flooring and staircases. Beech wood is also used extensively in the production of pulp and various boards, veneer and plywood. It is also used as fuelwood due to its relatively high energy content (Wuehlisch 2008).

3.3 Species Composition of Forests in the Czech Republic

The total area of main coniferous species, spruce in particurar, further declined. In contrast, the share of broadleaves, particularly beech, has been augmenting. (Forest Management Institute 2015).

Not only the overall proportion of individual tree species but also the distributions of forest stand mixtures within individual units of spatial arrangement of forest are the major indicators of assessing species biodiversity. The proportion between individual tree species within a unit has been continuously increasing in favour of mixed forest stands and forest stands with prevailing broadleaved tree species representation, which was also the case in 2015. This increasing trend is a result of permanent efforts to acquire an optimum species composition of forests, a practice that enjoys a long-term support under a goal-oriented national subsidy policy (Forest Management Institute 2015).

Species	Year					
	2000	2010	2012	2013	2014	2015
	Timber land in ha and %					
Beech	154 791	189 998	198 652	202 638	207 595	211 835
	6.0	7.3	7.7	7.8	8.0	8.2

Figure 1 Proportion of beech in total forested area of the Czech Republic (ha and %) (Forest Management Institute 2015)

3.4 Utilization of Biomass in the Czech Republic

The use of renewable energy sources has no contribution to global warming and to polluting emissions. In the process of transformation of renewable energy to other forms of energy, small amounts of CO_2 are released into the atmosphere. Almost none gaseous or liquid pollutants are released in the process (Hepbasli 2008).

The most frequently used renewable resource in the Czech Republic is biomass (Obršálová *et al*. 2011). The use of biomass for energy purposes in the Czech Republic is supported in accordance with the Czech Biomass Action Plan. (The Ministry of Agriculture of the Czech Republic 2012) The Czech Republic supports the use of biomass for heating and investment, at this time particularly the Green Investment Scheme (Káňa 2011). According to the natural conditions of the Czech Republic, biomass has the highest exportable potential. Around 70% of the biomass used for energy in the Czech Republic is used to produce heat. However, biomass also has week points such as its transportation. Growing biomass for energy purposes is only effective within a range of 50 km from its intended location of use. Gross electricity production from biomass amounted to 1 396 GWh in 2009. Heat production from biomass amounted to 15 463 TJ (without households) (Bufka *et al*. 2010).

3.5 Tree Biomass Equations

Tree Biomass equations are a useful instrument to calculate the C stored in the forests (Gasparini *et al*. 2006). Species-specific biomass equations for trees are vital to accurately estimate the biomass and productivity of forests. Variation in biomass within species occurs due to changes in site quality and management practices (Peuke *et al*. 2002, Coll *et al*. 2004). The importance of tree biomass led to the development of several allometric models (Bartelink 1997, Ter-Mikkelian and Korzukhin 1997, Forstreuter 1999, Santa Regina and Tarazona 2001, Zianis and Mencuccini 2003, Cienciala *et al*. 2005). Most equations use tree diameter at breast height (DBH) as the only scaling parameter:

$$y = a + DBH^b \qquad \text{(equation 1)}$$

where *a* is the allometric intercept and *b* is the allometric exponent. Some models apart from the sole DBH model also include tree height (H). Such models use three parameters and can be demonstrated on the examples of Zianis and Mencuccini (2003), Cienciala *et al.* (2005):

$$y = a + DBH^b + H*c \qquad \text{(equation 2)}$$

where *y* stands for biomass, *a*, *b*, *c* are parameters of allometric equation, DBH is diameter at breast height and H is tree height.

Each of these models was developed by statistical analysis of trees of a different range of DBH in one particular geographic region which is one of the reasons for the difference in results obtained by different models running over similar data. However, tree biomass can vary considerably not only between species, their size and geographic location but also between stand ages, site qualities, climates and stocking densities of individual stands (Cannell 1982, Bartelink 1997). Numerous studies have examined regression model equations for the estimation of tree biomass of different species for different regions (Marklund 1987, Jenkins *et al*. 2003, Zianis and Mencuccini 2003, 2005, Muukkonen 2007). Many of these papers have dealt with European beech (*Fagus sylvatica L.*), and their results have been used to develop general allometric equations for estimating beech biomass in Central Europe (Wutzler *et al*. 2008).

West *et al.* (1999), integrated the biomechanical and hydraulical principles of tree architecture, and developed a model, which seems to predict quite accurately several structural plant variables (tree height and stem diameter, number of leaves and branches, etc.) in relation to plant body size (i.e. plant biomass). They supported that theoretical values obtained by the model are accurate enough to predict aboveground forest biomass. Parde (1980) reviewed historical and methodological aspects of forest biomass studies and Cannell (1982) compiled data on biomass production from studies conducted throughout the world.

The aboveground tree phytomass is a considerable component of the total forest ecosystem biomass and there are two main methods to evaluate it. The most accurate is undoubtedly the direct measurement method, which consists in weighing the tree biomass in the field. This method is, however, destructive and extremely time demanding, and therefore, it is usually limited to little areas and samples of small size (Gasparini 2006).

The second method is indirect and applies two major constituents: biomass factors and prediction equations. The so-called Biomass Factors are used to convert the volume values (usually the stem volume or the merchantable volume) into biomass values, or to expand (Biomass Expansion Factor) the biomass of parts to the total tree biomass (Jenkins *et al*. 2003, Lethonen *et al.* 2004, Levy *et al*. 2004, Van Camp *et al.* 2004). Prediction equations, on the other hand, link easily measurable variables to the standing volume and the tree phytomass (Alemdag 1980, Crow and Laidly 1980, Satoo and Madgwick 1982, Snowdon 1985, Parresol 1999, Zianis and Mencuccini 2003, Fattorini *et al.* 2006 submitted).

Allometric equations for tree biomass estimation are particularly useful and easy to apply when the independent variables are DBH and H, two basic attributes used in each national forest inventory. They allow estimating forest biomass of large areas with little efforts (Gasparini 2006).

The above-mentioned instruments and methods are of basic importance to experts involved in the annual reporting of carbon stocks and carbon stock changes for the Kyoto Protocol. They also give basic information to politicians and decision makers useful to monitor sustainability of forest management and its effects on global carbon cycles (Gasparini 2006).

3.6 The Significance of the Forest Biomass

Forest biomass as a renewable resource is among the most promising substitutes for fossil fuels in clean and sustainable production of energy (McKendry 2002). Global climate change affects forest ecosystems by modifying the productivity (Charru *et al*. 2010), the composition and the structure of forests in many regions (Bolte *et al*. 2010, Dale *et al.* 2001). Adaptive actions are required to maintain these ecosystems, and data on forest biomass accumulation are essential to take up this challenge. According to Zianis (2008) the role of forest ecosystems in regional and global C cycle is largely based on the estimation of standing tree biomass. Moreover, as reported by Zianis (2008) information on forest biomass could be used for:

1. Describing the structure of ecosystems and indicating biomass resources
2. Studying the cycle of nutrients
3. Quantifying energy fixation
4. Modelling forest productivity

Biomass and C stocks are generally estimated using biomass functions (Cienciala *et al*. 2005, Ruiz-Peinado *et al*. 2012), applying the biomass expansion factors (BEFs) (Levy *et al*. 2004, Skovsgaard and Nord-Larsen 2012) or adopting non-destructive methods based on photo imagery (Ter-Mikaelian and Parker 2000). This method could be carried out by Airborne Light Detection And Ranging system (LIDAR), which is a time-tested technology that can be used to accurately assess aboveground forest biomass and bio-energy feedstocks (Popescu 2007). Laser scanning systems have been used to extract various kinds of parameters, such as tree height, crown size, DBH, canopy density, crown volume, and tree species (Donoghue *et al*. 2007, Means *et al.* 2000, Magnussen *et al*. 1999).

The development of species-specific biomass functions employs various approaches:

1. The construction of local models for specific sites (Albaugh *et al.* 2009, Bollandsås *et al*. 2009), or for specific age and size classes (Neumann and Jandl 2005, Pajtík *et al*. 2008, 2011)

2. The development of generalized models based on extensive data sets collected over a large area and representing a wide range of stand and site conditions (Pretzsch 2000, Joosten *et al*. 2004, Wirth *et al*. 2004, Wutzler *et al*. 2008) or based on pseudo-data generated by existing biomass functions (Jenkins *et al.* 2003, Zianis *et al.* 2003, Muukkonen 2007).

In most countries the forest biomass estimation on a national level is exclusively based on forest inventory data. Various biomass factors are routinely applied to volume data (Somogyi *et al.* 2006). Only countries with a high precision forest inventory may rely on the use of tree-level biomass equations. In such case generalized models enable reliable large-scale biomass prediction (Wirth *et al*. 2003). If site-specific biomass models are applied, it might introduce a serious bias into the estimate (Jenkins *et al.* 2003).

3.7 Forest Biomass at a Large Scale

According to the study of Zianis *et al*. (2005) a good candidate set of equations to accurately predict forest biomass at a large scale is supposed to comprise the following characteristics:

1. Consistency (referring to standard biomass compartments and additive tree compartments)

2. Robustness (a system operating correctly across a wide range of operational conditions with low sensitivity to sampling design and to working hypotheses)

3. Accuracy (the calibration of allometries that give little regard to the understanding of the biological processes involved in biomass development and accumulation in trees)

Assessment of tree biomass at a large spatial scale can:

1. Sample several trees of different sizes from a representative sample of species, regions and sites across the area of interest (Muukkonen 2007)

2. Find already existing equations for the geographically closest site (Ter-Mikaelian and Korzukhin 1997)

3. Use several available equations to estimate the range of biomass (Ter-Mikaelian and Korzukhin 1997)

4. Attempt as much as possible to collect sample data for reanalysis from all available sources of tree mensurational data (Wirth *et al*. 2004)

5. Produce a generalized equation based on those reported in literature (Schmitt and Grigal 1981, Pastor *et al*. 1984, Zianis and Mencuccini 2003)

If a large-scale replacement of spruce by beech is to occur, it will result in a significant alteration of biomass production, its allocation, turnover and ultimately C sequestration (Konôpka *et al*. 2013). Focusing on the differences in productivity and C cycling between spruce and beech forests is, therefore, of interest not only from an ecological but also from a timber production point of view. The productivity and biomass allocation in the initial stages of tree growth, when there are significant interspecific differences in these parameters, is of particular interest. An important observation – with significant bearing on the C cycle – is the ratio of C in compartments with fast turnover (foliage and fine roots) and C in slow turnover compartments (woody parts, i.e. coarse roots, stems and branches) (Konôpka *et al*. 2013).

Biomass studies are very costly, time-consuming and destructive methods, which are generally restricted to small areas and small amoounts of sampled trees (Ketterings *et al*. 2001, Fehrmann and Kleinn 2006). However, they prove to be the most appropriate methods that have been used by many researchers (Ketterings *et al.* 2001, Djomo *et al.* 2010, Henry *et al*. 2010) for biomass estimations and C accounting from forests. Thus, to predict biomass and C storage of forests, allometric models are powerful tools widely applied (Yen and Lee 2011, Alvarez *et al*. 2012). The most important variable used in these models is DBH (Zianis and Mencuccini 2004, Yen *et al.* 2010, Shackleton and Scholes 2011).

Furthermore, accurate forest C stocks are important to validate models (Vanclay and Skovsgaard 1997, Thurig and Schelhaas 2006) and for validating spatial extrapolations based on remote sensing (Lu 2006). The bases for the assessment of forest C stocks are biomass equations (Wutzler *et al.* 2007).

Compartments considered usually include the economically relevant aboveground woody compartments (timber, stem), less often branches and leaves, and rarely belowground compartments. However, monitoring and modelling changes of C stocks require the estimation of all of the biomass compartments (Wutzler *et al.* 2007).

The need for evaluating the biomass and consequently the C stored in forest ecosystems as an important resource from economical and political point of view, has led to a higher attention in monitoring and estimation issues. Consequently, many authors have developed new biomass equations and have studied their applicability (Gasparini 2006).

3.8 Estimates of Forest Biomass Carbon Storage

Accurate estimates of forest carbon storage and changes in storage capacity are critical for an assessment of the effects of forest management on the role of forests as carbon sinks (Dapao Yu *et al.* 2014).

From a global perspective forest ecosystems account for 80 % of carbon biomass of terrestrial vegetation and play an important role in carbon cycling in terrestrial ecosystems (Liu *et al.* 2000). Forest carbon biomass is significantly affected by timber harvesting, land use, climate change and other natural and human-induced disturbances (Canadell *et al.* 2007).

Carbon estimations are usually carried out using 'indirect' methods, which rely on forest inventories because direct estimation approaches are complicated and costly. Hence, biomass models, which relate different tree biomass components to dendrometrical variables, and biomass expansion factors, which relate biomass to stand volume are particularly useful tools in forest biomass estimation (Brown 2002, Somogyi *et al.* 2007). Biomass models require tree-level data, which are usually recorded in forest inventories, such as diameter and sometimes height (Teobaldelli *et al.* 2009). Tree-level data for available biomass models are often preferred (Ruiz-Peinado *et al.* 2012), since biomass expansion factors could depend on site (Wirth *et al*. 2004), age (Lehtonen *et al.* 2004) or stand timber volume (Fang *et al.* 2001).

Only biomass estimates of merchandable wood (stem and coarse branches with diameter over 7 cm) used to be conducted in forestry practice and subsequently a wide range of methods were developed for its inventory. However, biomass allocation in tree components influences the residence time of C fixation and therefore plays a critical role in the C cycle in forest ecosystems (Helmisaari *et al*. 2002, Konôpka *et al.* 2013).

Two basic tree component groups are considered important for biomass carbon storage:

1. Long-term fixed carbon storage (e.g. stem, branches and coarse roots) that contain C for decades or longer

2. Short-term carbon storage (e.g. foliage and fine roots) that store C for the maximum of months to a few years (Yuste *et al.* 2005)

Consequently, there is an urgent need to improve the existing methods for reliable assessments of non-stem components on both the tree and stand levels (Lehtonen 2005).

During the past couple of decades, the general focus has centered on tree biomass models with particular emphasis based on allometric equations or biomass expansion factors (West 2009).

3.9 Biomass Allocation R/S Ratio

The seedling and sapling biomass are important variables used to measure the net primary productivity, to estimate the C sequestration potential of forest stands and to evaluate the performance of forest regeneration after different silvicultural treatments (Schmidt *et al*. 2009, Øyen *et al*. 2011). Consequently, the estimation of seedling and sapling biomass and the analysis of the relationship between root to shoot (R/S) ratio and site characteristics might help forest managers to promote the growth of desired tree species (DeLucia *et al.* 1998).

Biomass allocation R/S ratio is mostly related to the light conditions but also to other ecological conditions (e.g. soil moisture, nutrient status, wind). According to the optimum allocation theory, trees modify their allocation pattern in order to capture the resource (i.e. light, water, nutrients) that most limits growth (Claveau *et al*. 2005). Responses to light availability differ according to the species: shade-tolerant species – e.g. European beech – allocate biomass preferentially to the foliage to optimize light capture (Wagner *et al.* 2010). Generally, these species have a higher R/S ratio than the shade-intolerant species (i.e. Scots pine or European larch) (Pastorella and Paletto 2014).

3.10 Biotic and Abiotic Factors Affecting Growth

Biotic and abiotic ecosystem factors are related to each other and if one factor is changed or removed the entire ecosystem can be affected. Abiotic factors refer to non-living physical and chemical elements in the ecosystem. Tree photosynthesis, and in a complex way tree growth, is affected by the sum of abiotic factors such as light intensity, temperature, precipitation, CO_2 supply, water supply and nutrient supply (Kramer and Kozlowski 1979). The environment is a key factor in growth and development of plants. Unfavourable environmental conditions pose negative impacts on plant physiology and phenotype (Osakabe *et al.* 2013). Plants are exposed to numerous abiotic stresses, which are the result of multifactor environmental conditions such as high and low temperatures, freezing, drought, UV, strong light, salinity, heavy metals and hypoxia. Better understanding of plant responses to abiotic stress is currently a leading topic in plant research as plants are sessile organisms and require tolerance towards these stresses. In fact, these stresses are expected to increase in the near future due to global climate change according to reports from the IPCC (Hirayama and Shinozaki 2010). Biotic factors basically are the sum of the living organisms within an ecosystem. Biotic factors such as pests and diseases also affect tree growth, especially when confronted with the physiological condition of trees (Koerber and Wickman 1970). Plants are in regular contact with various biotic agents, like bacterial, viral and fungal pathogens and even parasitic plants and insects or herbivores, which regularly attack and impose a negative impact (Bilgin *et al.* 2010).

4 MATERIAL AND METHODS

4.1 Study sites

4.1.1 Štítná nad Vláří study site

Štítná nad Vláří study site is located in the region of the Bílé Karpaty Mts. (the Czech Republic) and its coordinates are 49°02’ N and 17°58’ E. The altitude of Štítná nad Vláří study site is 560 m above the sea level. Alpine wrinkled tertiary rocks (slate, sandstone) represent the geology of the region and the soil type of the area is Cambisol. The region is moderately warm (MW 5) according to Quitt (1971). The characteristics of the MW 5 climatic region are: the summer is normally long, mild to moderately cold, and dry to slightly dry with a normal transition period and a moderate to long mild spring and autumn. The winter is normally long, slightly cool and dry to slightly dry with a normal duration of snow cover (Vondráková *et al.* 2013). More information about climatic conditions are shown in Table 1. The average annual temperature in 2009 – 2012 was 8.3 °C and annual precipitation was 770 mm. Mean air temperature is 16 – 17 °C in July and mean precipitation sum in the growing season is 350 – 450 mm. From the forestry point of view Štítná nad Vláří study site belongs to the 5th (beech and fir) forest vegetation zone according to Forest Management Institute (Marková *et al.* 2012). The total area of the experimental site was 14 000 m^2.

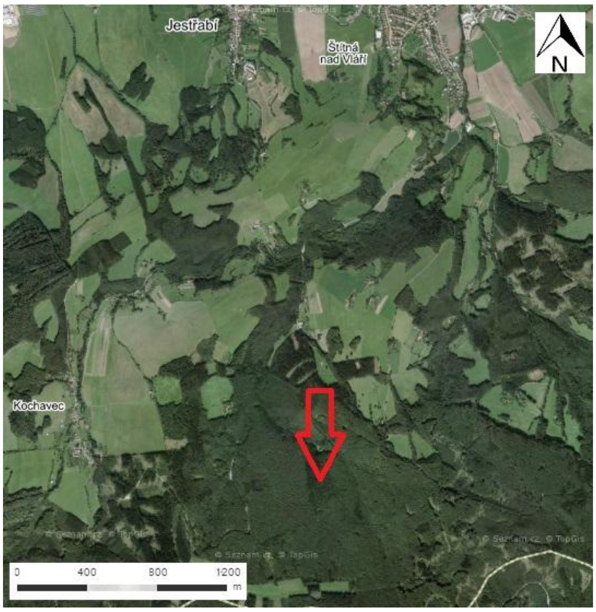

Figure 2 Site location of Štítná nad Vláří; Source: Seznam maps 2015

The study site is operated by CzechGlobe – Global Change Research Centre AS CR, v.v.i.. Štítná nad Vláří is included into significant infrastructures within ESFRI (European Strategy Forum on Research infrastructures), project ICOS (Integrated Carbon Observation System) (Marková *et al.* 2012).

Research in the beech stand of Štítná nad Vláří began in 2009. Štítná nad Vláří study site is located in the Natural Forest Area No. 38 (the Bílé Karpaty Mts. and the Vizovické vrchy Highlands) where european beech (*Fagus sylvatica L.*) is the dominant tree species. Undergrowth is typically demonstrated by the presence of bulbiferous coralwort (*Dentaria bulbifera)*, sweet woodruff (*Asperula odorata)*, hedge violet (*Viola reichenbachiana)*, wood sorrel (*Oxalis acetosella)* and false lily of the valley (*Maianthemum bifolium)* in spring. Grasses are represented by hairy sedge (*Carex pilosa)*, alpine grass (*Carex brizoides)*, false brome (*Brachypodium sylvaticum)* and ferns are represented by male fern (*Dryopteris filix-mas)*. The stand age was 109 years in 2012 and the stocking was 10 (filled canopy) (Marková *et al.* 2012).

Figure 3 View on Štítná nad Vláří study site 10th June, 2014

4.1.2 Study site Holíkov

Study site Holíkov is situated in the region of Drahanská vrchovina Highlands, which spans over 2.74 % of the total area of the Czech Republic. Forest coverage of the area is 55 % (Nikl 2000). Drahanská vrchovina Highlands is one of the best-preserved complexes of fir-beech forest vegetation zone of the region. Forests around Holíkov study site consist of production forests at a fairly large rate. Holíkov study site lies in a Southwest direction from the village of Valchov (Blansko district) and represents a significant regional biocentre in the Territorial system of Landscape ecological stability (Menšík 2006). The coordinates of Holíkov study site are 49°28' N and 16° 42' E. The altitude of the study site is 650 m above the sea level and the sloping of the area is about 5° (Menšík 2006). The soil type of the region is modal oligotrophic Cambisol with mull-moder litter form cover (Němeček *et al.* 2001). Two alternating climatic districts from slightly warm and dry up to slightly humid characterize climatic conditions of the region (Průša 2001). Quitt's climatic classification places the area into the MW 7 climatic region. MW 7 climatic region can be described as moderately warm and its characteristics are: summers are normally long, mild, and slightly dry with a short transition period, springs are mild and autumns are slightly warm. Winters are normally long, slightly warm, and dry to slightly dry with a short duration of snow cover (Vondráková *et al*. 2013). More information about climate conditions is shown in Table 1. The stand age was 120 years old in 2010, with an average height of 30.8 m, mean diameter at breast height 36.5 cm and stocking 10. The total area of the experimental site was 2 875 m^2.

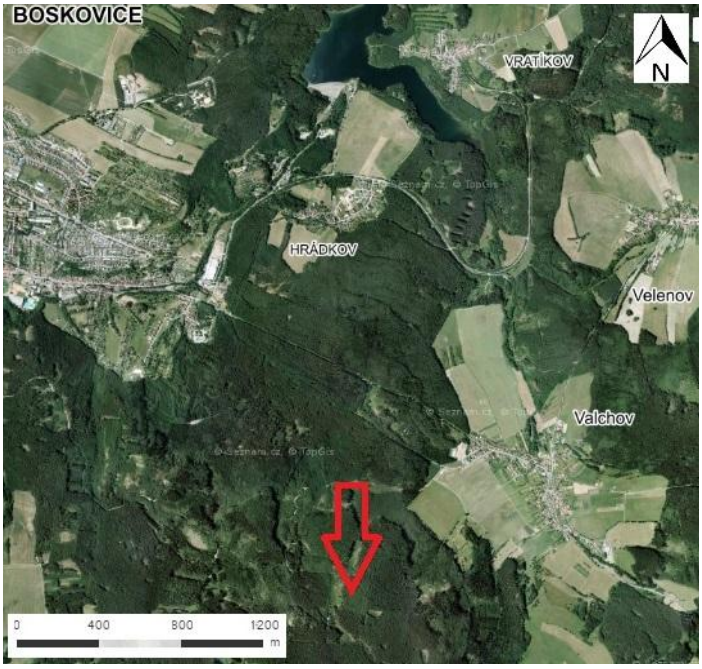

Figure 4 Site location of Holíkov; Source: Seznam maps 2015

Holíkov study site of beech stand is located in Natural Forest Area No. 30 (Drahanská vrchovina Highlands) (UHUL 2016) where European beech (*Fagus sylvatica L.*) dominates over scattered populations of spruce (*Picea abies (L.)* Karst.) and larch (*Larix decidua* Mill.) (Menšík 2006). It is a geomorphologicaly significant territory. Several plant species are found in the ecosystem. Undergrowth is formed by touch-me-not balsam (*Impatiens noli-tangere)*, bulbiferous coralwort (*Dentaria bulbifera)*, sweet woodruff (*Galium odoratum)*, false lily of the valley *(Maianthemum bifolium)*, wood sorrel (*Oxalis acetosella)* and raspberry bush *(Rubus idaeus)*. Grasses are represented by fescue grass (*Festuca sylvatica)*, reed grass (*Calamagrotis epigeios)*, wood bluegrass (*Poa nemoralis)* and *hairy wood-rush (Luzula pilosa)*. Ferns are represented by lady fern (*Athyrium filix-femina)*, male fern (*Dryopteris filix-mas)* and common oak fern (*Gymnocarpium dryopteris)* (Menšík 2006).

Figure 5 Aerial view on Holíkov study site; Source: Menšík (2013)

4.2 Dendrometric measurements

Stand measurements on the experimental areas were carried out in order to obtain dendrometric characteristics, such as diameter and height of the trees. Measured data served as the base for further biomass compartments calculation.

Two forest stands were chosen for the purpose of the study. Both of them are beech stands situated in the Czech Republic. The first study site was located in the region of Bílé Karpaty Mts., Štítná nad Vláří. The second study site was located in the region of Drahanská vrchovina Highlands, around the peak of Holíkov. Dendrometric characteristics of the trees were collected every year in the period of 2010 to 2015. This continuous inventory on experimental areas allowed for collecting accurate year-to-year information about monitored forest stands. Tree heights were measured by the Vertex altimeter (Haglöf Sweden AB) (Figure 2) and the DBH was measured by standard procedures at breast height (DBH at 1.3 m height) by an electronic caliper (Haglöf Sweden AB) with millimetric accuracy (Figure 3).

Figure 6 Haglöf Vertex Laser (Pacforest Supply Company) **Figure 7 Haglöf Computer Caliper (Forestry Suppliers)**

4.3 Sampling of tree compartments

Both study sites have a character of long-term research areas. For that particular reason, it was not possible to carry out destructive analysis and subsequently create local allometric equations. Annual inventories of trees were carried out on both study sites and the most suitable equations were selected for biomass estimation. Calculations of individual tree compartments were performed based on information published in several literary sources. The validity of previously published allometric equations was assessed across the entire range of mean diameters and heights of trees on both study sites with the geographic area, altitude, ages of stands, annual mean temperature, annual mean precipitation and abiotic conditions taken into account.

Figure 8 Štítná nad Vláří study site 10th June, 2014

Figure 9 Holíkov study site 18th July, 2014

4.4 Data processing

Data notes of the 2010 – 2015 experimental period collected in both study sites were first transferred into an electronic form. Datasets comprising of diameter and height of each tree were processed in Microsoft Excel. Consequently, histograms and figures with model values were created for all major biomass compartments, namely: aboveground, branches, foliage, total stem, stem wood, biomass of stem bark, roots, crown, timber, brushwood and stem volume. These figures were obtained form the utilization of published Central European allometric equations. The list of authors and used equations are shown in Table 2, respectively in Table 3. Norway spruce and

European larch were found besides beech in study site Holíkov. Allometric equations for coniferous trees are presented in Table 4.

Figure 10 depicts different schemes of woody aboveground biomass compartmentalization. Scheme A distinguishes between stem and branch wood with the assumption that the main stem can be clearly identified all the way to the top. Scheme B, which is less subjective and most commonly applied in forest sciences, separates between timber and brushwood based on a fixed diameter threshold (usually 7 cm) Wutzler *et al*. 2008.

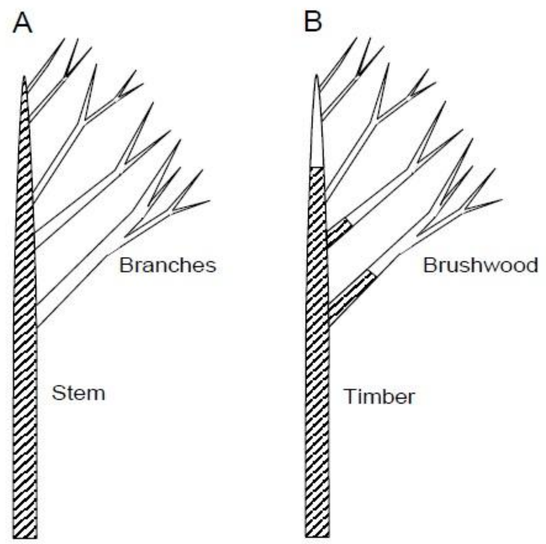

Figure 10 Schemes of different definitions of aboveground biomass compartments; Source: Wutzler *et al*. 2008

4.5 Tree biomass and stem volume estimation

Europian authors and their equations (listed in Table 2, respectively in Table 3) were used for predicting biomass of European beech (*Fagus sylvatica L.*). Listed equations were available for estimations of aboveground biomass, branches, foliage, stem, roots, crown biomass, timber, brushwood. Equations according to: Bartelink 1997 (Netherlands), Calamini and Gregori 2001 (Italy), Cienciala *et al*. 2005 (Czech Republic), Santa Regina and Tarazona 2001 (Spain), Vejpustková *et al*. 2013 (Czech Republic), Wutzler *et al*. 2008 (Central Europe), Duvigneaud *et al*. 1977 (Belgium), Hochbichler 2002 (Austria), Nihlgård 1972 (Sweden), Pretzsch 2002 (Germany), Le Goff and Ottorini 2000 (France), Drexhage and Colin 2001 (France and Germany), Broadmeadow and Matthews 2004 (United Kingdom) were used for these compartments. Stem volume equations were used according to: Broadmeadow and Matthews 2004, Dagnelie *et al*. 1999, De Vries 1961, Dik 1984, Giurgiu 1974, Pellinen 1986, Pollanschütz 1974, Schieler 1988. The total of 75 allometric models (including Norway spruce and European larch) were utilized based on literature review, 13 of which were for aboveground biomass, 15 for branch biomass, 9 for total foliage biomass, 14 for total stem biomass, 2 for stem wood biomass, 2 for biomass of stem bark, 7 for biomass of roots, 3 for crown biomass, 1 for timber biomass, 1 for brushwood biomass and 8 for stem volume.

Table 1 Climatic chart according to Vondráková (2013) with classes applicable to the study areas where frosty day stands for a day in which temperature reaches or falls bellow 0 °C, icy cold day is a day in which temperature stays bellow 0 °C all day and summer day stands for a day in which temperature reaches or exceeds 25 °C.

Table 1 Climatic chart according to Vondráková et al. (2013)

Climatic region	MW 5	MW 7
Sum of summer days	30 – 40	30 – 40
Sum of days with average temperature of at least 10 °C	140 – 160	140 – 160
Sum of frosty days	130 – 140	110 – 130
Sum of ice cold days	40 – 50	40 – 50
Average temperature in January (°C)	-4 to -5	-2 to -3
Average temperature in July (°C)	16 – 17	16 – 17
Average temperature in April (°C)	6 – 7	6 – 7
Average temperature in August (°C)	6 – 7	7 – 8
Average amount of days with at least 1 mm of precipitation (mm)	100 – 120	100 – 120
Total precipitation during the vegetation period (mm)	350 – 450	400 – 450
Total precipitation during the winter period (mm)	250 – 300	250 – 300
Sum of days with snow cover	60 – 100	60 – 80
Sum of overcast days	120 – 150	120 – 150
Sum of days with clear skies	50 – 60	40 – 50

Table 2 The list of authors used to determine tree biomass of European beech (*Fagus sylvatica L.*)

Authors	DBH (cm)	Height (m)	Age (years)	Stand density (trees/ha)	Altitude (height above sea level (m))	Annual mean precipitation (mm)	Annual mean temperature (°C)	Soil	Country
Bartelink 1997	3,13 – 27,87	3,5 – 22,5	8 – 59	-	-	-	-	Acid brown podsolic soil	Netherlands
Calamini and Gregori 2001	6,2 – 34	8,5 – 24,9	27 – 115	325 – 10416	1150 – 1300	2500	7,1 °C	Inceptisols and Spodosols	Italy
Cienciala et al. 2005	5,7 – 62,1	9,2 – 33,9	40 – 114	550	565	-	-	-	Czech Republic
Drexhage and Colin 2001	3 – 47	-	24 – 115	156	-	-	-	Rendzina and Gleyic Luvisol	Germany, France
Duvigneaud et al. 1972	mean 52,2	6 – 35	144	-	-	-	-	-	Belgium
Hochbichler et al. 2006	6,6 – 52	9 – 40,1	40–115	-	-	-	-	-	Austria
Le Goff and Ottorini 2001	mean 13	mean 7,6	30–115	3500	300	820	9,2 °C	A type of humus is mull	France
Nihlgård 1972	12 - 64	11 – 29	45 – 130	240	110	800	6 – 7 °C	Acid brown forest soil	Sweden
Pretzsch 2000	5,7 – 71,8	-	33 – 219	232 – 12899	-	-	-	-	Germany
Santa Regina and Tarazona 2001	2,5 – 92,5	mean 20 – 22	-	523	1100	890	12,4 °C	Humic Acrisol	Spain
Vejpustková et al. 2015	5,7 – 62,1	7,5 – 33,9	17 – 150	-	350 – 890	-	-	-	Czech Republic
Wutzler et al. 2008	1 – 79	2 – 40	8 – 173	-	23 – 1560	-	-	-	Central Europe

Table 3 The list of known equations of compartments of biomass for European Beech (*Fagus sylvatica L.*)

Equation number	Independent variables	Compartments	Equation	Author	R^2
1	D	Aboveground biomass	y=0,0306*D^2,347*H^0,590	Bartelink 1997	0,991
2	D	Aboveground biomass	y=0,0798*D^2,601	Bartelink 1997	0,988
3	D	Aboveground biomass	y=0,453*D^2,139	Cienciala et al. 2005	0,974
4	D	Aboveground biomass	log(y)=2,85102+2,0666*log(D)	Duvigneaud et al. 1977	0,995
5	DH	Aboveground biomass	ln(y)=-2,872+2,095*ln(D)+0,678*ln(H)	Hochbichler 2002	0,997
6	DH	Aboveground biomass	log(y)=-1,7194+log(H*(D^2))*1,0414	Nihlgård 1972	-
7	DH	Aboveground biomass	y=0,1143*D^2,503	Pretzsch 2000	-
8	D	Aboveground biomass	y=0,1315*D^2,4321	Santa Regina and Tarazona 2001	0,98
9	DH	Aboveground biomass	y=0,01118*(D^2*H)^1,08250	Vejpustková et al. 2013 DH2N	0,978
10	DH	Aboveground biomass	y=0,00962*D^2,15540*H^1,13788	Vejpustková et al. 2013 DH3	0,978
11	D	Aboveground biomass	y=0,22062*D^2,33865	Vejpustková et al. 2013 D2	0,961
12	DHA	Aboveground biomass	y=0,06340*(D^2*H)^1,08859*A^-0,27628	Vejpustková et al. 2013 DH2N	0,983
13	DH	Aboveground biomass	y=0,0523*D^2,12*H^0,655	Wutzler et al. 2008	-
14	DH	Branches	y=0,0114*D^3,682*H^-1,031	Bartelink 1997	0,92
15	D	Branches	y=0,0020*D^3,265	Bartelink 1997	0,916
16	D	Branches	y=0,021*D^2,471	Cienciala et al. 2005	0,806
17	D	Branches	log(y)=0,41439+3,18522*log(D)	Duvigneaud et al. 1977	0,981
18	D	Branches	ln(y)=-6,2524+3,328*ln(D)	Le Goff and Ottorini 2000	0,93
19	DH	Branches	log(y)=-3,2114+log(H*(D^2))*1,2481	Nihlgard 1972	-
20	D	Branches	y=0,0317*D^2,3931	Santa Regina and Tarazona 2001	0,89
21	D	Branches	y=0,03089*D^2,42536	Vejpustková et al. 2013 D2	0,836
22	DH	Branches	y=0,00116*(D^2*H)^1,13944	Vejpustková et al. 2013 DH2	0,836
23	DH	Branches	y=0,00611*D^2,35509*H^0,56104	Vejpustková et al. 2013 DH3	0,84
24	DH	Branches	y=0,123*D^3,09*H^-1,17	Wutzler et al. 2008	-
25	DH	Total foliage biomass	y=0,0167*D^2,951*H^-1,101	Bartelink 1997	0,923
26	D	Total foliage biomass	y=0,375+0,0024*D^2,517	Bartelink 1997	0,906
27	D	Total foliage biomass	y=0,00295*D^2,43854	Calamini and Gregori 2001	0,956
28	DH	Total foliage biomass	y=0,02408*D^3,04567*H^-1,51571	Calamini and Gregori 2001	0,961
29	D	Total foliage biomass	ln(y)=-4,8599+2,1935*ln(D)	Le Goff and Ottorini 2000	0,95
30	D	Total foliage biomass	y=0,0145*D^1,9531	Santa Regina and Tarazona 2001	0,89
31	DH	Total foliage biomass	y=0,0377*D^2,43*H^-0,913	Wutzler et al. 2008	-

Table 3 continued

Equation number	Independent variables	Compartments	Equation	Author	R^2
32	DH	Total stem biomass	y=0,0109*D^1,951*H^1,262	Bartelink 1997	0,996
33	D	Total stem biomass	y=0,0762*D^2,523	Bartelink 1997	0,979
34	DH	Total stem biomass	y=0,00519*D^1,49634*H^2,10419	Calamini and Gregori 2001	0,988
35	DH	Total stem biomass	y=0,03638*D^2,15436*H^0,6587	Calamini and Gregori 2001	0,995
36	DH	Total stem biomass	y=0,00269*D^2,02481*H^1,65219	Calamini and Gregori 2001	0,99
37	DH	Total stem biomass	y=0,00519*D^1,87511*H^1,27233	Calamini and Gregori 2001	0,996
38	D	Total stem biomass	y=0,494*D^2,07	Cienciala et al. 2005	0,954
39	D	Total stem biomass	y=0,0894*D^2,4679	Santa Regina and Tarazona 2001	0,99
40	DH	Total stem biomass	y=0,00560*D^2,10425*H^1,29184	Vejpustková et al. 2013 DH3	0,976
41	DH	Total stem biomass	y=0,01009*(D^2*H)^1,07222	Vejpustková et al. 2013 DH2	0,975
42	D	Total stem biomass	y=0,18819*D^2,32336	Vejpustková et al. 2013 D2	0,952
43	DH	Total stem biomass	y=0,0293*(D^2*H)^0,974	Wutzler et al. 2008	-
44	D	Stem wood biomass	ln(y)=-2,0445+2,3912*ln(D)	Le Goff and Ottorini 2000	0,99
45	DH	Stem wood biomass	log(y)=-1,6219+log(H*(D^2))*0,9813	Nihlgård 1972	-
46	D	Biomass of stem bark	ln(y)=-3,0741+2,0543*ln(D)	Le Goff and Ottorini 2000	0,99
47	DH	Biomass of stem bark	log(y)=-2,4279+log(H*(D^2))*0,8636	Nihlgård 1972	-
48	D	Biomass of roots	log(y)=-1,66+2,54*log(D)	Drexhage and Colin 2001	0,99
49	D	Biomass of roots	log(y)=-2+2,7*log(D)	Drexhage and Colin 2002	0,98
50	D	Biomass of roots	y=-3,8219+2,5382*ln(D)	Le Goff and Ottorini 2001	0,99
51	DH	Biomass of roots	log(y)=-2,8434+log(H*(D^2))*1,104	Nihlgård 1972	-
52	D	Biomass of roots	y=0,0282*D^2,39	Wutzler et al. 2008	-
53	DH	Crown biomass	y=0,0183*D^3,614*H^-1,078	Bartelink 1997	0,929
54	D	Crown biomass	y=0,0031*D^3,161	Bartelink 1997	0,924
55	D	Crown biomass	y=0,00686+1,92*0,000010*D^2,4658	Broadmeadow and Matthews 2004	-
56	DH	Timber	y=0,00775*D^2,11*H^1,21	Wutzler et al. 2008	-
57	DH	Brushwood	y=0,466*D^1,85*H^-0,349	Wutzler et al. 2008	-

Table 3 continued

58	DH	Volume	y=-0,014306+0,0000748*D^2*H^0,75	Broadmeadow and Matthews 2004	-
59	DH	Volume	y=-0,015572+0,00290013*D+(-0,0000070476)*D^2+0,000002393*D^3+(-0,0013528)*H+0,000039837*D^2*H	Dagnelie et al. 1999	-
60	DH	Volume	y=0,049*D^1,78189*H^1,08345	De Vries 1961	-
61	DH	Volume	y=D^1,55448*H^1,55880*exp(-3,57875)	Dik 1984	0,999
62	DH	Volume	y=0,0000757*10^(1,3791*log(D)+0,2127*log(D)^2+1,1992*log(H)+(-0,0584)*log(H)^2)	Giurgiu 1974	-
63	DH	Volume	y=0,016641+0,00072179*D*H^2+0,00000252*D^3	Pellinen 1986	0,973
64	DH	Volume	y=(π/4)*(0,989253*D^2*H+(-0,0371508)*D^2*H*ln(D)^2+(-31,0674)*D^2+(-0,386321)*D*H+0,219462*H+49,6136*D+(-22,372)	Pollanschütz 1974	-
65	DH	Volume	y=(π/4)*(0,517300*D^2*H+(-13,62144)*D^2+9,9888*D)	Schieler 1988	0,748

Table 4 The list of known equations of compartments of biomass for Norway spruce (*Picea abies*) 66–70 and European larch (*Larix decidua*) 71–75

Equation number	Independent variables	Compartments	Equation	Author	R^2
66	DHA	Needles	ln(y)=-0,58133+3,63845*ln(D)+(-0,21336)*(ln(D))^2+(-2,77755)*ln(H)+0,46540*(ln(H))^2+(-0,42940)*ln(A)	Wirth et al. 2003	0,9029
67	DHA	Branches	ln(y)=(-0,64565)+2,85424*ln(D)+(-2,98493)*ln(H)+0,41798*(ln(H))^2	Wirth et al. 2003	0,9179
68	DHA	Dead branches	ln(y)=(-3,090620)+2,04823*ln(D)+(-1,286761)*ln(H)+0,62836*ln(A)	Wirth et al. 2003	0,8136
69	DHA	Stem	ln(y)=(-2,83958)+2,55203*ln(D)+(-0,14991)*(ln(D))^2+(-0,19172)*ln(H)+0,25739*(ln(H))^2+(-0,08278)*ln(A)	Wirth et al. 2003	0,9947
70	DHA	Roots	ln(y)=(-8,35049)+4,56828*ln(D)+(-0,33006*(ln(D))^2+0,28074*ln(A)	Wirth et al. 2003	0,9668
71	DH	Needles	y=0,009514*D*H	Minerbi and Cescatti 2015	0,86
72	D	Branches	y=0,068074*D^2	Minerbi and Cescatti 2015	0,87
73	DH	Dead branches	y=0,030292*D^2+(-0,081967)*D*H+0,064423*H^2	Minerbi and Cescatti 2015	0,76
74	DH	Stem	y=0,011560*D^2*H+0,169109*D*H	Minerbi and Cescatti 2015	0,98
75	DH	Roots	y=0,000403*D^2*H^2	Minerbi and Cescatti 2015	0,99

5 RESULTS

5.1 Dendrometric characteristics of the stand on the study sites

5.1.2 Štítná nad Vláří study site

In the Štítná nad Vláří study site, on the whole, 399 trees (*Fagus sylvatica* L.) were measured in 2010. The stand density was 285 trees/ha. Four trees were removed due to sanitation during the measurement. 395 trees remained after this intervention in 2015.

Diameters at the breast height (DBH) in 2010 at Štítná nad Vláří study site were 6.8 – 64.3 cm. The average DBH of all tress on the site was 35.1 cm. DBH observed five years later was 7.1 – 65.6 cm and the average DBH of all trees was 36.9 cm. The distribution of DBH classes is shown in Figure 9. The most frequent diameter class in 2010 was the 35 – 40 cm range represented by 74 trees. The number of 76 trees was measured in 2015 at the same range. On the other hand, the least trees were found in the 60 – 65 cm range including only 3 trees in 2010 and the 65 – 70 cm range in 2015 with only one tree. Figure 11 shows that the 30 – 35 cm diameter class consisted of 55 trees in 2010 but only 32 trees remained five years later due to the movement into the next diameter classes, especially into the classes of 35 – 40 cm and 40 – 45 cm.

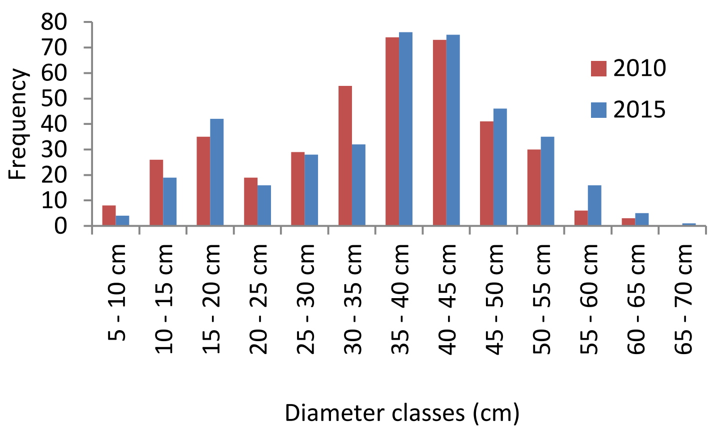

Figure 31 Tree frequency per diameter classes in the Štítná nad Vláří study site in 2010 and 2015

Figure 13 shows the height and DBH relationship for both study site where the continuous line belongs to the Štítná nad Vláří study site. Tree height of only 6.8 m and several trees with DBH smaller than 10 cm were observed on the Štítná nad Vláří study site. The heights ranged between 4.1 – 37.5 m in 2010 and between 4.6 – 37.9 m in 2015.

5.1.3 Holíkov study site

Data were collected in the period from 2010 to 2015 in the Holíkov study site. There were 85 trees in total of which 74 were European beech (*Fagus sylvatica* L.), 6 Norway spruces (*Picea abies* (L.) Karst.) and 5 European larches (*Larix decidua* Mill.). The stand density was 295 trees/ha.

In 2010 diameters at the breast height (DBH) ranged between 27.3 – 51.2 cm on the Holíkov study site. DBH averaged 37 cm. The DBH, observed five years later, was 28.3 – 52.5 cm with an average of 38.4 cm. DBH classes distribution is shown in Figure 12. The most frequent diameter class in 2010 was the 35 – 40 cm range with the number of 28 trees. The same range in 2015 contained the number of 29 trees. On the other hand the lowest number of trees (one) was measured in the 60 – 65 cm diameter class range in 2010. In 2015 it was the 50 – 55 cm range with two trees., 6 Norway spruces (*Picea abies* (L.) Karst.) and 5 European larches (*Larix decidua* Mill.) were measured on the plot as already mentioned above. Spruce trees had their DBH in 34.4 – 58 cm range in 2010 and in the 35 – 59.9 cm range in 2015. The DBH of Larch trees ranged from 41.5 to 48.4 cm in 2010 and from 41.2 to 49.5 cm in 2015.

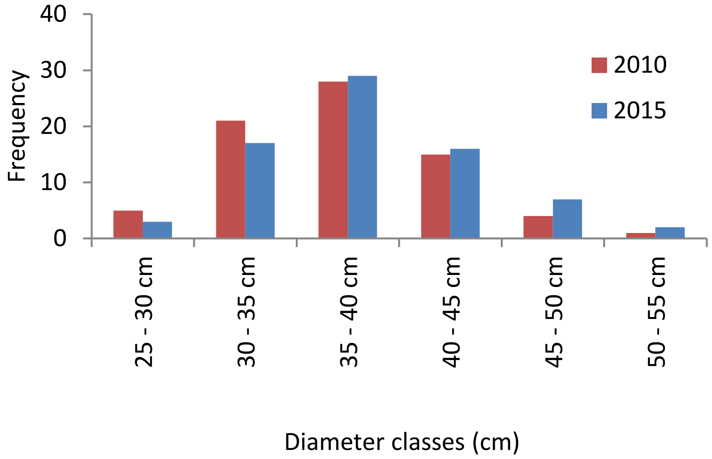

Figure 14 Trees frequency per diameter classes in the Holíkov study site in 2010 and 2015

Figure 13 shows the relationship between height and DBH of the Štítná nad Vláří and Holíkov study sites. The dashed line is for the Holíkov study site. The tree heights ranged from 25.9 to 35 m in the Holíkov study site in 2010 and from 26.1 m to 35.3 m in 2015. The heights averaged approximately 2 metres less in study site Holíkov than in Štítná nad Vláří study site but none of the trees was lower than 25 m.

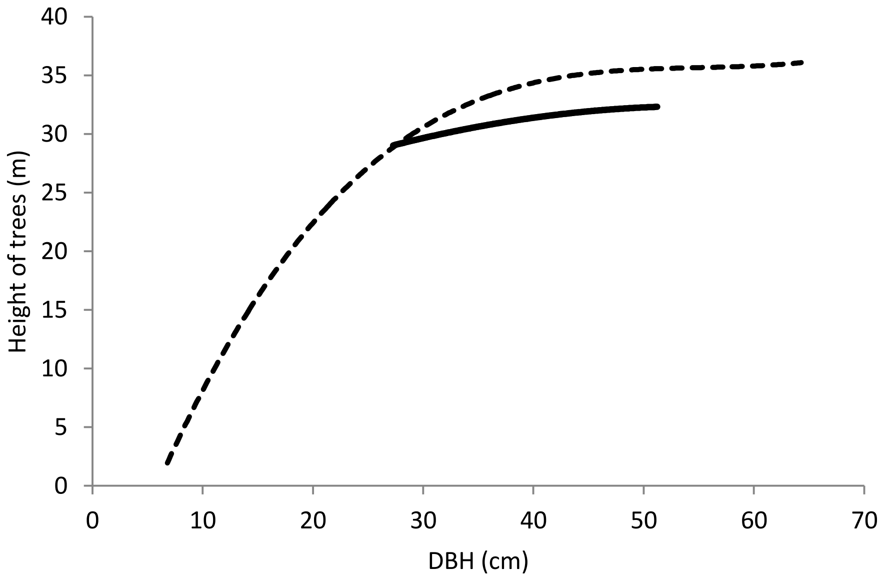

Figure 13 Dependence height on DBH of tree in Štítná nad Vláří study site (dashed line) and Holíkov study site (continuous line)

5.2 Model´s values of allometric equations

5.2.1 Aboveground biomass

Aboveground biomass of individual compartments based on model values was calculated for 13 allometric equations. Obtained values are displayed in Figure 14. The curve expressing the lowest performing model out of all equations was the Santa Regina and Tarazona 2001; eq. 8 (red continuous line) with a value of 718 kg in a valid DBH interval of 4 – 34.5 cm. The highest model value for the largest trees (4 939 kg) was reached by Vejpustková *et al.* 2013 allometric equation; eq. 12 and their model DH2A in which is an incorporation of several variables: DBH, tree height and altitude. Wutzler *et al.* 2008; eq. 13 (black line) estimated a value of 3 830 kg for the same tree.

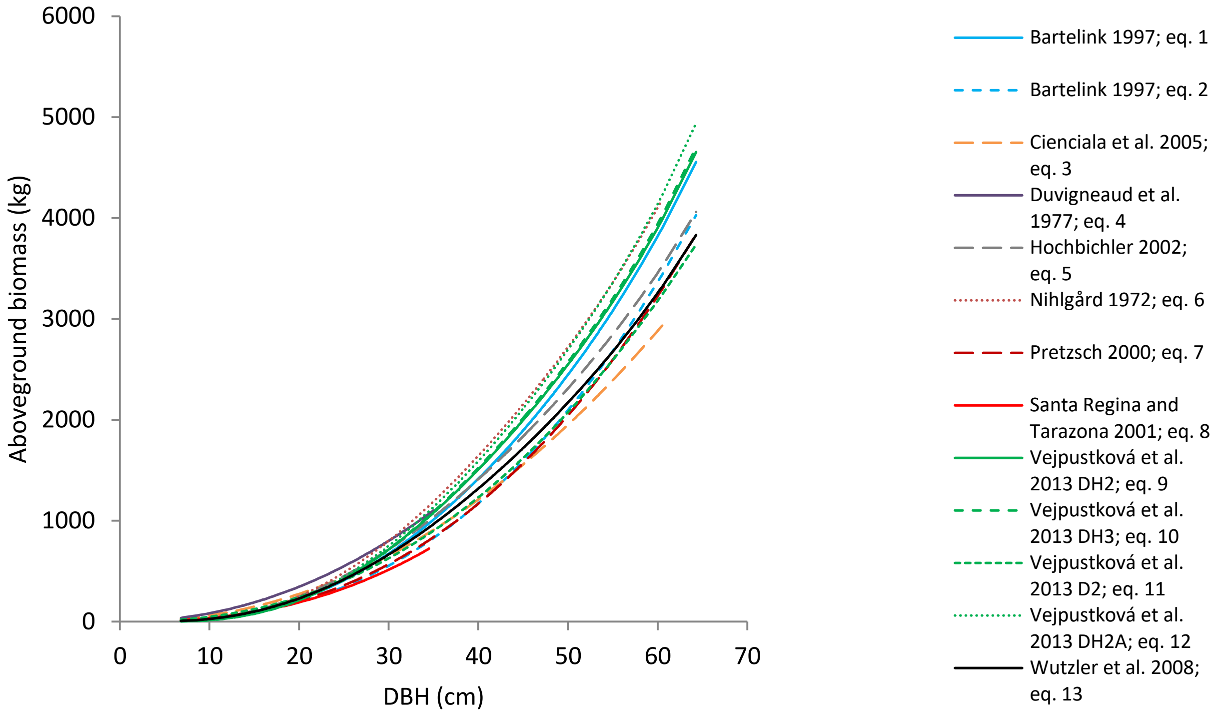

Figure 14 Estimation of beech aboveground biomass according to equations (eq. 1 – 13) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.2 Branch biomass

Branch biomass (compartment defined in Figure 10) was calculated with the use of 11 allometric equations. Resulting model values of these equations are very different (Figure 15). The lowest model values of branch biomass were estimated by Cienciala *et al*. 2005; eq. 16 and resulting values were only 26 % compared to Le Goff and Ottorini 2000; eq. 18. The curve by Cienciala *et al*. 2005 expressing the lowest model values determined branch biomass of 524 kg in the valid interval of DBH 5.7 – 62.1 cm. Only one equation (Le Goff and Ottorini 2000) exceeded 2000 kg, its value was 2006 kg for the largest trees. Wutzler *et al.* 2008 (black line); eq. 24 estimated a value of 684 kg for the biggest trees.

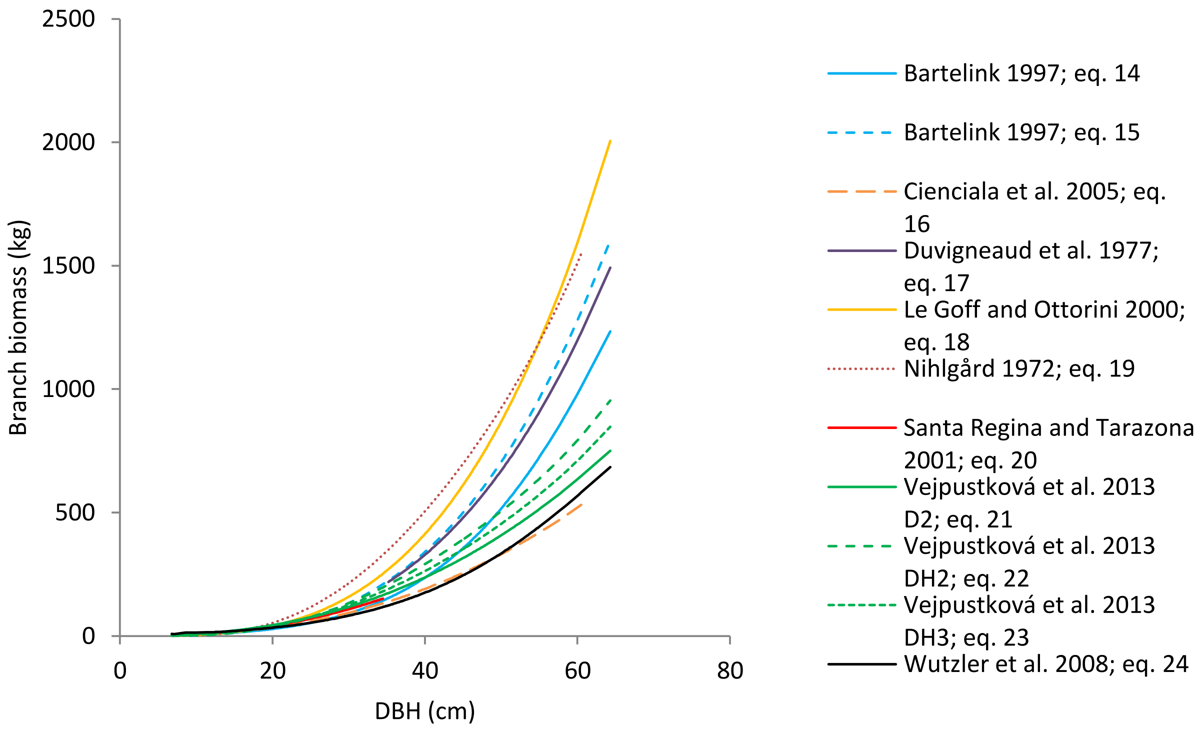

Figure 15 Estimation of beech branch biomass according to equations (eq. 14 – 24) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.3 Foliage biomass

7 allometric equations were used for the calculation of the foliage biomass compartment. Obtained values are shown in Figure 16. The resulting model values of these equations are very different from each other. The curve expressing the lowest model value of foliage biomass is by Calamini and Gregori 2001; eq. 28 with a value of 31.8 kg for the largest tree. The highest model value was reached by an allometric equation by Bartelink 1997; eq. 26 with a value of 85.8 kg. The difference between these two equations for the biggest trees was 54 kg. The black line represents model values according to Wutzler *et al.* 2008; eq. 31 with a value 34 kg for the largest trees. In this model does not feature the Vejpustková *et al.* 2013 equation because their research was conducted in the winter season.

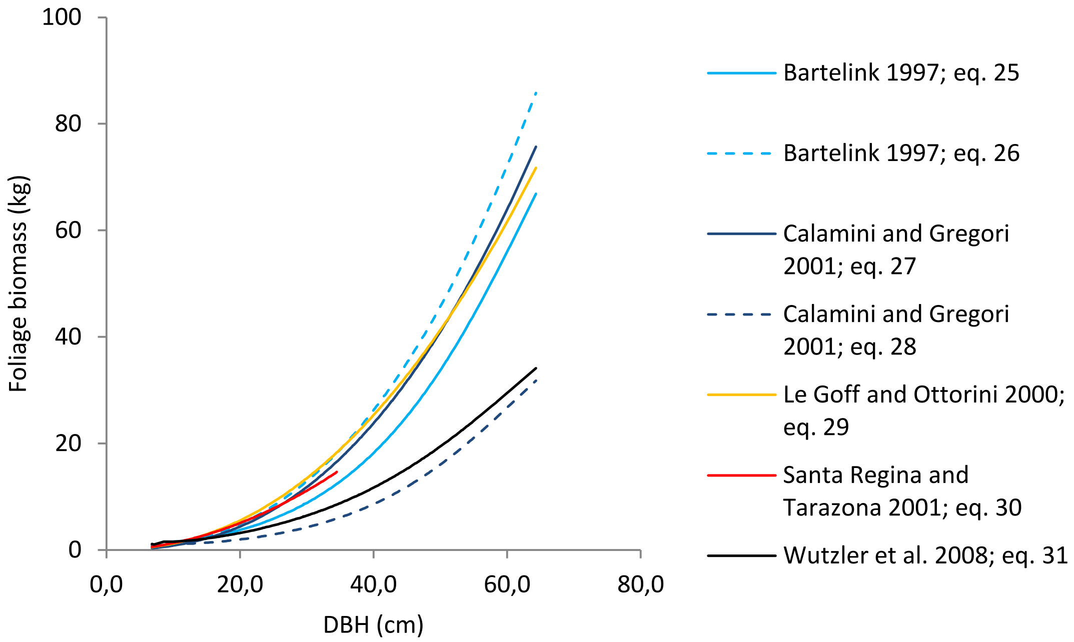

Figure 16 Estimation of beech foliage biomass according to equations (eq. 25 – 31) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.4 Total stem biomass

Total stem biomass compartment comprises of stem wood biomass and stem bark biomass. 12 allometric equations of total stem biomass were used for the calculations. The resulting model values of these equations are very different and their performance differs greatly from each other (Figure 17). The curve expressing the lowest model value of stem biomass was deviced for by Calamini and Gregori 2001; eq. 37 (dark blue dotted line). The highest model values were also derived from an allometric equation by Calamini and Gregori 2001; eq. 34 (dark blue continuous line), The highes measured value for the biggest trees on the Štítná nad Vláří locality was 5 421 kg. In comparison, the same trees evaluated according to Wutzler *et al.* 2008; eq. 43 (black line) was 3 333 kg. The Calamini and Gregori 2001 model; eq. 37 has reached underperfomed by 20% compared to the other model by Calamini and Gregori 2001; eq. 34. The allometric equation by Cienciala *et al.* 2005; eq. 38 and Santa Regina and Tarazona 2001; eq. 39 displayed shorter curves than other equations due to limits presented in their research articles. Valid DBH intervals of these equations were: Cienciala *et al.* 2005 5.7 – 62.1 cm and Santa Regina and Tarazona 2001 4 – 34.5 cm.

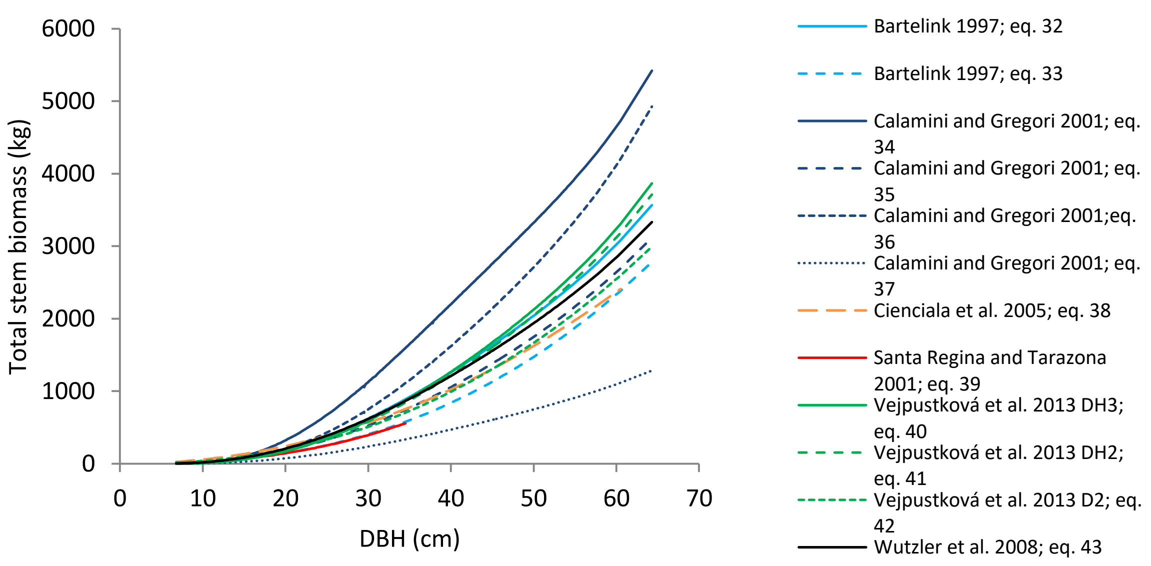

Figure 17 Estimation of beech total stem biomass according to equations (eq. 32 – 43) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.5 Stem wood biomass

2 allometric equations were used to estimate the compartment of stem wood biomass. Obtained values are shown in Figure 18. The resulting model values of these two equations are almost identical. The curve expressing values of stem wood biomass according to Le Goff and Ottorini 2000; eq. 44 came to a value of 2 728 kg for the biggest trees. The equation by Nihlgård 1972; eq. 45 had a value of 2 575 kg in a valid DBH interval of 12 – 64 cm.

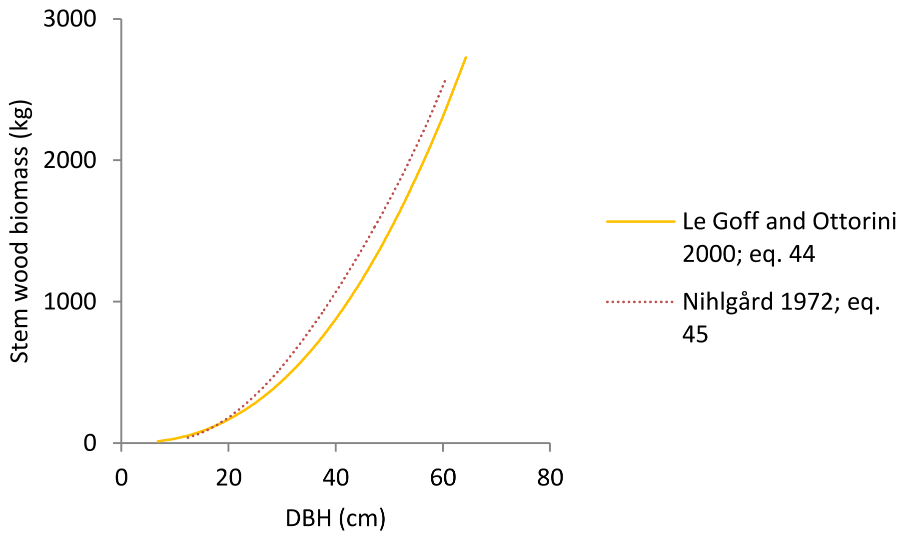

Figure 18 Estimation of beech stem wood biomass according to equations (eq. 44 – 45) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.6 Biomass of stem bark

2 allometric equations were used to determine the biomass of the stem bark compartment. The obtained values are displayed in Figure 19. The resulting model values, thus the curves of these equations are very different from each other. The equation for the biomass of stem bark calculation by Nihlgård 1972; eq. 47 generated the value of 98 kg in the valid 12 – 64 cm DBH range and that compared to Le Goff and Ottorini 2000; eq. 46 with estimated 240 kg was a lot lower.

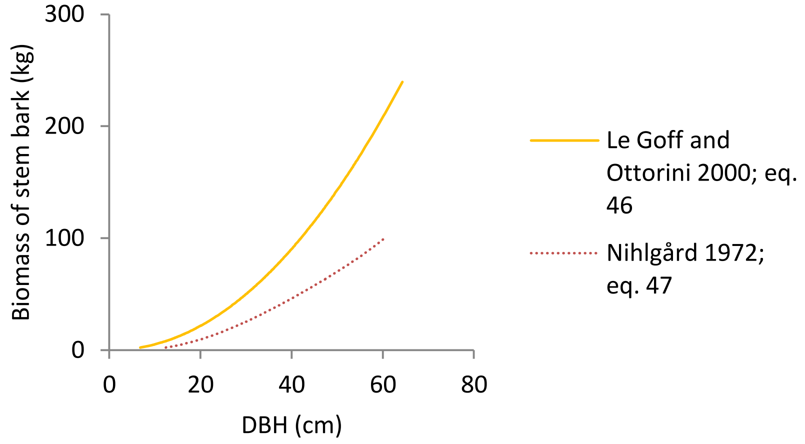

Figure 19 Estimation of beech stem bark biomass according to equations (eq. 46 – 47) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.7 Root biomass

5 allometric equations were used for the compartment of root biomass calculation (Figure 20): Drexhage and Colin 2001, Le Goff and Ottorini 2001, Nihlgård 1972 and Wutzler *et al*. 2008. The resulting model values of these equations are, again, very different from each other. The curve expressing the highest model values was the one according to Le Goff and Ottorini 2001; eq. 50 with a highes measured value of 850 kg. The less pronounced the equation according to Drexhage and Colin 2001; eq. 48 (light green continuous line) was only valid for the 3 – 20 cm DBH interval. The equation by Wutzler *et al.* 2008; eq. 52 (black line) showed a value of 591 kg for the largest trees.

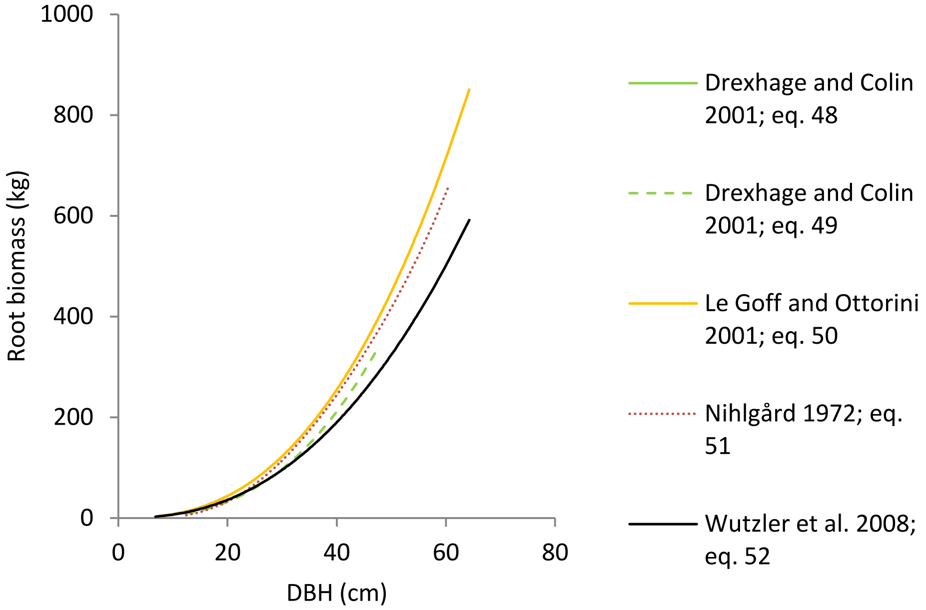

Figure 20 Estimation of beech root biomass according to equations (eq. 48 – 52) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.8 Crown biomass

This biomass compartment is composed of branch biomass and total foliage biomass. 3 allometric equations were adopted for the compartment of crown biomass estimation. Obtained model values are displayed in Figure 21. Equations by Bartelink 1997 and Broadmeadow and Matthews 2004 were used for this biomass fraction. These equations performed differently. The curve that expressed the lowest model value of crown biomass (559 kg) for the largest trees was the equation according to Broadmeadow and Matthews 2004; eq. 55. The highest model value was reached by the Bartelink 1997allometric equation; eq. 54 with a value of 1 611 kg for the largest trees. The difference between these two equations was 1 052 kg.

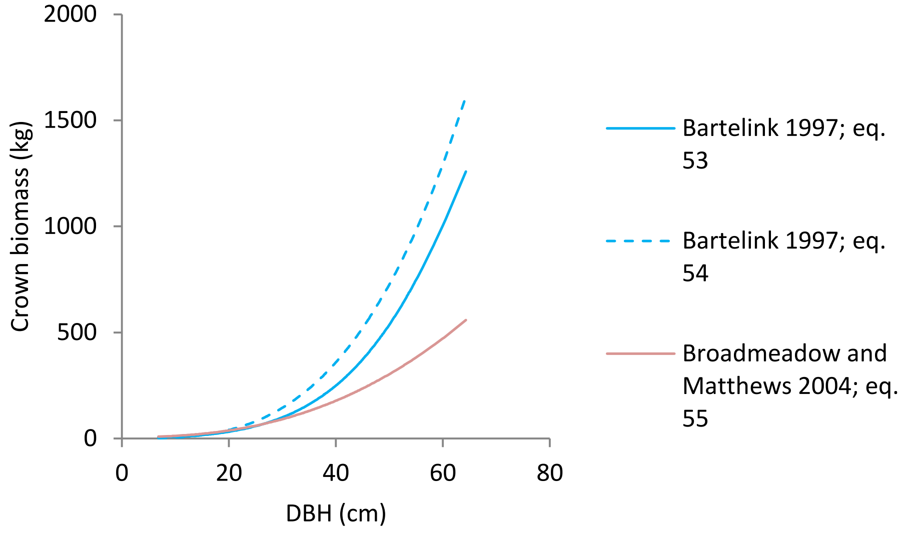

Figure 21 Estimation of beech crown biomass according to equations (eq. 53 – 55) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.9 Timber biomass

The timber biomass compartment (definition in Figure 10) was evaluated only by one allometric equation. Allometric equation by Wutzler *et al*. 2008; eq. 56. was used in this model (Figure 22). The highest measured value by this model on Štítná nad Vláří locality was 4 072 kg.

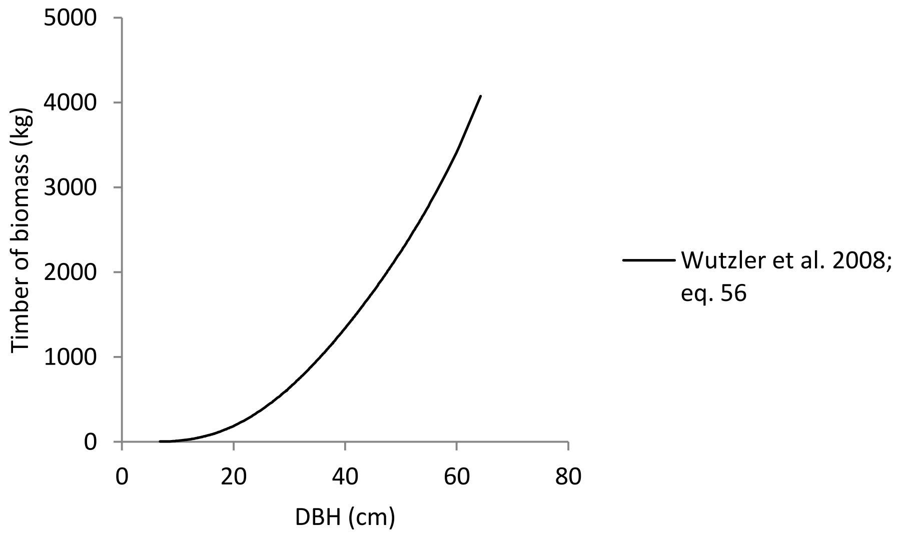

Figure 22 Estimation of beech timber biomass according to equation (eq. 56) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.10 Brushwood biomass

One allometric equation was evaluated for the brushwood biomass compartment (definition in Figure 10). The brushwood is defined as wood with diameter smaller than 7 cm. The only allometric equation used for this compartment was by Wutzler *et al*. 2008; eq. 57 (Figure 23). The biggest model value of this equation exhibited 291 kg for the biggest tree class on the Štítná nad Vláří locality.

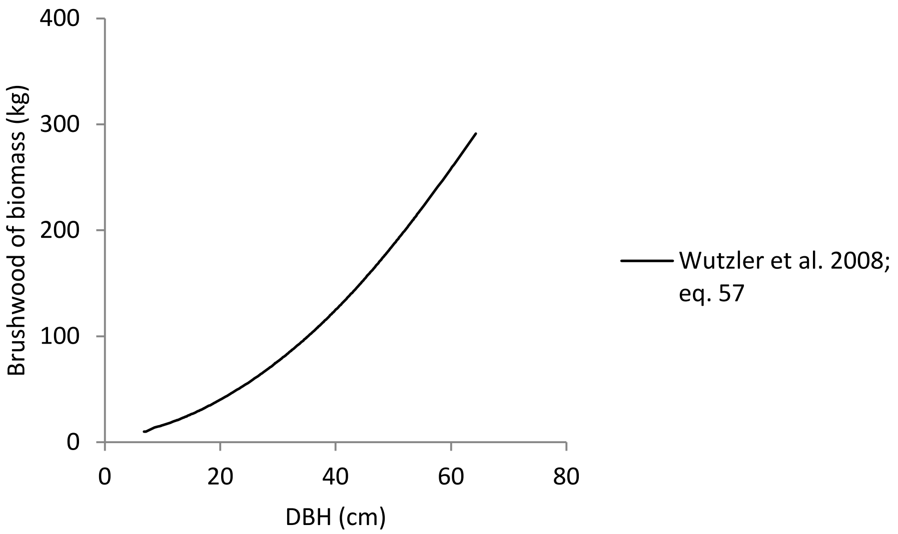

Figure 23 Estimation of beech brushwood biomass according to equation (eq. 57) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.2.11 Stem volume

8 allometric equations were used for the stem volume compartment calculation. Stem is defined as a segment of the main trunk with a minimum diameter of 7 cm. The resulting model values of these equations are very different from each other (Figure 24). The curve expressing the lowest model value for the biggest trees was that devised by De Vries 196; eq. 60 (green dotted line). The highest model values were reached by the Pollanschütz 1974; eq. 65 in the valid interval of DBH > 10 cm, which gives the biggest tree on the Štítná nad Vláří locality a stem volume of 9 m^3. The second highest model values were obtained by the Dagnelie *et al*. 1999 equation; eq. 59 with a stem volume of 6.9 m^3. The other equations averaged stem volume of about 5 m^3.

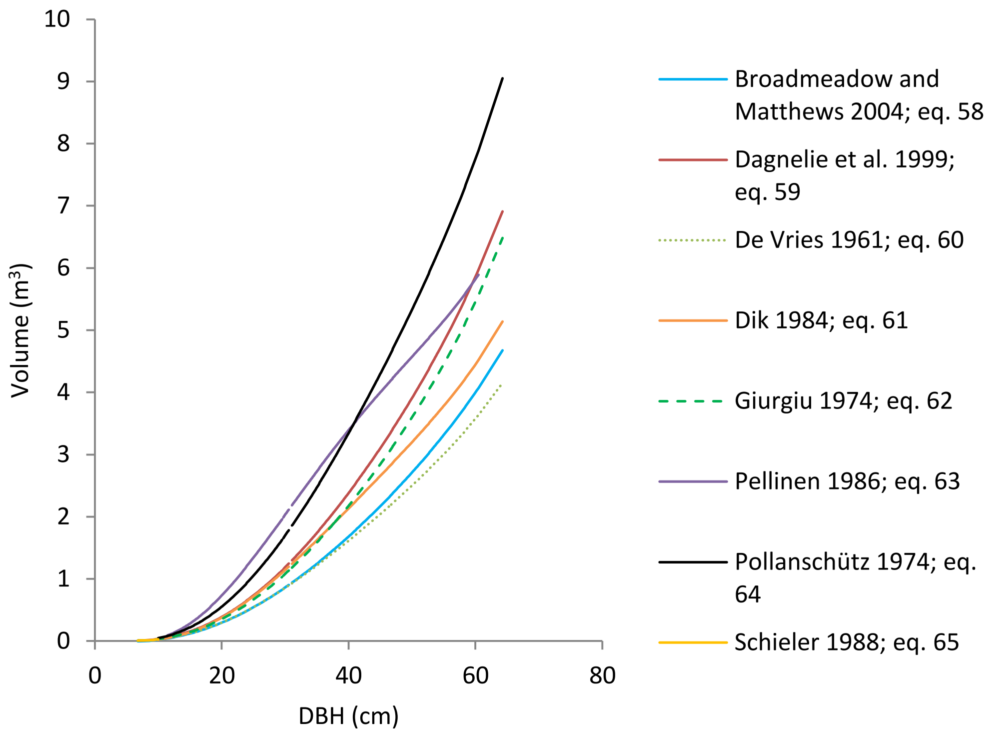

Figure 24 Estimation of beech stem volume biomass according to equations (eq. 58 – 65) listed in Table 3 and its dependency on diameter at breast height (DBH)

5.3 Stock and increment of biomass

Model values of beech biomass according to Wutzler *et al.* 2008 were chosen in this chapter, because its study was focused on Central Europe. The model tree height range was 2 – 40 m and the DBH was in the 1 – 79 cm range. The age of trees ranged from 8 – 173 years and the altitude ranged from 23 – 1 560 m above sea level. The complete outline is shown in Figure 2.

5.3.1 Foliage biomass

Foliage biomass of the Holíkov study site was 2 821 kg/ha of beech trees, 399 kg/ha of spruce trees and 70 kg/ha of larch trees at the beginning of the 2010 study period (as shown in Figure 25). The estimated amount of needle biomass was 469 kg/ha in 2010 and 491 kg/ha in 2015, which represents a 14 % increment. The total foliage biomass estimation has increased by 276 kg, which represents 8 % of total foliage biomass on the stand during the 6-year period. The highest annual change of stock of foliage was in 2012 with an increment of up to 59 kg. There was 2 977 kg/ha of foliage biomass in the Štítná nad Vláří study site in 2010. It was 3 262 kg/ha of foliage biomass in 2015. The highest annual change of foliage biomass was in 2013 with an increment of up to 86 kg/ha.

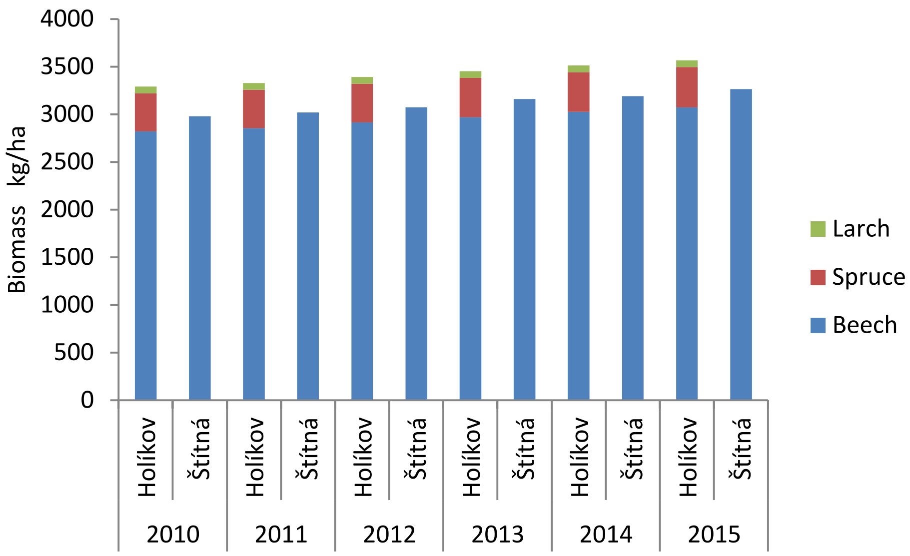

Figure 25 Stock of foliage biomass during the 2010 - 2015 period on the Štítná nad Vláří and Holíkov study sites Holíkov

5.3.2 Branch biomass

The branch biomass of the Holíkov stand was 42 361 kg/ha of beech trees, 1 091 kg/ha of spruce trees and 746 kg/ha of larch trees at the beginning of study period in 2010 (as shown in Figure 26). The estimated amount of branch biomass (coniferous trees) per hectare was 1 837 kg/ha in 2010 and 1 936 kg/ha in 2015, which represents a 4 % increase. The estimated stock of foliage biomass has increased during the 6-year monitored period by 5 005 kg, which represents 11 % of total branch biomass of the stand. The highest annual change of branch stock was in 2012 with an increment of up to 1 145 kg. There was 46 132 kg/ha of branch biomass on the Štítná nad Vláří study site in 2010. It went up to 52 128 kg/ha of branch biomass in 2015. The highest annual change of branch biomass was in 2013 with an increment of up to 1 713 kg/ha.

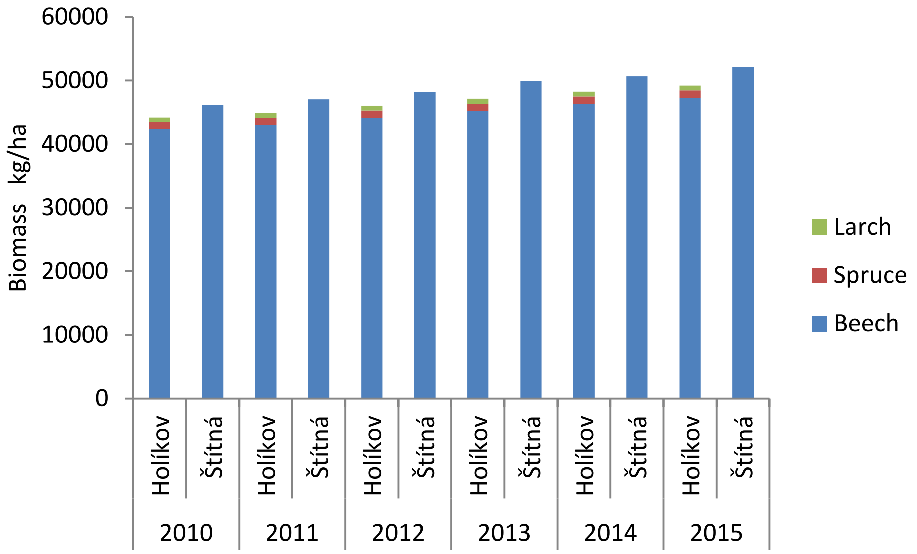

Figure 26 Stock of branch biomass during the 2010 - 2015 period on the Štítná nad Vláří and Holíkov study sites

5.3.3 Total stem biomass

Total stem biomass of the Holíkov study site was 247 080 kg/ha of beech trees, 5 847 kg/ha of spruce trees and 5 076 kg/ha of larch trees at the beginning of the study period in 2010 (as shown in Figure 27). The estimated amount of total stem biomass (coniferous trees) per hectare was 10 923 kg/ha in 2010 and 11 359 kg/ha in 2015, which represents a 4 % increment. The estimated the stock of total stem biomass has increased by 21 270 kg during the 6-year study period, which represents 8 % of total stem biomass in stand. The highest annual change of total stem stock was in 2012 with an increment of up to 4 909 kg. There was 292 331 kg/ha of total stem biomass in the Štítná nad Vláří study site in 2010. It was 321 636 kg/ha of total stem biomass in 2015. The highest annual change of total stem biomass was in 2013 with an increment of up to 8 573 kg/ha.

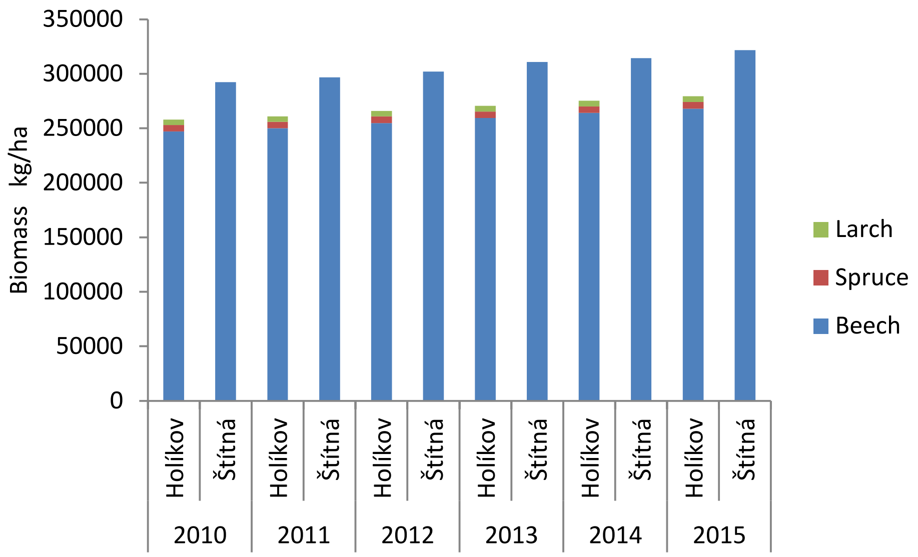

Figure 27 Stock of total stem biomass in the 2010 - 2015 period on the Štítná nad Vláří and Holíkov study sites

5.3.4 Root biomass

Root biomass of the Holíkov study site was 41 911 kg/ha of beech trees, 1 749 kg/ha of spruce trees and 4 352 kg/ha of larch trees at the beginning of the study period in 2010 (as shown in Figure 28). The estimated amout of root biomass (conifer trees) per hectare was 6 101 kg/ha in 2010 and 6 375 kg/ha in 2015, which represents a 12 % increase of total amout root biomass of the stand. The estimated stock of root biomass has increased by 4 270 kg during the monitored period, which represents an 8 % increase. The highest annual change of rootstock was in 2012 with an increment of 938 kg. There was 47 453 kg/ha of root biomass on the Štítná nad Vláří study site in 2010.

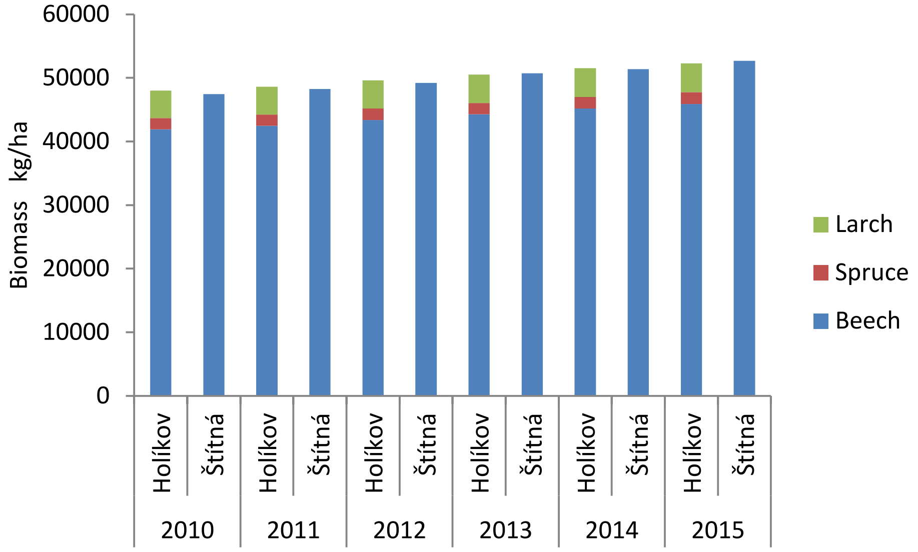

Figure 28 Stock of root biomass in the 2010 - 2015 period on the Štítná nad Vláří and Holíkov study sites

5.3.5 Aboveground biomass

The aboveground biomass of the Holíkov stand was 275 718 kg/ha of beech trees, 7 336 kg/ha of spruce trees and 6 304 kg/ha of larch trees at the beginning of the study period in 2010 (as shown in Figure 29). The estimated amout of aboveground biomass (coniferous trees) per hectare was 13 641 kg/ha in 2010 and 14 238 kg/ha in 2015, which represents a 4 % gain of total amout aboveground biomass in stand. The estimated stock of aboveground biomass has increased by 25 160 kg during the 6-year period, which represents 8 % of total aboveground biomass in stand. The highest annual change of stock of aboveground biomass was in 2012 with an increment of 5 779 kg. There was 322 400 kg/ha of aboveground biomass in the Štítná nad Vláří study site in 2010. It was 356 175 kg/ha of aboveground biomass in 2015. The highest annual change of aboveground biomass was in 2013 with an increment of up to 9 837 kg/ha.

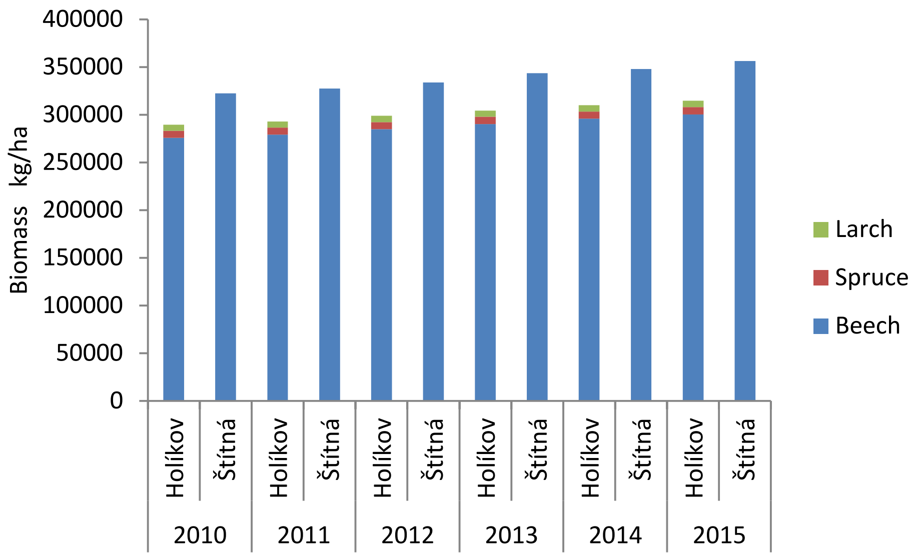

Figure 29 Stock of aboveground biomass in 2010 - 2015 the period on the Štítná nad Vláří and Holíkov study sites

5.4 Beech biomass distribution in diameter classes

This chapter only deals with beech biomass distribution on the stands, although the Holíkov study site also features spruce and larch trees

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5.4.1 Štítná nad Vláří study site

5.4.1.1 Aboveground biomass

Figure 30 shows a sum of model values of aboveground biomass according to each diameter classs. Used allometric equations are by Vejpustková *et al*. 2013 and Wutzler *et al*. 2008. Estimations for each diameter class differ greatly. The biggest relative difference of model values was found in the 5 – 10 cm diameter class, where model by Vejpustková et al. 2013 DH2; eq. 9 reached only 24 % of the value of another model by Vejpustková *et al.* 2013 D2; eq. 11. The highest sum of model values was measured in the 40 – 45 cm diameter class by Vejpustková *et al.* 2013; eq. 12 with a value of 95 053 kg of aboveground biomass. Wutzler *et al.* 2008 estimated a value of 78 111 kg of aboveground biomass in the 40 – 45 cm range.

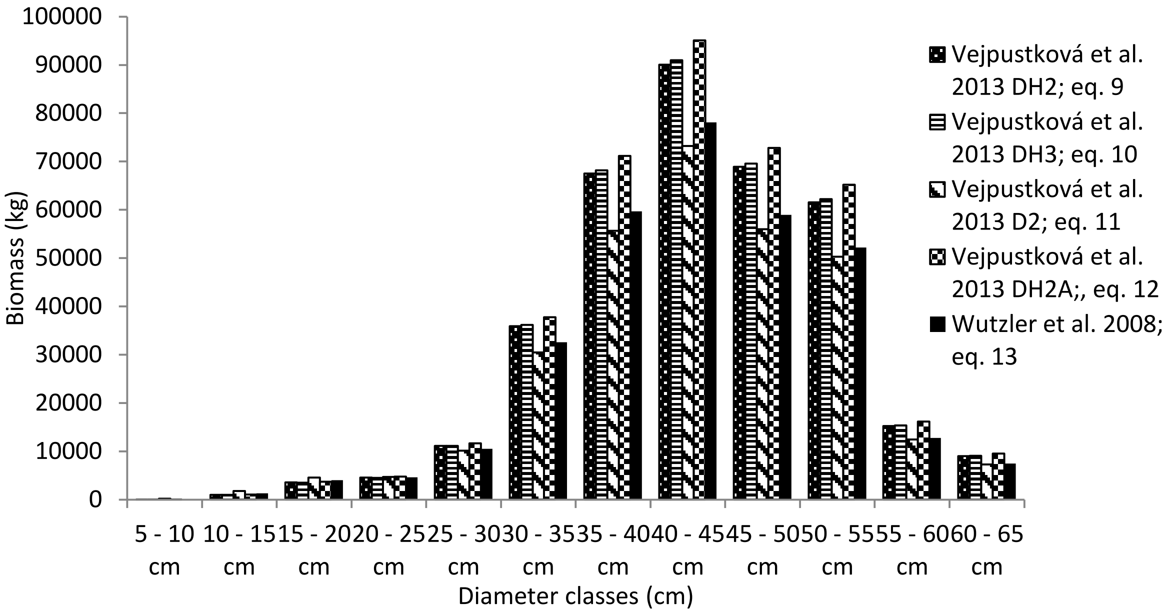

Figure 30 Distribution of beech aboveground biomass on the Štítná nad Vláří study site

5.4.1.2 Branch biomass

Figure 31 shows a sum of model values of branch biomass according to each diameter classs. Used allometric equations are by Vejpustková *et al*. 2013 and Wutzler *et al*. 2008. Estimations for each diameter class differ. The biggest relative difference of model values was found in the 40 – 45 cm diameter class, where model by Vejpustková et al. 2013 DH2; eq. 9 and reached 6 773 kg. The highest value of 10 742 kg was measured according to Wutzler *et al.* 2008; eq. 24 in the 40 – 45 cm diameter class.

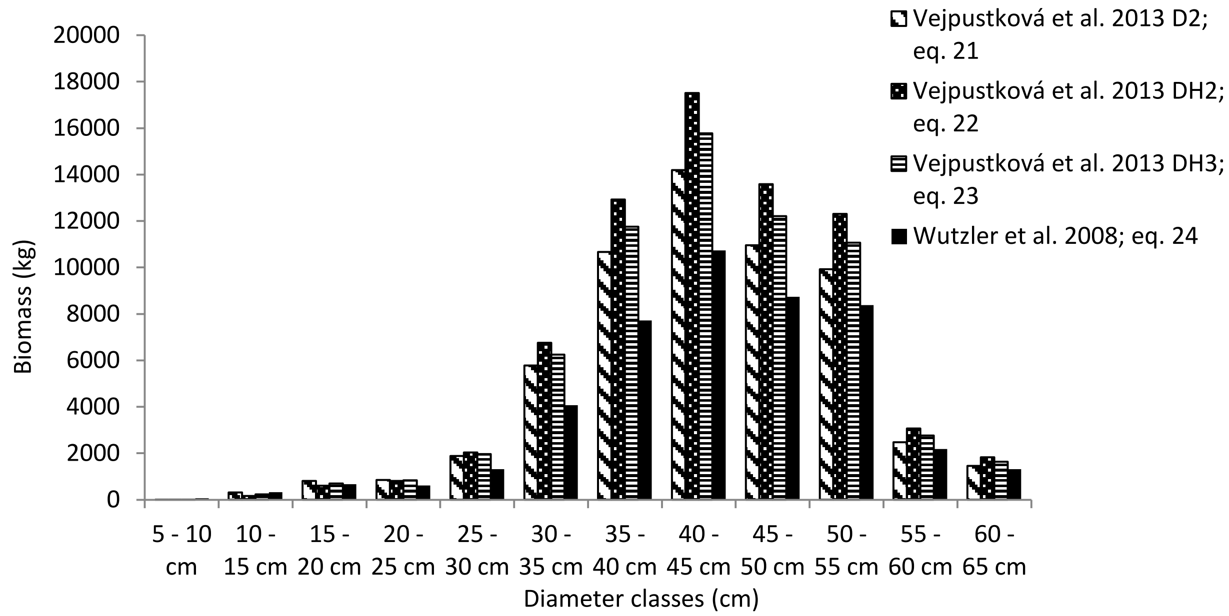

Figure 31 Distribution of beech branch biomass on the Štítná nad Vláří study site

5.4.1.3 Foliage biomass

Figure 32 shows a sum of model values of beech foliage biomass according to each diameter class estimated according to Wutzler *et al*. 2008 on the Štítná nad Vláří study site. Allometric equations by Vejpustková *et al.* 2013 are not available for this compartment. The highest sum of model value was reached in the 40 – 45 cm diameter class with a value of 691 kg. The lowest value (7 kg), on the other hand, was estimated for the 5 – 10 cm diameter class.

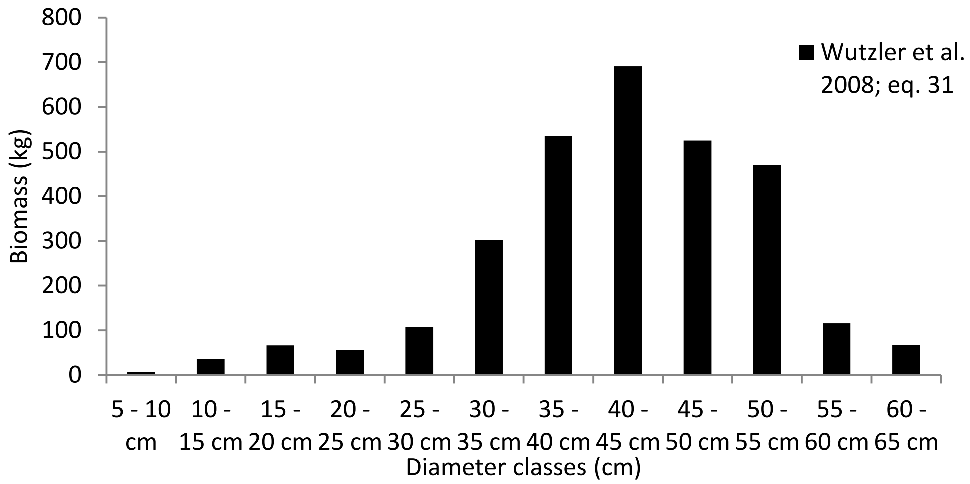

Figure 32 Distribution of beech foliage biomass on the Štítná nad Vláří study site

5.4.1.4 Total stem biomass

Figure 33 shows sum of model values of total stem biomass according to each diameter classses and determined according to Vejpustková *et al.* 2013 and Wutzler *et al.* 2008 on the Štítná nad Vláří study site. Diameter class estimations are very different from each other. The biggest difference of model values was found between the allometric equations by Vejpustková et al. 2013 D2; eq. 42 and Vejpustková *et al.* 2013 DH3; eq. 40 in the 40 – 45 cm diameter class and reached 16 489 kg of stem biomass. Allometric equation according to Vejpustková *et al.* 2013 DH3; eq. 40 reached 14 % higher values than that by Wutzler *et al.* 2008; eq. 43 in the biggest diameter class 60–65 cm. Wutzler *et al.* 2008; eq. 43 measured a value of 71 226 kg of total stem biomass in the 40 – 45 cm range.

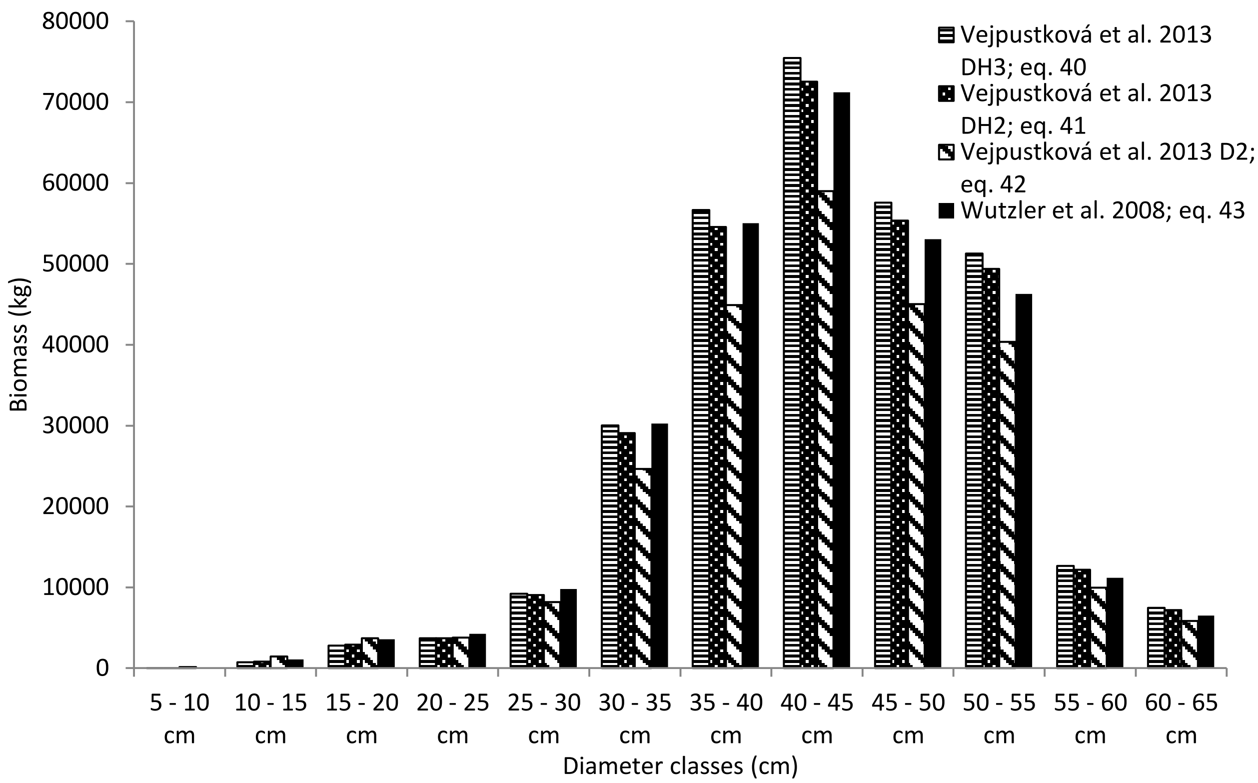

Figure 33 Distribution of beech total stem biomass on the Štítná nad Vláří study site

5.4.1.5 Root biomass

Figure 34 shows a sum of model values of root biomass according to each diameter classses estimated with the help of allometric equation by Wutzler *et al.* 2008 on the Štítná nad Vláří study site. Allometric equations according to Vejpustková *et al.* 2013 are not available for this compartment. The highest model value of 11 344 kg was reached in the 40 – 45 cm diameter class. The lowest value of 25 kg of root biomass was measured in the 5 – 10 cm diameter class.

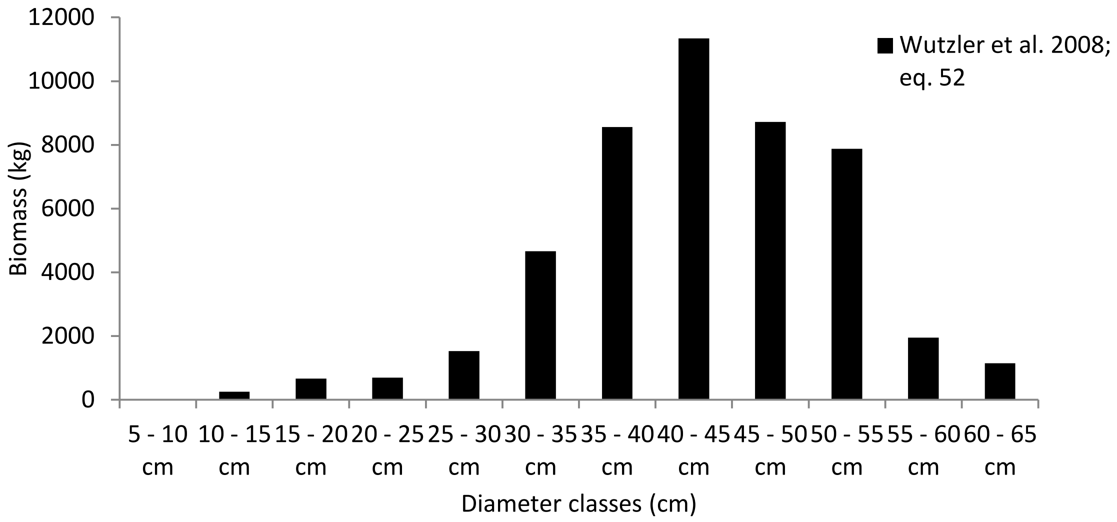

Figure 34 Distribution of beech root biomass on the Štítná nad Vláří study site

5.4.1.6 Timber biomass

Figure 35 shows sum of model values of root biomass according to each diameter classses determined according to Wutzler *et al*. 2008; eq. 20 on the Štítná nad Vláří study site. Allometric equations byVejpustková et al. 2013 are not available for this compartment. The highest model value of timber biomass of 79 831 kg was reached in the 40 – 45 cm diameter class. The lowest value of 36 kg was in the 5 – 10 cm diameter class.

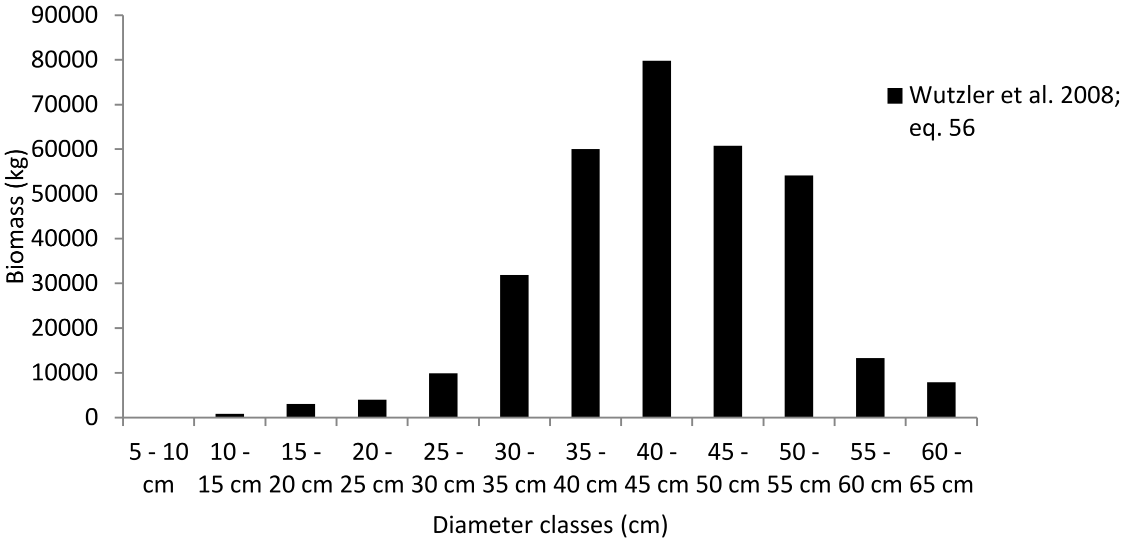

Figure 35 Distribution of beech timber biomass on the Štítná nad Vláří study site

5.4.1.7 Brushwood biomass

Figure 36 shows sum of model values of root biomass according to each diameter classs determined by Wutzler *et al*. 2008; eq. 57 on the Štítná nad Vláří study site. Allometric equations according to Vejpustková *et al.* 2013 are not available for this compartment. The highest value of brushwood biomass of 7 191 kg was reached in the 40 – 45 cm diameter class. The lowest value was measured in the 5 – 10 cm diameter class with a value of 68 kg.

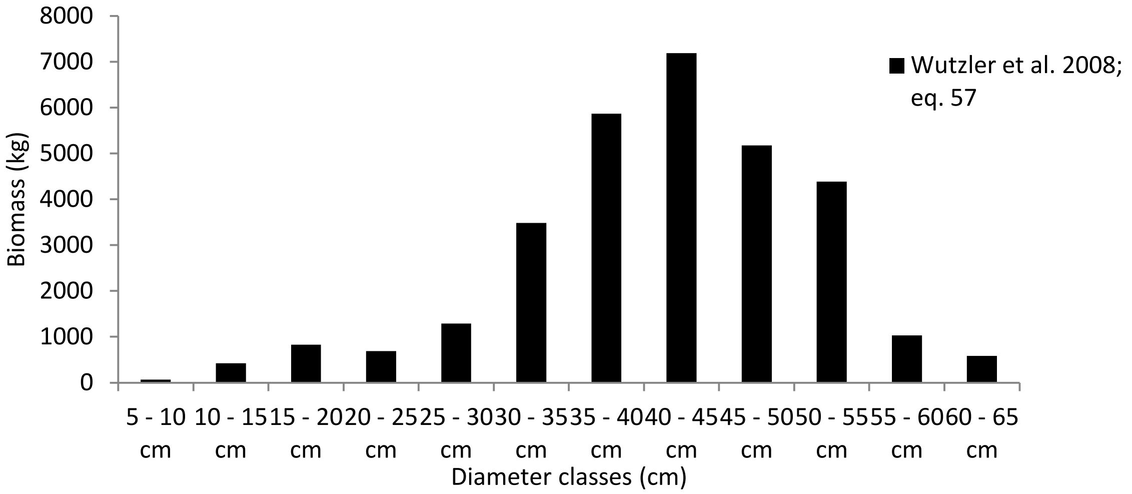

Figure 36 Distribution of beech brushwood biomass on the Štítná nad Vláří study site

5.4.2 Holíkov study site

5.4.2.1 Aboveground biomass

Figure 37 shows a sum of model values of aboveground biomass according to each diameter classs in the Holíkov study site. Used allometric equations are by Vejpustková *et al.* 2013 and Wutzler *et al.* 2008. Estimations for each diameter class differ greatly. The biggest relative difference of model values was found in the 35 – 40 cm diameter class, where the model by Vejpustková et al. 2013 DH2; eq. 11 reached only 89 % of the value of another model by Vejpustková *et al.* 2013 DH2A; eq. 12 The highest sum of model values was measured in the 35 – 40 cm diameter class by Vejpustková *et al.* 2013; eq. 12 with a value of 114 461 kg of aboveground biomass. Wutzler *et al.* 2008 estimated a value of 103 511 kg of aboveground biomass in the 35 – 40 cm range.

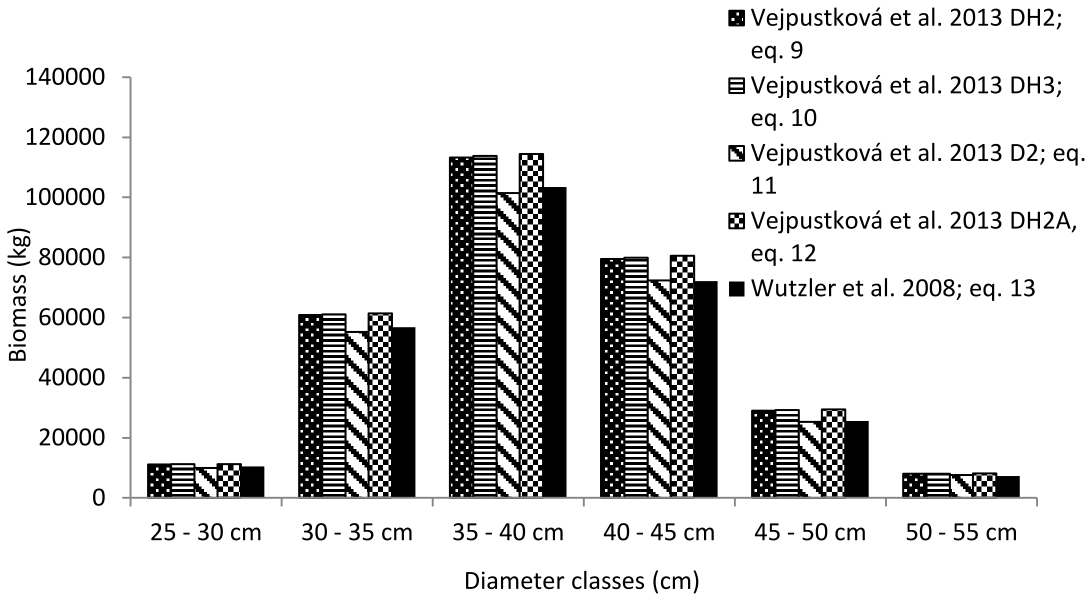

Figure 37 Distribution of beech aboveground biomass on the Holíkov study site

5.4.2.2 Branch biomass

Figure 38 shows a sum of model values of branch biomass according to each diameter classs. Used allometric equations are by Vejpustková *et al*. 2013 and Wutzler *et al*. 2008. Estimations for each diameter class differ greatly. The biggest relative difference of model values was 6 152 kg between the Vejpustková *et al.* 2013 and Wutzler et al. 2008 allometric equations and was found in the 35–40 cm diameter class. The highest value of 15 423 kg was measured according to Wutzler *et al.* 2008; eq. 24 in the 35 – 40 cm diameter class. All models performed evenly in the 50 – 55 cm diameter class where Vejpustková et al. 2013 D2; eq. 21 has reached only 2,2 % higher value than the model by Wutzler *et al.* 2008.

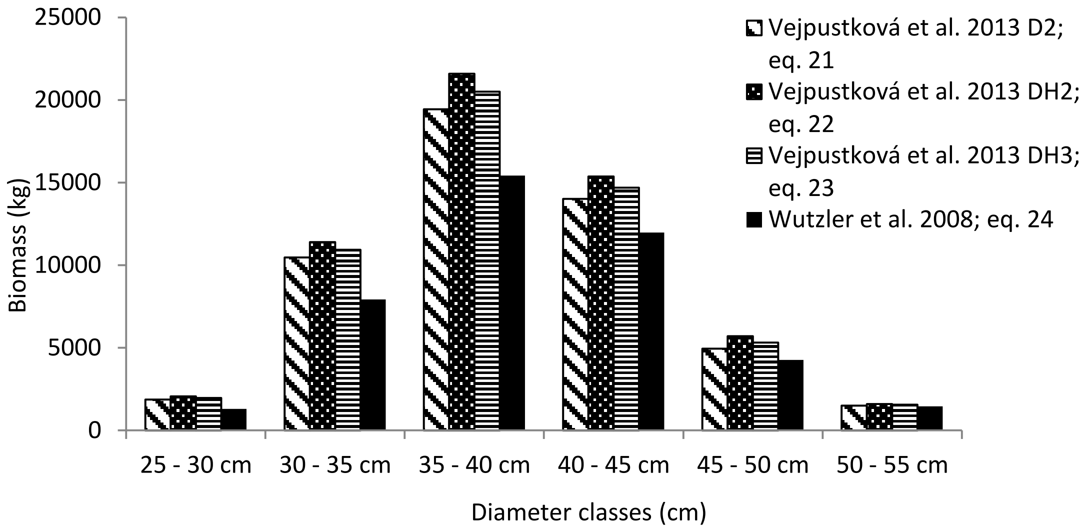

Figure 38 Distribution of beech branch biomass on the Holíkov study site

5.4.2.3 Foliage biomass

Figure 39 shows a sum of model values of beech foliage biomass according to each diameter class estimated according to Wutzler *et al*. 2008 on the Holíkov study site. Allometric equations by Vejpustková *et al.* 2013 are not available for this compartment. The highest sum of model value was reached in the 35 – 40 cm diameter class with a value of 1049 kg. The lowest value of 81 kg, on the other hand, was estimated in the 50 – 55 cm diameter class.

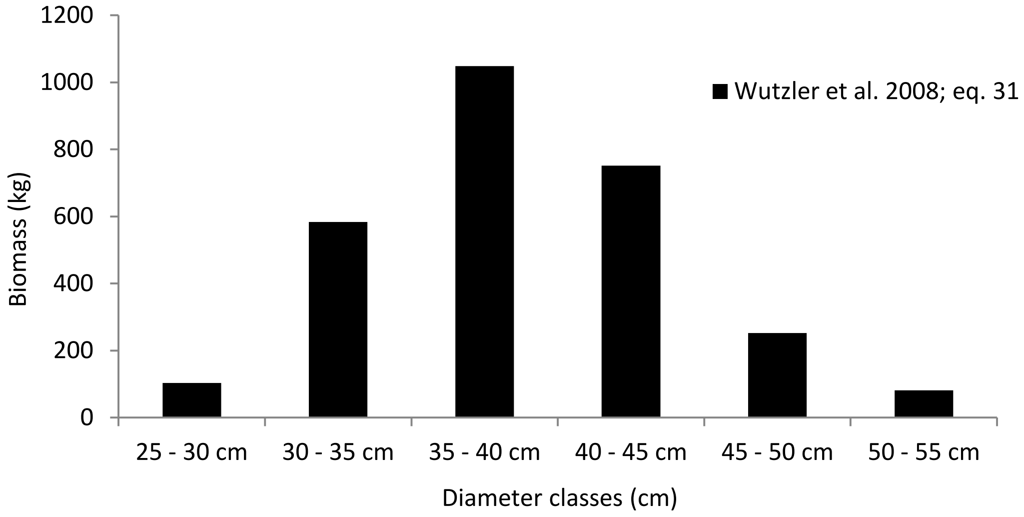

Figure 39 Distribution of beech foliage biomass on the Holíkov study site

5.4.2.4 Total stem biomass

Figure 40 shows sum of model values of total stem biomass according to each diameter classs and determined according to Vejpustková *et al*. 2013 and Wutzler *et al*. 2008 on the Holíkov study site. Diameter class estimations are very different from each other. The lowest sum of of model values were recorded by the Vejpustková et al. 2013 D2; eq. 42 in each diameter class. The biggest difference of model values was found between the allometric equations by Vejpustková et al. 2013 D2; eq. 42 and Wutzler *et al*. 2008; eq. 43 in the 35 – 40 cm diameter class where the Wutzler *et al*. 2008 equation outperformed the other by 14 %.

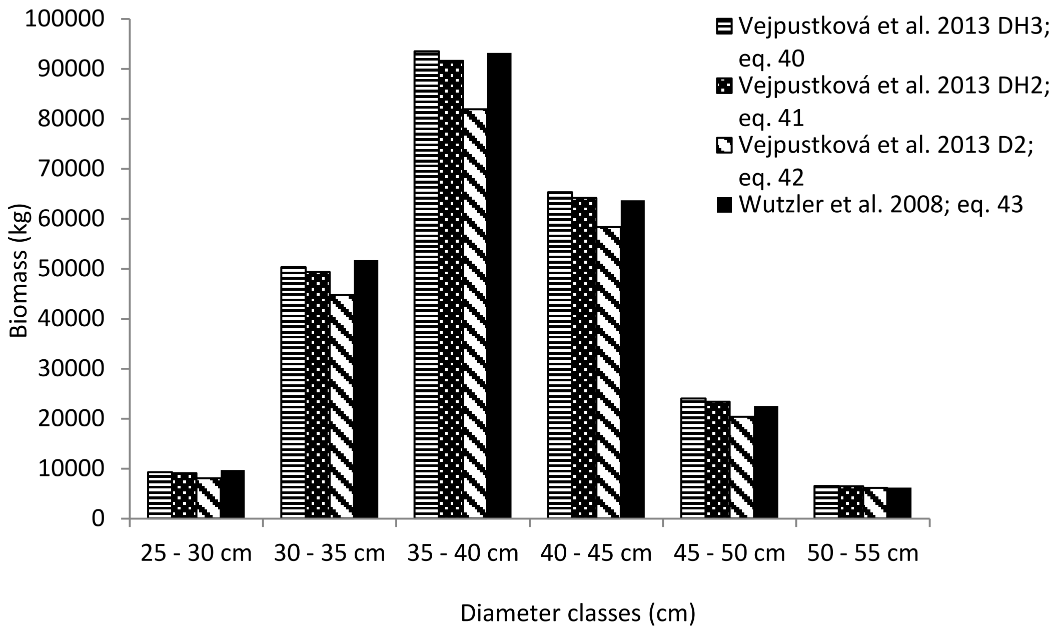

Figure 40 Distribution of beech total stem biomass on the Holíkov study site

5.4.2.5 Root biomass

Figure 41 shows a sum of model values of root biomass according to each diameter classses estimated with the help of allometric equation by Wutzler *et al*. 2008; eq. 52 on the Holíkov study site. Allometric equations according to Vejpustková *et al.* 2013 are not available for this compartment. The highest model value of 15 613 kg was reached in the 35 – 40 cm diameter class. The lowest value of 1 194 kg of root biomass was measured in the 50 – 55 cm diameter class.

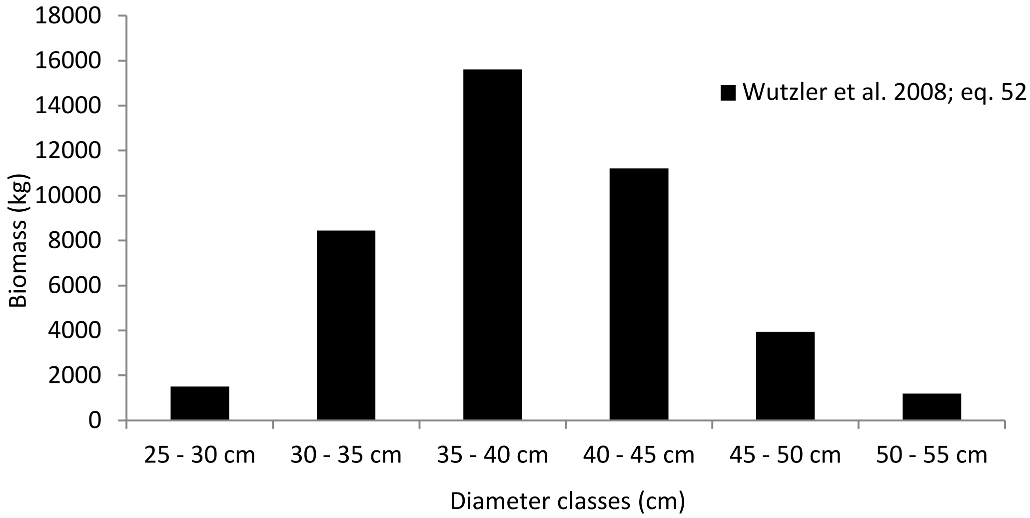

Figure 41 Distribution of beech root biomass on the Holíkov study site

5.4.2.6 Timber biomass

The sum of model values of timber biomass according to each diameter classses according to Wutzler *et al*. 2008; eq. 56 on the Holíkov study site is shown in Figure 42. Allometric equations according to Vejpustková et al. 2013 are not available for this compartment. The highest value of 99 710 kg of timber biomass was reached in the 35 – 40 cm diameter class. The lowest value of 6 966 kg was recorded in the 50 – 55 cm diameter class.

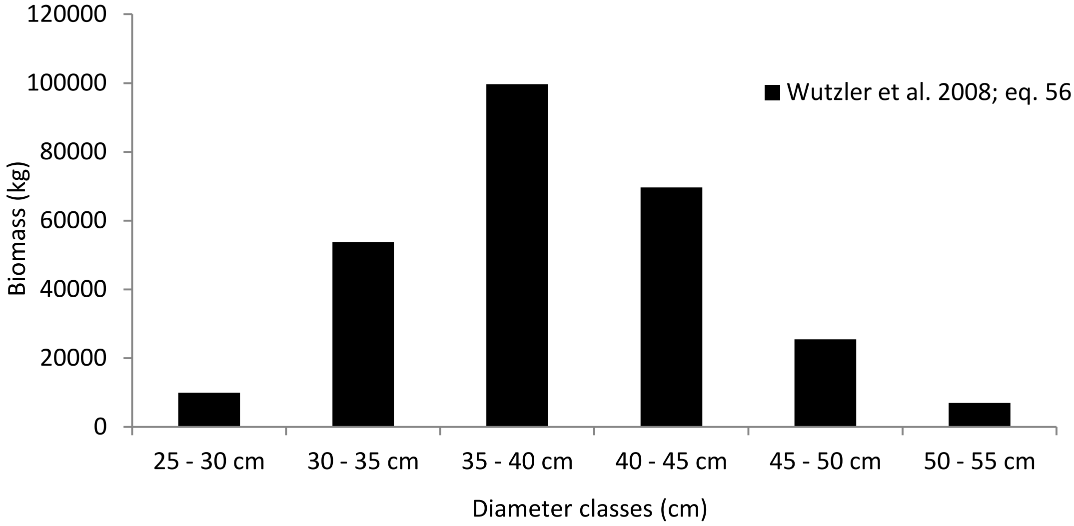

Figure 42 Distribution of beech timber biomass on the Holíkov study site

5.4.2.7 Brushwood biomass

Figure 43 shows sum of model values of brushwood biomass according to each diameter class. Allometric equation by Wutzler *et al.* 2008; eq 57 was applied to calculation for the Holíkov study site. Allometric equations by Vejpustková et al. 2013 are not available for this compartment. The highest model value of brushwood biomass of 11 025 kg was reached in the 35 – 40 cm diameter class with. On the other hand, the lowest value of 710 kg was recorded in the 50 – 55 cm diameter class.

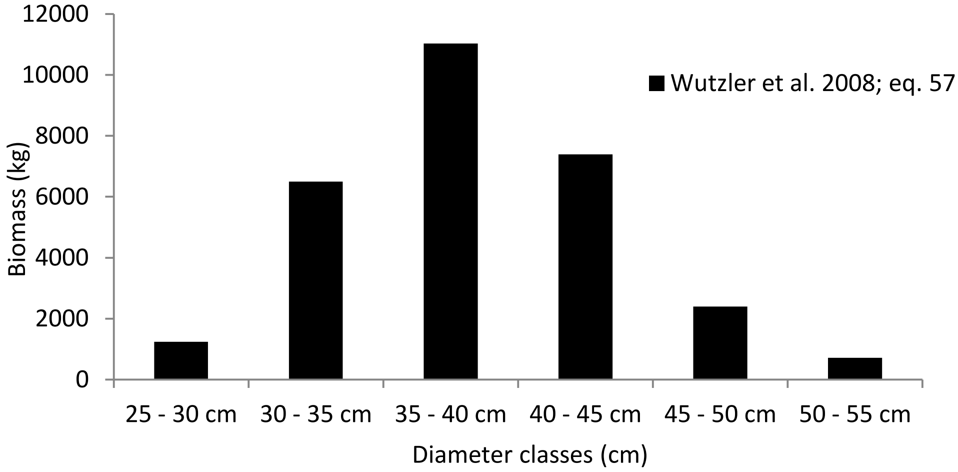

Figure 43 Distribution of beech brushwood biomass on the Holíkov study site

5.5 Total stock of aboveground biomass

5.5.1 Štítná nad Vláří study site

Figure 44 shows all model values of beech aboveground biomass on the Štítná nad Vláří study site in 2010. The total stock of aboveground biomass was calculated with the use of 13 allometric equations. This model proved big variability in biomass estimations of individual compartments. The highest estimated amout of biomass was 97 612 kg/ha and was detected in the 40 – 45 cm diameter class, whereas the lowest estimate in the same class was by Nihlgård 1972; eq. 6 with 97 612 kg/ha. The overall lowest estimate of biomass was 1 551 kg/ha in the 5 – 10 cm diameter class, where the lowest amount of biomass had a model by Vejpustková et al. 2013 DH3; eq. 10 with only 43 kg/ha. The whole stand contains 389 000 kg of beech aboveground biomass according to Vejpustková *et al*. 2013; eq. 12 and 322 000 kg according to Wutzler *et al.* 2008. Model values of Cienciala *et al*. 2005; eq. 3 show a total amount of 299 000 kg of total aboveground biomass. The lowest result are recorded by Santa Regina and Tarazona 2001; eq. 8 in a diameter class of 20 – 25 cm.

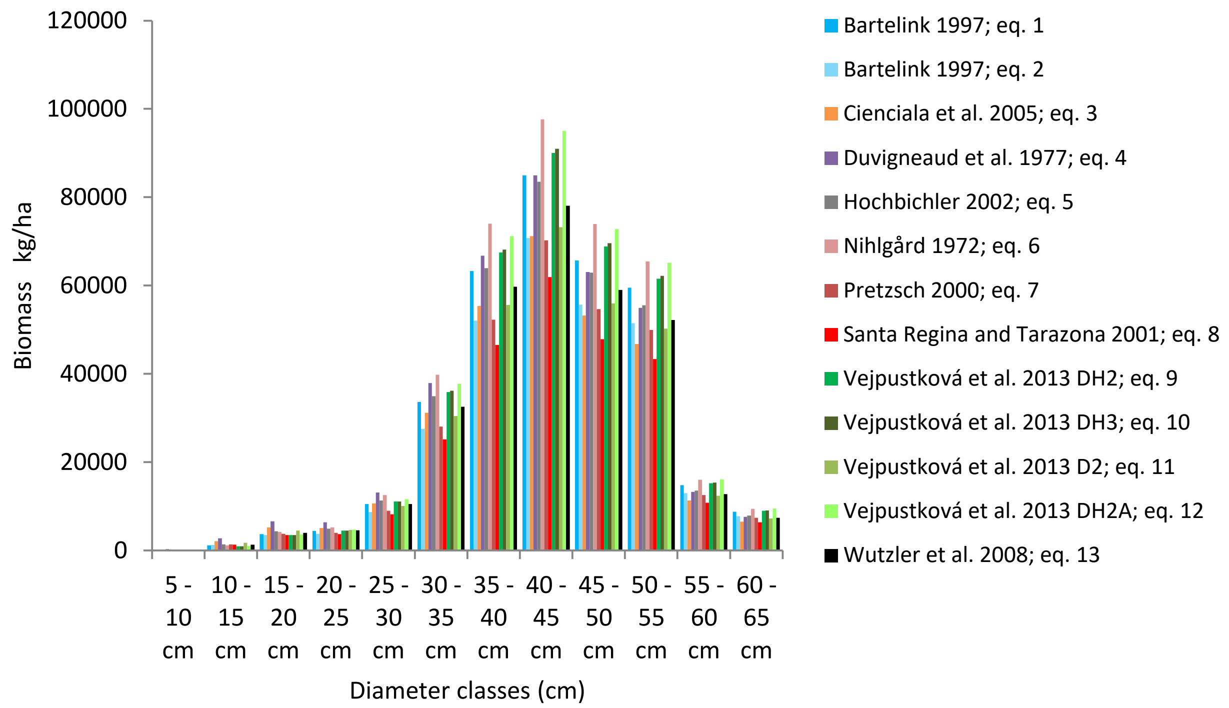

Figure 44 Total stock of aboveground biomass on the Štítná nad Vláří study site

5.5.2 Holíkov study site

Figure 45 shows all model values of beech aboveground biomass on the Holíkov study site in 2010. The total stock of aboveground biomass was calculated with the use of 13 allometric equations. This model proved big variability in biomass estimations of individual compartments. The highest estimated amout of biomass was 124 599 kg/ha and was detected in the 35 – 40 cm diameter class. The lowest estimate of biomass was 6 571 kg/ha in the 50 – 55 cm diameter class, estimated in accordance with the Regina and Tarazona 2001; eq. 8. The largest difference in model values combined for all diameter classes lied between the equations by Nihlgård 1972; eq. 6 and Santa Regina and Tarazona 2001; eq. 8; it was 104 000 kg of aboveground biomass. According to Vejpustková *et al.* 2013; eq. 12 the whole stand has 305 000 kg of beech aboveground biomass and according to Wutzler *et al.* 2008 it accounts for 276 000 kg of biomass. The Santa Regina and Tarazona 2001; eq. 8 shows the lowest estimates in all diameter classes.

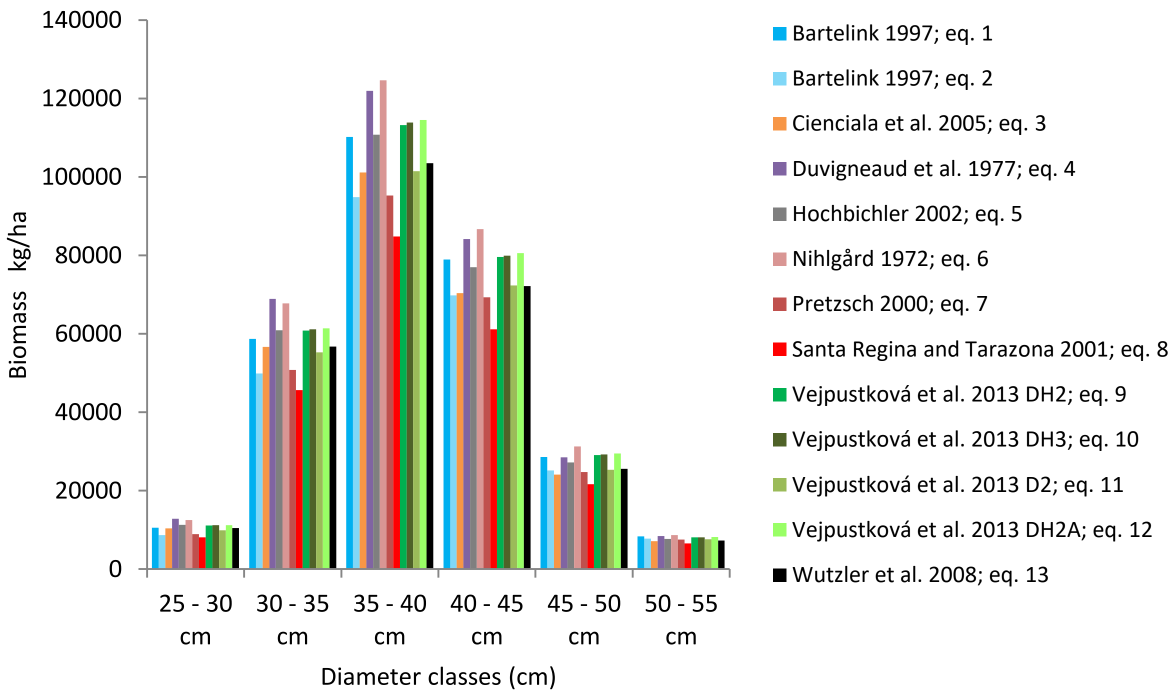

Figure 45 Total stock of aboveground biomass on the Holíkov study site

6 DISCUSSION

The present study provides en estimation of biomass of European beech stands for all major tree compartments on the Štítná nad Vláří and Holíkov study sites, the Czech Republic The dataset was compiled between 2010 and 2015. Estimations of biomass accumulation of forest ecosystem are important for assessing the productivity and sustainability of forests. Biomass estimation of forest ecosystems also enables to determine the amount of CO_2 that can be sequestered from the atmosphere. Accurate assessment of forest biomass is important for many applications such as timber extraction, tracking changes in the carbon stocks of forest and global carbon cycle. Forest biomass can be estimated through several methods (Vashum and Jayakumar 2012). This study utilized non-destructive methods and the estimation of aboveground biomass was calculated with the use of allometric equations. This method implies the application of premeasured variables: diameter at breast height (DBH) and height of the tree. This is the most widely used method for forest biomass estimation (Vashum and Jayakumar 2012). In cases where individual tree data are not available, biomass is normally estimated with biomass expansion factors (BEFs) that use estimated timber volume in combination with other stand-level variables to estimate plot-level biomass (Tobin and Nieuwenhuis 2007). Allometric equations are developed and applied to forest inventory data to assess the biomass and carbon stocks of forests (Vashum and Jayakumar 2012). The characterization of allometric relationships between individual parts of biomass and size-related variables (DBH and height) has been widely accepted and applied by numerous previous studies for estimating forest biomass (Vejpustková *et al.* 2013, Wutzler *et al.* 2008, Zianis *et al.* 2005). The accuracy of forest biomass estimates depends on the variation and quality of data used for developing allometric equations because allometric relationships between tree biomass and size-related variables show specific tendencies under different environmental conditions e.g.: tree species, climatic zone, etc. (Kira and Shidei 1967). In addition, site-specific characteristics such as soil conditions, forest structure, tree density, age and climate may influence the allometric relationships between size-related variables and biomass compartments e.g.: foliage, stem, brushwood, roots etc. (Saito *et al.* 1968).

Only limited amount of sources focused on biomass estimation exists in Czech forestry, (Cienciala *et al.* 2005, Vejpustková *et al.* 2013). Simirarly, not many outputs with general allometric equations for the estimation of aboveground biomass and especially for belowground biomass were yet published. Allometric models, which are parameterized for European conditions are generally used (i.e.: Wutzler *et al.* 2008).

65 allometric equations for predicting biomass compartments of European beech (*Fagus sylvatica* L.) were used in the presented study as well as 10 allometric equations for Norway spruce (*Picea abies*) and European larch (*Larix decidua*). Allometric equations are usually devised to determine the biomass of economically relevant aboveground woody compartments (timber, stem), less often branches and leaves, and rarely belowground compartments. However, monitoring and modelling changes of carbon stocks require the estimation of all of the biomass compartments (Wutzler *et al.* 2008). All major tree compartments, which were calculated according to appropriate equations were used in this study according to different authors available for Europe. Most of them were compared with the Vejpustková *et al.* 2013 and Wutzler *et al.* 2008 models, due to the fact that these models performed similarly but mainly both are for Central Europe, so they are locally acceptable. They were also compiled and constructed from locations with similar climatic conditions as study sites in this work. The equations by Wutzler *et al.* 2008 are based on data from 443 trees from 13 studies and their research included several biomass compartments. Allometric equations for biomass estimation are generally developed by establishing a relationship between various physical parameters of the trees (DBH, total tree height, tree species, etc.) (Vashum and Jayakumar 2012).

Since destructive methods were not conducted in this study, verification of considered models was based on geographical, environmental and climatic similarities of the models.

Model values of allometric equations used for biomass estimation were calculated for all major tree compartments, namely: aboveground, branch, foliage, total stem biomass, stem wood, biomass of stem bark, root, crown, timber, brushwood biomass and stem volume. The highest model value of 4 939 kg of aboveground biomass for the largest tree was reached by the allometric equation according to Vejpustková *et al.* 2013; eq. 12 and their model DH2A which incorporated DBH, tree height and altitude into the calculation. We could expect that this model gave us the most accurate value because it included three-variable factors. According to

Vejpustková *et al.* 2013 increasing number of variables leads to more accurate biomass estimations and the highest accuracy can achieved by additional predictor variables such as tree age site index and altitude. The most accurate model as published by Vejpustková *et al.* in 2013 is DH2AS, which incorporated side index and DH2AT, which comprises of altitude and tree age. However, these equations could not be used in this study because of the lack of additional information.

Zianis *et al*. 2005 investigated a large number of equations of various authors in his study named *Biomass and stem volume equations for tree species in Europe* (2005). The author argues the importance of the size of sample sets and the DBH range of the sample trees. The equations by Duvigneaud *et al.* 1977 (Belgium) and Santa Regina and Tarazona 2001 (Spain) are devised on the basis of only 6 and 7 samples respectively. I did not only lead to the creation of equations of a very local character but also these models had a very limited DBH range. Due to this fact it was difficult to compare their model values with the models by Vejpustková *et al*. 2013 and Wutzler *et al*. 2008.

When estimations of individual compartmens were compared, it became evident that the model values of aboveground biomass showed the smallest standard deviation (4260 ± 451.4 of 13 equations for the biggest tree) and behaved most similarly out of all examined compartments. The model values of 13 different equations ranged from from 4 939 kg to 3 736 kg. An interesting fact is that the highest and the lowest estimation was by the same author (Vejpustková *et al.* 2013) and that the lowest number derived from a basic model and the highest from the above mentioned DH2A. Model values according to Wutzler *et al*. 2008 approached rather lower model values. The question is why the model closeness even though not only central European equations were included. An answer is at hand, perhaps it is the most widely and time tested and researched compartment of all. On the contrary, the model values for the estimation of total stem biomass were very different from each other. The model values of 12 different equations ranged from from 1 286 kg to 5 421 kg with an average of 3 499.8 ± 1 143.3 of total stem biomass of the biggest tree. These model values included two models by Calamini and Gregori 2001, which were based on a stand located in northern and central Italy near to Appenino Tosco-Emiliano National Park. Calamini and Gregori´s equations under and over-performed so that gave the lowest and the highest result of all equations tested for the stem biomass content. Their study is based on a medium sized sample set of 60 trees which could indicate that these equations are not suitable for the calculation of central European beech stands or that their computations include an error.

It is surprising that only one equation was found dealing with the timber and brushwood biomass compartments, both developed by Wutzler *et al.* 2008. The reason could be that the research of these compartments is demanding and expensive At the same time the economical point of view has to be considered in the case of timber biomass.

The resulting numbers of total foliage biomass could suggest that an unimportant compartment is being dealt with. However, the resulting values also show quite a wide range. The model values of the foliage biomass compartment estimated by Wutzler *et al.* 2008 show a model value of 34 kg for the biggest tree, which above ground biomass was estimated by the same author to 3 830 kg. That indicates that foliage consists of 0.88 % of its total aboveground biomass. However fractional it may seem most of the other authors reached markedly higher values. The highest model value by a model according to Bartelink 1997 with a value 86 kg of biomass, which is focused on stands in central Netherlands. Unfortunately, this compartment was not evaluated by Vejpustková *et al.* 2013 because their research was conducted in the winter season.

Vejpustková *et al.* 2013 also did not have construct any equations for the root compartment. It is perhaps the most difficult to collect destructive data for. It is also the one where we are most uncertain about the outcome. The model values of the compartment of roots biomass estimated by Wutzler *et al.* 2008 had a value of 591 kg for the biggest tree. Other equations reached higher values, the highest of them was equation according to Le Goff and Ottorini 2001. Their research was conducted in the East of France, near to the city of Nancy.

Based on observations obtained by applying different allometric equations for biomass estimation onto the same model values it can be noted, that not all of the used equations by different authors and different countries are ideal for studied Štítná nad Vláří and Holíkov experimental sites. Beech (*Fagus sylvatica*) in comparison with spruce (*Picea abies*) is insufficiently evaluated and only a small number of suitable allometric equations for beech exist. Originally, beech occurred in the Czech republic by around 40 %. Forestry, alike agronomy was influenced by the need for production, which resulted in planting vast areas with spruce monocultures (Scherer-Lorenzen *et al*.

2005). Mixed stands currently receive more and more attention mainly because they present closer-to-nature alternative. Mixed species stands seem to meet the whole range of ecological, economical and socio-economical forests goods and services in a similar or even better way as far-from-nature monocultures (Olsthoorn *et al.* 1999). And not only that, Norway spruce is currently one of the species most threatened by climate change in Europe as it is already grown outside its ecological optimum (Spiecker *et al.* 1996). There are numerous examples of beech stands that were replaced by Norway spruce plantations (Hahn and Fanta 2001) where the spruce is already showing signs of climatic stress (Jonard *et al*. 2011). Targeted underplanting or replacement of spruce and beech is a widely adopted method in many European countries (Ammer *et al.* 2008) since beech is a shade tolerant species and is less susceptible to the change in climatic conditions (Pretzsch and Dieler 2011). If a large scale replacement of spruce by beech were to occur, it could result in a significant alteration of biomass production, its allocation, turnover and ultimately C sequestration. Focusing on the differences in productivity and carbon cycling between spruce and beech forests is, therefore, of interest not only from an ecological but also from a policy point of view. The productivity and compartment biomass allocation in the first stages of growth are of particular interest due to a rise in the area covered by even-aged young forests in the last decade as a consequence of afforestation and salvage cuttings. Slow (woody parts of plants) and fast carbon turnover (foliage and fine roots) also plays an important role in carbon sequestration. All in all, precise allometric equation will be needed for precise monitoring of plots of different ages and composition at this time, when European beech is making a comeback on the forestry scene.

7 SUMMARY

The importance and utilization of biomass estimation was defined at the beginning of this thesis. Estimation of stem volume and tree biomass is needed for both sustainable planning of forest resources and for studies of the energy and nutrients flows in ecosystems.

Based on observations obtained by applying different allometric equations for biomass estimation onto sample set model values it was found, that not all of the used equations by different authors and from different countries are ideal for examined Štítná nad Vláří and Holíkov experimental sites. Literature review proved that the availability of suitable allometric equations is low, moreover, it became obvious that only a small number of allometric equations are applicable to estimate the biomass of beech (*Fagus sylvatica*) at studied plots. The differences between the performances of individual models can be very high. Models for biomass calculation of individual compartments of beech are available, however, only in very low numbers, especially for timber and brushwood biomass estimation. Only one equation for these compartments (Wutzler *et al.* 2008) was found even after thorough literature sources examination. According to Wutzler *et al.* 2008 and their model it was estimated that there was an increment of 33 775 kg/ha of aboveground biomass at the Štítná nad Vláří study site between 2010 and 2015. The increment at the Holíkov study site was 24 563 kg/ha for the same study period. Both experimental stands had a very different structure of diameter classes. Štítná nad Vláří study site consisted of 5 to 70 cm diameter classes and Holíkov study site the of 25 to 55 cm. From the forestry management and production point of view it is possible to estimate the amount of different sortiments according to used allometric equations. For instance, estimate the amount of stock contained in branch wood (firewood) or to make a valid decision whether the stands can be harvested or not. From an ecological point of view it is possible to convert the results into amounts of base nutrient flows and from the policy point of view information about carbon sinks and the amount of carbon sequestration is obtained. It became obvious that accurate allometric equation for European beech will be needed for precise monitoring of plots of different ages and compositions at this time its growing importance.

8 ZÁVĚR

Důležitost a využití odhadu biomasy bylo definováno na začátku této diplomové práce. Odhad objemu kmene a dřevní biomasy je potřebný pro udržitelné plánování lesních zdrojů a koloběhu živin v lesních ekosystémech.

Na základě pozorování získaných při využití rozdílných alometrických rovnic pro odhad biomasy bylo zjištěno, že všechny rovnice z různých zemí a několika autorů nejsou ideální pro použití na experimentálních plochách ve Štítné nad Vláří a na Holíkově. Na základě literárního přehledu bylo prokázáno, že dostupnost pro použití vhodných alometrických rovnic je malá, navíc je žrejmé, že pouze malé množství rovnic je použitelné pro odhad biomasy buku lesního (*Fagus sylvatica*) na experimentálních plochách. Rozdíly mezi testovanými jednotlivými modely ukázaly, že můžou být velmi vysoké. Modely pro vypočítání biomasy jednotlivých frakcí jsou pro buk lesní dostupné, ale pouze ve velmi malém množství. Zejména pro odhad biomasy větví, které mají menší průměr než 7 cm. Pro tuto frakci byla v literárních zdrojích nalezena pouze jedna rovnice, podle Wutzlera *et al.* 2008. Podle autora Wutzler *et al.* 2008 a jejich modelu bylo odhadnuto, že přírůst nadzemní biomasy na lokalitě Štítná nad Vláří činil 33 775 kg/ha mezi lety 2010 až 2015. Ve stejném studovaném období na lokalitě Holíkov byla tato hodnota 24 563 kg/ha. Oba studované porosty měly velmi odlišnou strukturu tloušťkových tříd. Na lokalitě Štítná nad Vláří se tloušťkové třídy pohybovaly od 5 do 70 cm a na Holíkově od 25 do 55 cm. Z lesnického úhlu pohledu, je možné odhadovat množství v jednotlivých sortimentech podle alometrických rovnic. Například, odhadované množství zásoby ve větvích, které se dají použít jako palivové dřevo. Může pomoci i při plánovaní lesnických prací. Z ekologického pohledu a dalšího využití je možnost, výsledky přepočítat podle koncentrací na zásoby živin. Je zřejmé, že přesnost použití alometrických rovnic pro buk lesní bude pro monitorování porostů různého věku a složení nezbytné, a bude mít v současné době rostoucí význam.

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