Comparison of Carbon Calculation Methods

MASTER'S THESIS

submitted by

Thomas Gerritzen

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Supervisor: **Univ.Prof. Dipl.-Ing. Dr.nat.techn. Hubert Hasenauer**
Co-supervisor: **Dipl.-Ing. Christopher Thurnher**

Institute of Silviculture
Department of Forest- and Soil Sciences
University of Natural Resources and Life Sciences (BOKU) Vienna, Austria

Abstract

The United Nations Framework Convention and in particular the Kyoto Protocol stress the importance of forests as carbon stocks and carbon sinks. Therefore, different methods how to estimate the carbon content of forests have been developed. With the introduction of computer aided modeling the possibility of obtaining carbon estimations from models was created. In general, there are two different approaches of how carbon calculations can be obtained. The first one is through calculation methods that use terrestrial input data. The second one is by mimicking flux cycles such as the photosynthesis cycle, which is done by mechanistic models like the BIOME-BGC model. The objectives of this study were (i) to investigate differences in carbon stock estimations obtained by four different biomass calculation methods that utilize terrestrial input data, (ii) to analyze the carbon estimations obtained by the BIOME-BGC model, and (iii) to compare the results of the calculation methods to those of the model. In order to detect general trends, the four biomass calculation methods were applied to standardized tree data sets for three major tree species growing in Austria. Furthermore, they were used to estimate the carbon stock of the Montafon study region to see if local effects have an influence on the general trends. The BIOME-BGC model was applied to the Montafon study area to estimate the carbon storage of the forests. As a last step the results of the two approaches of carbon estimation were compared. Our results show that for small trees with a DBH of up to 60 cm all four biomass calculation methods produced comparable results. For trees with a higher DBH deviations were detected for spruce (Burger function) and beech (ABF function). The application of the BIOME-BGC model and comparing the results to the results of the different calculation methods showed, that the gives realistic results for the Montafon region. Both approaches, carbon estimations generated by biomass functions or with the help of mechanistic modeling, exhibit similar results for the Montafon study area.

Keywords: carbon storage, biomass functions, BEF, BCEF, mechanistic biogeochemical modeling, BIOME-BGC, Montafon

Abstrakt

Die Bedeutung von Wäldern als Kohlenstoffspeicher und –senken wurde in den letzten Jahrzehnten hervorgehoben (Kyoto Protokoll). Daher wurden verschiedene Methoden der Biomasseberechnung entwickelt, um den Kohlenstoffvorrat von Wäldern zu bestimmen. Mit der Einführung von Simulationsmodellen wurde eine weitere Möglichkeit zur Kohlenstoffschätzung kreiert. Generell lassen sich zwei Vorgehensweisen der Kohlenstoffschätzung unterscheiden. Die Erste ist die Berechnung mit Hilfe von Biomasseschätzungen, die terrestrische Eingangsdaten benutzen. Die Zweite ist die Nachahmung von Stoffkreisläufen wie z.B. des Photosynthese Kreislaufes, welche von mechanistischen Modellen verwendet wird. Die Zielsetzung dieser Studie war (i) die Unterschiede der Ergebnisse von vier verschiedenen Biomasseschätzmethoden, die terrestrische Eingangsdaten benutzen, zu untersuchen, (ii) die Kohlenstoffschätzung des BIOME-BGC Modells zu analysieren und (iii) die Ergebnisse der beiden verschiedenen Vorgehensweisen zur Kohlenstoffschätzung zu vergleichen. Generelle Tendenzen in den Ergebnissen der vier Biomasseschätzmethoden sollten anhand standardisierter Baumdatensets verglichen werden. Der Kohlenstoffgehalt im Versuchsgebiet Montafon wurde mit den vier Methoden berechnet, um zu sehen, ob lokale Effekte die generellen Trends beeinflussen. Das BIOME-BGC Modell wurde auf die Montafon Region angewandt und die Ergebnisse der beiden Vorgehensweisen zur Kohlenstoffschätzung miteinander verglichen. Die Resultate dieser Studie zeigen, dass mit allen 4 Biomasseschätzmethoden vergleichbare Werte für Bäume mit einem BHD von bis zu 60 cm erzielt wurden. Für Bäume mit einem größeren BHD konnten Abweichungen lediglich bei Fichte (bei der Burger Funktion) und bei Buche (bei der ABF) erkannt werden. Das BIOME-BGC Modell zeigte realistische Kohlenstoffschätzungen für die Montafon Region. Die beiden Vorgehensweisen zur Kohlenstoffschätzung (Biomasseschätzmethoden mit terrestrischen Eingangsdaten vs. mechanistische Modellierung) zeigten vergleichbare Resultate für die Montafon Region.

Schlagwörter: Kohlenstoffvorräte, Biomassefunktionen, BEF, BCEF, BIOME-BGC Model, biogeochemische Modellierung

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Acronyms and Abbreviations Used

A	area
ABF	Austrian biomass function
a_n	coefficient
AFI	Austrian Forest Inventory
a.s.l.	above sea level
BCEF	biomass conversion and expansion factor
BEF	biomass expansion factor
BGC	biogeochemical
b_n	coefficient
CCF	crown competition factor
CF	carbon fraction of dry matter
cm	centimeter
c_n	coefficient
CO_2	carbon dioxide
CS	case study
DBH	diameter at breast height
dbm	dry branch mass
dm	decimeter
dnm	dry needle mass
dsm	dry stem mass
EU	European Union
e.g.	exempli gratia
H	height
IPCC	International Panel on Climate Change
m	meter
mm	millimeter
Min	minimum
Max	maximum
N	number of trees
NFI	national forest inventory
PCA	potential crown area
S.D.	standard deviation
SEE	standard error of estimates
SDI	stand density index
SMF	Stand Montafon Fund
V	volume
25.p	25. percentile
75.p	75. Percentile

1 Introduction

During the last decades, the topic of global change emerged in the scientific world. Reports by the Intergovernmental Panel on Climate Change (IPCC) try to objectify the discussion on global change. As a consequence impacts, mitigation, and the scientific basis of climate change are addressed in the IPCC reports (IPCC, 2007, 2001, 1996). Jones et al. (1999) reveal an increase in the measured average temperature on a worldwide level. Böhm et al. (2001) indicate an even higher temperature increase for the European Alps.

The United Nations Framework Convention and in particular the Kyoto Protocol stress the importance of forests as carbon stocks and carbon sinks. As changes in the forest carbon stock influence the atmospheric CO_2 concentration, the need to monitor, preserve and enhance terrestrial carbon stock is a main task to combat climate change (IPCC, 2003). Thus, forest management plays an important role in this context. European forests have a long history of management, in which sustainability has not always played such an important role as it does today. In pre-industrial times, forest management mainly served the demands of local populations. Timber production, litter raking and fuel wood extraction were common practice (Mayer, 1974). In industrial times, the use of timber and forest products increased and therefore, management practices such as tending, thinning and shelterwood cutting were developed to avoid overcutting and to ensure sustainable timber productions (Assmann, 1970). Nowadays, sustainability is defined in a much broader sense, including the concept of biodiversity, forest health, productivity, soil and water quality as well as socioeconomic benefits (Oliver, 2003). Sustainable forest management aims to ensure the production of wood products and a range of environmental services such as the protection of natural resources, the conservation of biodiversity, recreation and tourism (FAO, 2003).

Since so many factors have to be considered, more research on climate change, its mitigation and the role that forests play in this context is needed. In February 2012, the European Union (EU) launched the ARAGNE (Advanced multifunctional management of European mountain ranges) project. The aim of the project is to provide improved insight into the multifunctional management of European mountain forests (Lexer, 2013). Therefore, the capacity of current forest management regimes and possible future management alternatives are evaluated to provide portfolios of ecosystem services (ES) for mountain forests. In addition, the project includes a wide range of forest types in the major European mountain ranges. It seeks to develop and evaluate strategies for their multifunctional management under risk and uncertainty, due to changing climatic and socio-economic conditions (Lexer, 2013). Four major ES are addressed in the ARANGE project:

- Timber production
- Protection against gravitational natural hazards
- The role of forests regarding climate change mitigation via carbon sequestration as well as bioenergy production
- Nature conservation and the maintenance of biodiversity

That is why the four main pillars of the concept underlying ARANGE include:

1. Regional case studies
2. Strong stakeholder involvement
3. State-of-the-art models and tools to predict forest conditions and assess ES
4. Novel planning and decision support tools.

Regional case studies for seven different mountain regions across the continent that cover the most important forest types will be carried out. The case study regions are:

- CS 1 : Iberian mountain (Spain)
- CS 2 : Western Alps (France)
- CS 3 : Eastern Alps (Austria)
- CS 4 : Dinaric mountains (Slovenia)
- CS 5 : Scandinavian mountains (Sweden)
- CS 6 : Western Carpathians (Slovakia)
- CS 7 : Western Rhodopes (Bulgaria)

A wide array of models, tools and methods will be applied in the case studies in order to investigate the current status and to assess the space- and time-dependent interrelationships among ecosystem services and possible future developments in forest management (Lexer, 2013).

As mentioned above, carbon sequestration in forests is one important aspect investigated by the ARANGE project. However, there are different ways to estimate the carbon stock of a forest. In general, two diverse approaches can be distinguished. Carbon estimations can either be calculated based on terrestrial data, or carried out by mimicking flux cycles such as the photosynthesis cylce.

Biomass estimations can be derived from terrestrial data in two different ways. One way is to use biomass functions that are based on allometric relationships and calculate the biomass of a tree directly from its DBH. Another way to obtain carbon estimations is the use of biomass expansion factors (BEF). In this method, the merchantable timber volume is calculated with suitable tree volume functions and then multiplied with a BEF to expand the timber volume to the overall biomass of a tree (Brown, 2002). Many biomass equations and BEFs have been developed throughout the world. Zianis et al. (2005) compiled biomass and stem volume equations that use the DBH and/or height as independent variables for tree species growing in Europe. They found a total of 607 biomass estimations and 230 stem volume predictions (Zianis et al., 2005). Most biomass equations are only based on a few sample sites with a limited number of sample trees. Therefore they should only be applied to areas with comparable geographical conditions. Contrarily, volume equations are generally based on more representative data and can thus be used to calculate the tree volume of larger geographical regions (Zianis et al., 2005).

Different forest models have implemented the possibility of estimating the biomass or carbon of a forest. As different forest models are important tools in the context of carbon estimations, a look at the different kinds of models that are available is necessary. A variety of ecosystem models have been developed to reproduce, quantify and describe forest ecosystem processes (Hasenauer, 2003). Modeling describes a real world scenario in a less complex approach by including a certain level of abstraction. Therefore, a model is defined as a simplification of a much more complex reality (Shugart, 1998). Yield and growth models were the first to be developed during the last century, whereas improved technology later paved the way for computer-aided modeling. Today, we can divide forest models in population models and mechanistic models (Hasenauer et al., 2000). Whereas population models deal with individuals and describe their growth with statistical relations, mechanistic models illustrate biological, geophysical and chemical processes of a given ecosystem. Population models can further be distinguished into management models and succession models.

Management models such as MOSES (Hasenauer, 1994), PROGNAUS (Monserud et al., 1997) and SILVA (Pretzsch et al., 2002) operate on an individual tree level. They can be used to forecast the expected profit from the next harvest and to analyze previously undertaken treatments in order to gain knowledge for future decisions (Thurnher et al., 2011). As management models are parameterized by empirically driven growth and yield data, future predictions are only based on past measurements and thus, they are not designed to reproduce the effect of external drivers such as the climate (Petritsch, 2008).

Succession models such as JABOWA (Botkin et al., 1972) and PICUS (Lexer and Hönninger, 2001) include species composition of forest stands and its natural development. They are based on the idea that in gaps, created by the death of old trees, new vegetation will sprout (Shugart, 1998). Succession models are designed to describe vegetation patterns over time and thereby they simulate stand dynamics.

Key issues for this model type are the interaction between the species as well as the growth and death of single trees (Petritsch, 2008).
Both, management models and succession models follow the first approach of estimating the biomass of a forest by utilizing biomass equations that use terrestrial data.
In contrast to that, mechanistic models represent the alternative way of how carbon stocks can be estimated, which is to mimic the natural flux cycles such as the photosynthesis cycle. An example for a mechanistic model is the BIOME-BGC model, which was developed to simulate ecosystem processes of a forest stand on a daily time step (Eastaugh and Hasenauer, 2011). Within a given ecosystem the model simulates the cycling of energy, water, carbon and nitrogen (Thornton et al., 2002). Processes such as the photosynthesis, respiration and decomposition are incorporated as far as they are investigated. BGC models describe the interaction between plants and their surrounding environment and are based on the current understanding of key mechanisms (Waring and Running, 2007). The input data for BGC models consist of daily climate information together with general site conditions. Whereas management models operate on a single tree level, mechanistic models operate on a stand level. The cycling of carbon, water and nitrogen can be simulated for generalized biome types (Thornton, 1998), or for species (Pietsch et al., 2005).

The main difference between the model types is that empirical models use the current stand as input data, which leads to a realistic calculation of the initial stage of a forest. Mechanistic models, in contrasts are based on processes and their input consists of climate and site specific data. Therefore, it is an important step for simulations with mechanistic models to get to the initial stage of a forest, which then has to be validated by comparing the model output data with terrestrial data. Once the initial stage is reached, further simulations of the future can be made. For example, predicted future changes of the climate can be used to investigate the impacts that such changes could have on forests. Furthermore, mechanistic models (especially the BIOME-BGC model) can produce a variety of more than 600 output variables. Consequently, not only tree related aspects can be investigated, but also information on water, soil, nitrogen and carbon balances can all be obtained by just one model run.

1.1 Objectives and research questions

The aim of this study is to compare different carbon calculation methods, commonly used in Austria, regarding their methodological approaches and results. The specific objectives were

1. to investigate differences in carbon stock estimations obtained by four different carbon calculation methods that utilize terrestrial input data,
    a. to detect general trends, occurring when these methods are applied to species specific standardized tree data sets,
    b. to detect local effects, occurring when the methods are applied to a specific area,
2. to analyze the carbon estimations obtained by the BIOME-BGC model, and
3. to compare the results of carbon estimations based on terrestrial input data with the results of the BIOME-BGC model.

The following research questions derive from these objectives:

1. Do general trends in the results of carbon estimations become apparent if different carbon estimation methods are applied to species-specific standardized tree data sets?
2. Are those general trends influenced if the carbon estimation methods are applied to a specific region (Montafon)?
3. Can the BIOME-BGC model be used for carbon estimations in the Montafon study area?
4. Do both approaches, obtaining carbon estimations from terrestrial data or by using mechanistic model predictions, exhibit similar results?

1.2 Thesis structure

The introduction addresses the problems, objectives and research questions of this thesis. In the second part, a description of the different methods to estimate the carbon stock of a forest is given, including all relevant formula and modeling assumptions. Third, an overview of the data that were used is presented, which includes information about the standardized tree data sets and the Montafon study region. Fourth, the results of the different carbon estimation methods as well as the BIOME-BGC model results are shown. Fifth, the results are analyzed and a final conclusion is given.

2 Methods

In the following part, all methods to estimate the carbon stock of a forest that were used in this study will be described. For national forest inventories (NFI) angle count plots (Bitterlich, 1948) are usually carried out to estimate the growing stock of forest. In these angle count plots, the diameter at breast height (DBH) of all trees inside the plots is measured. Furthermore, some tree heights per plot are measured and the heights of the rest of the trees are calculated by using allometric functions derived from DBH / height relationships. These two commonly measured parameters can also be used to calculate further stand parameters such as timber volume, tree biomass or the crown competition factor (CCF).

Mechanistic models are not based on stand specific data such as DBH or tree height. They use information on climate and soil as their input. A general description of how the BIOME-BGC model works can be found in 2.3.

2.1 Stand parameters

With the measured DBH tree heights can be estimated, using DBH / height relationships. The DBH and height of each tree can then be used to calculate the tree volume. Furthermore, the DBH is used to calculate the CCF of each tree.

2.1.1 Height

As the DBH and the height of a tree are used to calculate its volume, it is essential to either measure heights or to calculate them. Some tree heights were measured and showed best conformity with the tree height function according to Prodan (Schmidt, 1956). For calculations, the allometric relationship between diameter and height is utilized.

The height of trees was calculated using the tree height function according to Prodan (Schmidt, 1956):

$$h_{Prodan} = \frac{DBH^2}{a0 + a1 * DBH + a2 * DBH^2} + 1.3 \tag{1}$$

where DBH is the measured diameter at breast height in cm and a_0, a_1, and a_2 are species specific parameter coefficients (see Table A 1 in appendix for species specific parameters).

2.1.2 Volume

The volume of each tree was calculated, using the tree volume function by Kennel (1973):

$$V_{Kennel} = DBH_i^2 * \frac{\pi}{4} * fh_i \tag{2}$$

Kennel's tree volume function is based on the calculation of a cylindrical body. But trees are no cylindrical bodies. Trees have a certain taper which mean that the diameter at the bottom of the stem is larger than the diameter of the top. Therefore, the height is adapted accordingly using the allometric relationships between DBH and height. In equation (2) the height is calculated using the function *fh(h_i)*:

$$fh_i = e^{a+b*\ln(h_i)+c*ln^2(h_i)} \tag{3}$$

$$a = a_0 + a_1 * \ln(dbh) + a_2 * ln^2(dbh) \tag{4}$$

$$b = b_0 + b_1 * \ln(dbh) + b_2 * ln^2(dbh) \tag{5}$$

$$c = c_0 + c_1 * \ln(dbh) + c_2 * ln^2(dbh) \tag{6}$$

V	tree volume (m^3)
DBH	diameter at breast height (m)
fh(h_i)	“Formhöhenfunktion”
h	height (m)
a_n,b_n,c_n	parameters, varying among different tree species
dbh	diameter at breast height (cm)

The *DBH* in meter is used for calculating the volume. In contrast to that, the *DBH* in centimeters is used for calculating parameters *a*, *b* and *c*.

The species specific parameter estimates a_n, b_n, and c_n are used to determine the tree volume, according to the volume function proposed by Kennel 1973. Table A 2 in the appendix gives the species-specific values for calculating the tree volume.

Fh(hi) is a function of

2.1.3 CCF

Due to the lack of management history of the case study region, management trends were investigated using density indicators. Density indicators like the crown competition factor (CCF) or the stand density index (SDI) are commonly used to describe density of forest stands (Hasenauer et al., 2012). The stand density affects individual tree growth and is an important indicator of growth and growing conditions. For this study the, the CCF was calculated as a measure of competition (see equation (7)). According to Krajicek et al. (1961), the CCF is the sum of the species-specific potential crown area (PCA_i) divided by the plot area (A).

$$CCF = \frac{PCA}{A} \tag{7}$$

The potential crown area is derived from open grown tree dimensions (Hasenauer, 1997) and defines the crown area of a tree at a given diameter at breast height (DBH, in cm), assuming open grown growing conditions.

$$PCA = \frac{\pi * CW^2}{4} \tag{8}$$

$$\ln(CW) = a + b * \ln(dbh) \tag{9}$$

CW stands for the crown width and is calculated using species-specific parameters *a* and *b* (see Table A 3 in appendix), according to Hasenauer (1997).

2.2 Carbon estimations from terrestrial data

For the comparison of the forest's carbon estimations, four different methods, commonly used in Austria, are used. These are:

1. the Austrian biomass functions (ABF) (Hager, 1988; Hochbichler et al., 2006, 1994; Sekot, 1982)
2. the biomass equation developed after allometric relationships as described by Burger (1953)
3. the expansion factor method described in Pietsch et al. (2005)
4. the method of estimating carbon by using a conversion and expansion factor recommended by the IPCC (IPCC, 2003)

The four methods can be divided into two categories. The Austrian biomass function (ABF) and the function developed after Burger (Burger) are biomass functions. Since they are based on allometric relationships, biomass functions calculate the biomass of a tree (or tree compartment) directly from the DBH and/or height of a tree. Allometry is the study of the relationship of body size to shape first outlined by Snell

(1892). Tree allometry establishes quantitative relations between some key characteristic dimensions of trees (usually fairly easy to measure) and other properties (often more difficult to assess) (Smith and Brand, 1983).

The BEF and BCEF method fall into the category of calculating the biomass using a biomass expansion factor. Biomass expansion factors describe the relationship between the merchantable biomass and the total biomass of a tree (Fehrmann, 2006). The merchantable biomass accounts for a large fraction of the biomass of a tree, but not for the whole. Therefore, it is multiplied with a BEF to calculate the overall biomass of a tree (Cannell, 1995).

The difference in the two methods is, that a BEF is used to expand merchantable biomass to aboveground biomass, whereas a BCEF directly expands merchantable timber volume to aboveground biomass (Skovsgaard and Nord-Larsen, 2011).

2.2.1 Austrian biomass function (ABF)

A comprehensive summary of the first biomass function that was used can be found in Hasenauer et al. (2012). It is called the Austrian biomass function (ABF) and it calculates the biomass for each tree section separately. Somehow, it is a mixed function, as the stem biomass is calculated from the stem volume, whereas the branch and foliage biomasses are calculated by allometric functions.

To obtain the total aboveground carbon the following equation is used:

$$C_{aboveground} = CF * (dsm + dbm + dnm) \qquad \textbf{(10)}$$

where *CF* is the carbon fraction of dry matter, *dsm* the dry stem mass, *dbm* the dry branch mass and *dnm* the dry needle mass. The *CF* is species specific and can be found in the appendix (Table A 4).

The *dsm* is calculated from tree volume functions and conversion factors:

$$dsm = Vol_{Kennel} * D * (1 - WC) \qquad (11)$$

where *Vol* is the volume calculated according to equation (2), *D* is the wood density and *WC* is the water content. The density and the water content are species specific and can be found in the appendix (Table A 4).

The *dbm* for broadleaf trees is calculated using equation (**12**), according to Hochbichler et al. (2006):

$$dbm = e^{(b_0 + b_1 * \ln(DBH) + b_2 * \ln(H))} \quad (12)$$

where *bo*, *b1* and *b2* are species specific parameters which can be found in the Appendix Table A 5. *DBH* is the diameter at breast height (cm) and *H* is the tree height (m).

The *dbm* and the *dnm* for needle trees are calculated using equation (13), according to Hochbichler et al. (2006):

$$dbm\ [dnm] = e^{(b_0 + b_1 * \ln(DBH))} \quad (\mathbf{13})$$

where *b0* and *b1* are species specific parameters which can be found in the appendix (Table A 6). *DBH* is the diameter at breast height (cm).

The coefficients used for the Austrian biomass function were taken from Hochbichler et al. (2006). Table 1 shows the data material and its statistical description, which was used to develop these coefficients. A DBH range for spruce from 9.2 to 43.2 cm, for pine from 5.3 to 34.8 cm and for beech from 6.6 to 52.0 cm was covered.

Table 1 Data material from Hochbichler (2006). Number (N), mean, standard deviation (s), minimum (Min), maximum (Max), 25. Percentile (25.p) and 75. Percentile (75.p) of diameter at breahst height (DBH), tree height (H), needle biomass (ND), branch biomass (BR), and needle and branch biomass (NDBR) of the sample trees.

	Norway spruce (Hochbichler et al., 2005)						
	N	mean	s	Min	Max	25.p	75.p
DBH [cm]	89	21,8	6,7	9,2	43,2	16,9	34,6
H [m]	89	21	3,8	12,2	31,2	18,5	26,3
ND [kg]	89	16,3	12,3	0,7	60,2	7	42,9
BR [kg]	82	28,9	27,1	2,3	166,7	10,6	81,6
NDBR [kg]	82	45,1	38,1	3	215,6	17,6	134,8
	Scots pine (Hochbichler and Bellos, 2005)						
DBH [cm]	23	20	8,6	5,3	34,8	12,8	25,8
H [m]	23	17,9	5,9	3,9	25,3	18,7	22,4
ND [kg]	23	5,5	4,2	0,3	16,1	2,2	9
BR [kg]	23	20,4	18,6	0,9	70,5	6	28,5
NDBR [kg]	23	26,9	22,6	1,2	86,6	8,2	38
	Beech (Hochbichler, 2005)						
DBH [cm]	36	20,8	11,5	6,6	52	9,9	28,7
H [m]	36	23,4	10,3	9	40,1	12,7	30
BR [kg]	36	54,4	73,2	0,8	304,7	4,1	78,2

Table 2 shows the coefficients and standard deviations of the model that were utilized to calculate the needle and branch compartments.

Table 2 Coefficients developed by Hochbichler (2006) for the needle (ND) and branch (BR) compartment with number of trees (N), regression coefficients (S.E. standard error), coefficients of determination, standard error of estimates (SEE), the biometric estimator ($c=e^{SEE2/2}$), arithmetic mean of the ratios between observed mass and estimated mass (U), standard error of those rations (s); weighted average of the ratios between observed mass and estimated mass ($U_{weighted}$) [* P < 0.001, ** P < 0.01, * P < 0.05, n.s. not significant]**

Species	Biomass compo-nent [kg]	N	Const (S.E.)	LnDBH [cm] (S.E.)	LnH [m] (S.E.)	R²	SEE	C	µ ± s	µweighted
Spruce	ND	89	-6,17165 ***	2,83519 ***		0,83	0,3889	1,0785	1,0801 0,3295	0,9954
	BR	82	-5,1689 ***	2,69049 ***		0,93	0,2255	1,0258	1,0251 0,231	0,9619
Pine	ND	23	-3,78862 ***	1,78458 ***		0,91	0,2818	1,0405	1,0359 0,2896	1,0334
	BR	23	-3,34766 ***	2,04663 ***		0,93	0,2775	1,0393	1,0345 0,2672	1,0625
Beech	BR	36	-3,54015 ***	3,93514 ***	-1,59363 **	0,91	0,4957	1,1307	1,1106 0,5222	1,0202

2.2.2 Burger function (Burger)

These biomass functions are based on the allometrics developed by Burger (1953) who researched tree allometrics for many species in Switzerland.

In this approach, the biomass of each tree compartment is calculated separately. To calculate the total aboveground carbon content, the biomasses of each compartment are summed up and multiplied with the carbon fraction of the dry matter.

Thus, the equation of the total aboveground carbon is:

$$C_{aboveground} = CF * (dsm + dbm + dnm) \qquad \textbf{(14)}$$

where *CF* is the carbon fraction of the dry matter, *dsm* the dry stem mass, *dbm* the dry branch mass and *dnm* the dry needle mass. The *CF* is species specific and can be found in the appendix (Table A 4).

The biomass of the stem and of the branches is calculated with the following equation:

$$dsm[dbm] = a * DBH^b \qquad \textbf{(15)}$$

where *a* and *b* are species specific coefficients (see annex

$$C_{aboveground} = (Vol_{Kennel} * D * BEF2) * \ CF \qquad (18)$$

Table A 8 for stem and Table A 9 for branches) and *DBH* is the diameter at breast height in cm.

The foliage biomass is calculated with the following equation:

$$dnm = a * b * c * DBH^d \qquad \textbf{(16)}$$

where *a*, *b*, *c* and *d* are species specific coefficients that can be found in the annex (Table A 10) and *DBH* is the diameter at breast height in cm.

2.2.3 Biomass expansion factor (BEF)

The approach of the expansion factor method, as described in Pietsch et al. (2005), is different than the allometric function approach, since an expansion factor is used to compute the overall volume of the woody biomass (stem and branches) from the merchantable biomass (*dsm*). However, the formula does not include foliage and thus, to be able to compare the results of the different functions, the biomass of the needle and leaf compartment is calculated using equation (**12**).

The stem biomass (*dsm*) is calculated according to equation (**11**). The aboveground carbon content is then calculated using equation (17):

$$C_{aboveground} = \frac{dsm * CF}{MT} + dnm * CF \tag{17}$$

where *dsm* is the dry stem biomass, *dnm* the dry needle mass, *CF* the carbon fraction of the dry matter (see appendix, Table A 4). *MT* is the merchantable timber fraction which is species specific and can be found in the appendix (Table A 4). The ratio of merchantable timber to whole tree timber is used to expand the merchantable volume to the overall volume of the wooden part of the tree.

The coefficients for spruce were taken from Hager (1988). His study was based on 80 sample trees of a young growth spruce forest stand with a mean DBH of 6.09 cm and a range from 5.81 to 6.43 cm.

For pine the coefficients were taken from Sekot (1982). He based his research on 20 sample trees of which 6 trees had a DBH of less than 6 cm, 5 trees a DBH between 7 and 10 cm, 5 trees a DBH between 11 and 14 cm, 3 trees a DBH between 15 and 18 cm and one tree a DBH higher than 19 cm.

2.2.4 Biomass conversion and expansion factor (BCEF)

The IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003) suggests to use a biomass conversion and expansion factor. According to this approach, the merchantable stem biomass is calculated by using equation (2) to calculate the stem volume which is than multiplied with a biomass conversion and expansion factor (BCEF) to get the total aboveground biomass (including stem, branches and needle/leafs). The carbon stored in the aboveground biomass is then calculated using equation (18):

$$C_{aboveground} = (Vol_{Kennel} * D * BEF2) * CF \tag{18}$$

where the volume (*Vol*)(see Equation (2) is multiplied with the basic wood density (*D*) to get the dry biomass of the merchantable timber. Then the biomass expansion factor (*BEF2*) is used to convert the merchantable biomass to aboveground biomass. The amount of the total biomass is then multiplied with the carbon fraction of dry matter (*CF*) to get the carbon stock. The values for *D*, *BEF2* and *CF* can be found in the appendix (Table A 7). *CF* has a value of 0.48 for broadleaf species and 0.51 for conifers (default value is 0.5) (IPCC, 2003). The *BEF2* is assigned in relation to the climatic growing region. The IPCC recommends to use regional or national specific parameters when they are available (IPCC, 2003). Table 3 presents an overview of the *BEF2* values and their respective ranges. In this study, the suggested default values which differ from 1.3 in temperate conifer forests to 1.4 in temperate broadleaf forests were used, because the forests stands were neither young growth (upper value of the range), nor natural or old growth forests (IPCC, 2003).

Table 3 Values for biomass expansion factor (BEF) suggested by the IPCC; minimum diameter at breast height (DBH), biomass expansion factor for expanding merchantable timber to aboveground biomass (BEF 2)

climatic zone	forest type	minimum DBH [cm]	BEF 2 (overbark)
Boreal	Conifers:	0 - 8,0	1,35 (1,15 - 3,8)
	Broadleaf	1 - 8,0	1,35 (1,15 - 4,2)
Temperate	Conifers:		
	Spruce-fir	0 - 12,5	1,3 (1,15 - 4,2)
	Pines	1 - 12,5	1,3 (1,15 - 3,4)
	Broadleaf	2 - 12,5	1,4 (1,15 - 3,2)

Note: BEF2s given here represent averages from growing stock or age, the upper limit of the range represents young forests or forests with low growing stock; lower limits of the range approximate nature forests or those with high growing stock. The values apply to growing biomass (dry weight) including bark and for given minimum diameter at breast heights; Minimum top diameters and treatment of branches is unspecified. Result is above-ground tree biomass.

Sources: (IPCC, 2006)

2.3 Biogeochemical mechanistic modeling

One of the carbon estimation methods that are analyzed in this study is the BIOME-BGC model as a representative of biogeochemical mechanistic modeling. It is interesting to see if the model provides accurate carbon estimations for the study area, because the use of such a mechanistic model holds several advantages over the use of the other carbon estimation methods. One of the benefits of mechanistic modeling is that the labor intensive recording of forest inventory data becomes obsolete. Another plus is that, besides carbon estimations, around 600 additional output variables can be produced by the model in just one simulation. The fact that possible future climate change effects can also be predicted with this approach contributes to its added value. These aspects indicate that the BIOME-BGC model is a useful diagnostic tool.

In this section, a general description of the BIOME-BGC model, its principal of operation as well as its general input can be found. More specific input data are presented in 3.3.

2.3.1 BIOME-BGC model

The model follows the second approach of obtaining carbon estimations, which is to mimic flux cycles such as the photosynthesis cycle. This study used the Austrian version of the Biome-BGC model. The Biome-BGC model was originally developed by Thornton (1998) and Thornton et al. (2002). It is based on the Forest-BGC model by Running and Coughlan (1988). The adapted version includes a species-specific parameterization for major European tree-species (Pietsch et al., 2005), a dynamic mortality routine to simulate virgin forests (Pietsch and Hasenauer, 2006) and thinning routines (Pietsch and Hasenauer, 2002). The Austrian version of the Biome-BGC has been used for several studies in central Europe (Eastaugh et al., 2011; Hasenauer et al., 2012; Merganičová et al., 2012, 2005; Pietsch et al., 2003).

The daily simulations calculate (Pötzelsberger, 2008):

- daily canopy interception, evaporation and transpiration
- soil evaporation, outflow, water potential and water content
- leaf Area Index (LAI) (m^2 leaf area per m^2 ground area)
- stomatal conductance and assimilation of sun-lit and shaded canopy fractions
- Gross Primary Production (GPP) and Net Primary Production (NPP)
- allocation of carbon and nitrogen to the different ecosystem compartments (soil, litter, roots, stem, leafs)
- litter-fall and –decomposition
- mineralization, denitrification, leaching, and volatile nitrogen losses.

In the BGC model the Leaf Area Index (LAI, m² leaf area/m² ground area) controls canopy radiation absorption, water interception in the canopy, photosynthesis and litter inputs to the detrital pools and is calculated by multiplying the carbon, that is allocated to the leaves, times the specific leaf area (m² leaf area/kg leaf carbon) (Pietsch et al., 2005).

The photosynthesis is calculated with the Farquhar photosynthesis routine (Farquhar et al., 1980) and results in the gross primary production (GPP). The net primary production (NPP) is calculated by subtracting the autotrophic respiration form the GPP. The autotrophic respiration comprises maintenance respiration and growth respiration. The former is a function of tissue nitrogen concentration, the latter a function of the amount of carbon allocated to the different plant compartment (leaf, roots and stem). The NPP thus, shows the amount of carbon that is fixed per square meter ground per year (kg C $m^{-2}yr^{-1}$). It is partitioned into the leaves, roots and stems as a function of dynamic allocation patterns, considering possible limitations regarding the availability of nitrogen (Pötzelsberger, 2008). The total ecosystem carbon storage is composed by the balance between the NPP and the heterotrophic respiration. The latter is regulated by decomposition activity, the seasonal input of vegetation biomass into litter and soil organic matter pools as well as the annual mortality rate (Pietsch and Hasenauer, 2006)

2.3.1.1 Input data

The input data for the BIOME-BGC model include: daily meteorological data, atmospheric (CO_2 content, nitrogen deposition) and soil characteristics, geographic location and eco-physiological parameters of the vegetation/tree species. For the spin-up run very low starting values of carbon in the ecosystem were provided, as they are necessary for the self-initialization procedure. The water input is taken from precipitation. The specific input data for this case study are further explained in sections 3.2 and 3.3.

2.3.1.2 Simulation

The simulation is carried out in two steps. First the spin-up run needs to be conducted. After that, historic land use and management need to be taken into consideration.

2.3.1.2.1 Spin-up

The goal of the spin-up is to achieve a steady state in the temporal averages of all ecosystem pools (Pietsch and Hasenauer, 2006). For the spin-up run the extension of Pietsch and Hasenauer (2006) for self-initialization with improved mortality assumptions was used. In this approach the mortality follows an elliptical function with a longer period of low mortality, followed by a shorter period of high mortality. A low carbon content of 1 g m^{-2} and a soil water saturation of 50% were used as starting values, whereas all other ecosystem pools were set to zero (Eastaugh et al., 2011). During the simulation, organic matter is accumulated in the different ecosystem pools and the spin-up run ends when the temporal average of soil carbon content does not change by more than 0.0005 kg C m^{-2} between two successive simulation periods. Depending on the respective ecosystem type, site and climate conditions this can take 3,000 to 60,000 years (Pietsch and Hasenauer, 2006).

The tree species for the spin-up run needs to be selected in relation to the natural potential vegetation in the investigated area. In the case study region anthropogenic influence was low, no clear cuts and no planting had taken place. As a result, we assumed that the current vegetation corresponds to the potential natural vegetation. Accordingly, the parameterization of “Highland Norway Spruce” with an elliptical mortality was used for the simulation in this study. In our case, the value of the annual low mortality rate of vegetation biomass was set to 0.74 % and lasted 225 years and the high annual mortality rate of vegetation biomass had a value of 6.0 % and lasted 75 years (according to (Pietsch and Hasenauer, 2006)). Consequently, one complete mortality cycle lasted 300 years. The self-initialization took 4,500 to 7,200 years in this simulation, depending on the plots.

At the end of the self-initialization procedure, the ecosystem potential of a fully stocked forest without any human interference was given. Since the ideal virgin forest is not very homogenous and different succession stages can be found over time, the average of the last completed mortality cycle was calculated to get the value of the potential carbon stock.

2.3.1.2.2 Historic land use

After the spin-up run is completed, the historic land use needs to be integrated in order to address potential changes in the carbon pool caused by management. Today’s forests usually do not represent virgin forests. In Central Europe the use of forests in various ways has a long history, which becomes visible in the reduction of forest-covered land area, changes in forest species distribution and soil condition (Spiecker, 2002). Land use practices like logging, litter raking, pruning for fodder production and firewood as well as livestock grazing were common practice and interfered with the natural state of ecosystems over several centuries (Pötzelsberger, 2008). A reduction in site-productivity developed as a result of the loss of carbon and nutrients (Pietsch and Hasenauer, 2002).

The historic land use should be considered as precise as known to get unbiased model predictions. Each rotation period starts with a clear cut, followed by the planting of new trees (Pietsch and Hasenauer, 2002).

2.3.1.2.3 Thinning

Not only historic land use, but also current management activities influence the state of forest ecosystems. This has to be considered in order to be able to compare the model output with the observed values. Thinning interventions can be simulated with a sub-module for the BIOME-BGC model (Pietsch and Hasenauer, 2002). A thinning intervention can be defined by the user, who can i.e. set up the amount or percentage of stem carbon removal, leaf carbon removal, stem carbon that is left in the forest and is transferred to the coarse woody debris carbon compartment and many other settings effecting the carbon content of the different pools (i.e. coarse woody debris, litter pool etc.)

2.3.1.3 The BGC model output

The BIOME-BGC model produces more than 600 output variables which can be given in a yearly, monthly, weekly or daily time step. The following variables were selected for this study: live stem carbon, dead stem carbon and leaf carbon. The dead stem carbon represents the inner part of the tree, not the deadwood. The live stem carbon represents the living part of the stem like the cambium and the leaf carbon represents the carbon stored in the leaves (needles). By summing these three variables up, the aboveground carbon content that is stored in the wooden part of the stem, branches and foliage, is calculated. The output is given in kg C m^{-2} yr^{-1}.

3 Data

The tree diameter distribution of uneven-age forests naturally follows a reverse J-shape (Prodan, 1953). This means small diameter classes have a high number of trees, whereas large diameter classes are only represented by a small number of trees. To equalize this imbalance, standardized tree data sets were generated, in which each diameter class had nearly the same number of trees (see 3.1). This was done in order to avoid biased results which otherwise might be given due to the small number of trees in high diameter classes. For each of the three main tree species growing in Austria such a standardized tree data set was created. These standardized trees data sets were used to detect general trends in the results of the four different ways of how carbon stocks are calculated from terrestrial data.

In order to see if local conditions influence these general trends, original data from sample count plots measured during the forest inventory of the Montafon area was utilized (section 3.2.).

Since angle count plot sampling under-represents small diameter trees, the number of trees for small diameter classes needs to be multiplied with the corresponding representative number of trees (N_{rep}) to obtain realistic results per hectare, which reflect the natural J-shape. It is necessary to get such results to be able to compare the carbon estimations of the model with those of the methods using terrestrial data on area level. To do so, a third data set was generated which represents the natural distribution of trees and weights the diameter classes accordingly (see Table7).

3.1 Standardized tree data sets

Standardized tree data sets for three of the main Austrian tree species, Norway spruce, Scots pine and European Beech were generated. 50 trees per DBH class were randomly selected from the Austrian national forest inventory (NFI). Each DBH class has a range of 5 cm (5-10, 10-15 etc.). The number of trees in higher DBH classes was sometimes smaller, because fewer trees with such high DBHs were available.

Table 4 shows the number of trees, their mean, minimum, maximum DBH and height as well as the standard deviation of the means for each tree species.

Table 4 Number (N), mean, standard deviation (s.d.), minimum (min) and maximum (max) of diameter at breast height (DBH) and tree height (H) of the trees recorded in the study area

Species	DBH [cm]					H [m]			
	N	mean	s.d.	min	max	mean	s.d.	min	max
Spruce	1097,0	60,3	32,7	5,0	134,0	27,2	10,0	3,0	49,0
Pine	628,0	36,2	18,1	5,0	69,8	20,6	7,4	4,0	40,3
Beech	958,0	52,9	28,0	5,0	109,7	23,8	8,0	3,2	41,7

The data set contained 1097 trees of spruce with a DBH range from 5 cm to 134 cm, with a mean of 60 cm. The height of the trees ranges from 3 m to 49 m, while the mean height was 27 m. The 628 analyzed pine trees had a mean DBH of 36 cm and range from 5 cm to 70 cm. The minimum height of the pine trees was 4 m, while the maximum height measured 40 m. This leads to a mean height of about 21 m. 958 trees of beech were used with a mean DBH of 53 cm and a range from 5 cm to 110 cm. Their height range varied from 3 m to 42 m with a mean height of 24 m.

3.2 Montafon study region data

The Montafon region is part of the ARANGE project, in which it serves as the case study area for Austria. In this study, the Montafon region was used to see if local attributes of forests affect the outcomes of the carbon estimations using terrestrial data. Further the BIOME-BGC model was applied to this region to obtain carbon estimations for the forests, which were then compared with the estimations derived from the four methods using terrestrial data.

In the following section, general information about the case study area as well as forest specific data are presented.

3.2.1 Montafon

The Montafon region is located in the Northern Alps, in the state of Vorarlberg, which is the most western province of Austria (see Figure 1). The valley floors are densely populated and the forests serve multipurpose functions. Tourism is the most important source of income in this region. The forest area comprises 6470 ha. The main characteristics of the forested area are:

- 595-1900 m a.s.l
- average temperature: 8-1 °C
- average annual precipitation: 1300-1500 mm
- species distribution of 96% Norway spruce, 3% Silver fir and 1% others
- mean annual increment of 5.9 m^3/ha
- average annual cut of 18,000 m^3

The Stand Montafon Forstfond (SMF) is the largest forest owner in the province Vorarlberg. Public land use has a long tradition in the Montafon region. The inhabitants chartered the right to use non-public forests as a source of timber and fuelwood since 1601 AD. Until 1832, the state held the ownership. After that, 8 municipalities purchased around 8,000 ha from the emperor and the SMF was founded. Nowadays, the SMF owns 8,474 ha land of which 6,470 ha are forested area. Operational management is done by foresters, strategic management by representatives of the eight majors of the municipalities (Maier, 2007).

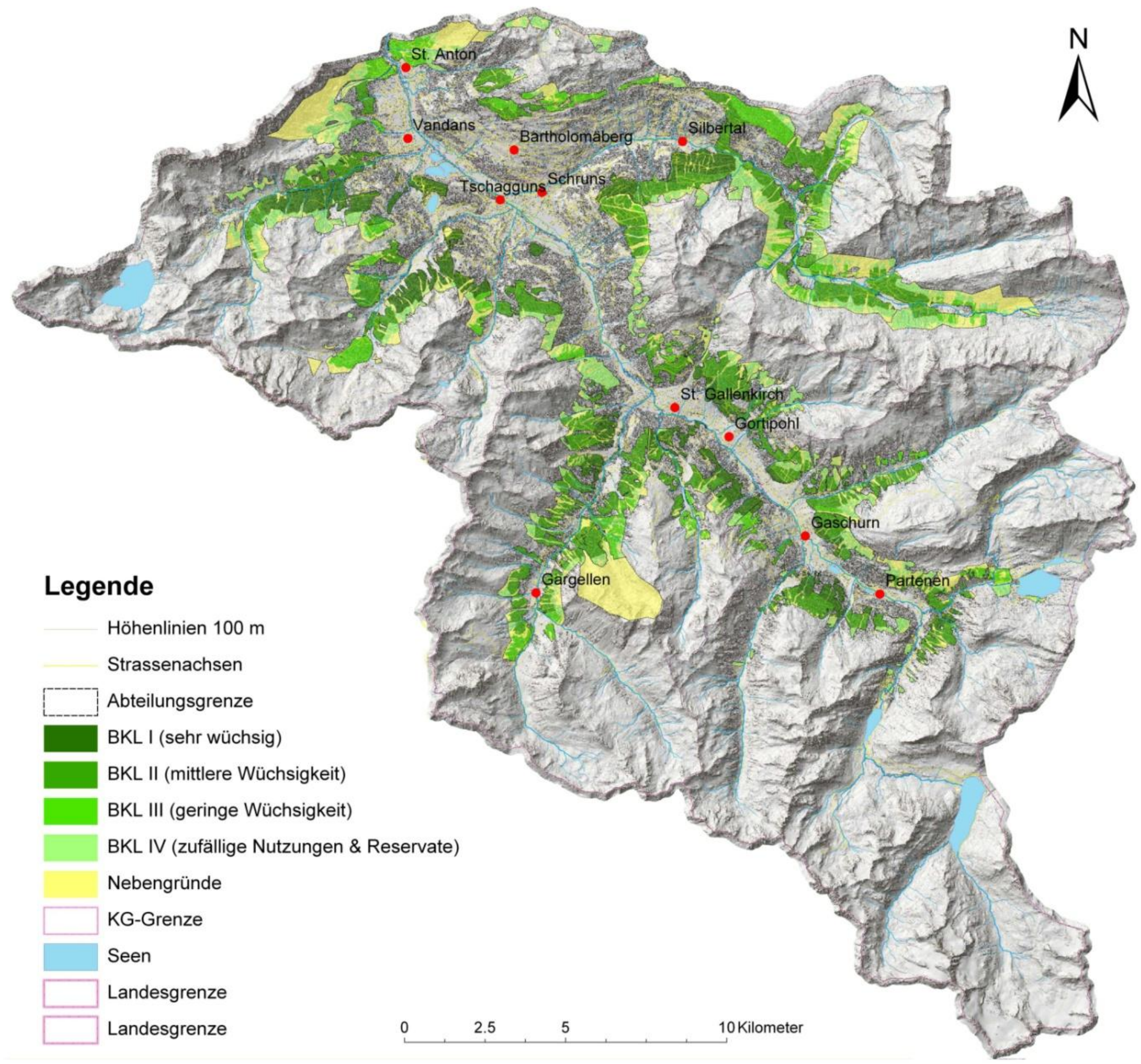

Figure 1 Map of the Montafon study region (source: Forstfond Stand Montafon (2013))

For this study, information on the stands, including stand and site characteristics, have been delivered by Michael Maroschek through the ARAGNE project. Angle count sampling (Bitterlich, 1948) was used in the inventory process. The forest inventory data are available for 53 stands of which the DBH and the height of the trees were measured. At least 5 angle plot counts were taken per stand. The statistics of the measured trees can be seen in Table 5.

Table 5 Number of trees (N), mean, standard deviation (s.d.), minimum (min) and maximum (max) of the DBH and height per tree species of the Montafon case study region measured in the inventory process

Species		DBH [cm]				Height [m]			
	N	mean	s.d.	min	max	mean	s.d.	min	max
Spruce	818	56.1	22.1	3.5	120.5	30.3	10.0	2.0	49.1
Fir	123	64.2	15.0	16.5	92.5	32.1	7.0	9.0	44.0
Beech	53	35.3	13.7	10.5	74.5	18.6	6.4	6.9	35.9
Sycamore maple	20	47.9	33.6	4.0	117.5	13.8	4.8	5.0	25.3
Black alder	11	10.2	6.0	3.5	23.5	8.1	3.0	3.5	12.0
Rowan	2	23.5	1.4	22.5	24.5	10.6	2.1	9.1	12.0
Aspen	2	35.0	10.6	27.5	42.5	11.0	2.8	9.0	13.0
Grey alder	1	23.5				11.0			

In the Montafon case study forests, spruce is the dominating species. In the inventory process, 818 spruce trees were measured. The DBH has a mean of 56.1 cm and the mean height is 30.3m. For fir, 123 trees were recorded and the mean DBH and height were slightly higher (with 64.2 cm and 32.1 m respectively) compared to spruce. Only 53 beech trees were measured. The mean DBH was 35.3 cm and the mean height measured 18.6 m. The number of trees for other broadleaves in the Montafon forests was very low, only 20 Sycamore maple, 11 Black alder, 2 Rowan, 2 Aspen trees and 1 Grey alder were found.

3.3 Input for BIOME-BGC

In this part, specific input data on climate, sites and stands which was used to apply the BIOME-BGC model to the Montafon region are presented.

3.3.1 Weather data and other atmospheric characteristics

In order to run the BIOME-BGC model, daily climate input such as the minimum and maximum temperature, precipitation, short wave radiation and the vapor deficit are needed. For the ARANGE project, climate files for each case study area were generated. Thus, the climate files from the ARANGE project for the case study area 3 (Eastern Alps) were used in this study, because our forests stands are located within that area. In the following, the procedure on how these climate files were generated and a table containing all relevant climate information are presented.

First, a 100 year baseline climate was generated with weather station data and E-OBS grid points. Available weather data from 1961 to 1990 served as the basis to generate a 100 year time series, using the stochastic weather generator LARS-WG (Racsko et al., 1991; Semenov and Barrow, 1997). The generated records consist of 365 days per year, as leap years were not considered (Thurnher, 2013).

Second, to adopt the baseline climate for the altitudinal zones, slopes and aspects, the program MT-CLIM (Running et al., 1987; Thornton and Running, 1999) was used. This program further estimated the average solar radiation of the daylight period and the vapor pressure deficit (Thurnher, 2013).

The generated climate records include:

year:	year (1 - 100)
yday:	day of the year (1 - 365)
Tmax:	maximum temperature [°C]
Tmin:	minimum temperature [°C]
Tday:	daylight temperature [deg C]
prcp:	precipitation [cm]
VPD:	vapor pressure deficit [Pa]
srad:	solar radiation [W/m2] according to Thornton et al. (2000)
daylen:	length of the day [s]

The input record for the climate was assigned to each point according to the site characteristic aspect, slope and altitude. From these characteristics the corresponding baseline file for the climate data was chosen for each point.

The CO_2 content for the spin-up run was set to an atmospheric CO_2 concentration of 280ppm (IPCC, 1996). After 1765 onwards, the CO_2 concentration was annually increased to present-day levels. To achieve this, the CO_2 file “IS92a.dat”, which contains all the necessary data, was used.

The pre-industrial nitrogen deposition value of 0.45 g m^{-2} yr^{-1} was assumed (Ulrich and Willot, 1993) and increased at the same rate as the CO_2 concentration to an actual value of 2.7 g m^{-2} yr^{-1}.

Table 6 Elevation, aspect, inclination, mean maximum temperature (Tmax), mean minimum temperature (Tmin), mean daily temperature (Tday), mean yearly precipitation (prcp), mean vapour pressure deficit (VPD), mean solar rediation (srad), mean daylenght (daylen) of the different used climate files

met row number	elevation [m]	aspect	inclination [deg]	Tmax [deg C]	Tmin [deg C]	Tday [deg C]	prcp [mm]	VPD [Pa]	srad [W m-2]	daylen [sec.]
1	1300	north	25	8.43	0.69	6.30	1448	372.42	219.89	43200
2	1300	north	35	8.43	0.69	6.30	1448	372.42	201.64	43200
3	1300	south	25	8.43	0.69	6.30	1448	372.42	290.91	43200
4	1300	south	35	8.43	0.69	6.30	1448	372.42	292.78	43200
5	1650	north	25	6.36	-0.89	4.37	1540	315.15	235.90	43200
6	1650	north	35	6.36	-0.89	4.37	1540	315.15	217.00	43200
7	1650	south	25	6.36	-0.89	4.37	1540	315.15	310.55	43200
8	1650	south	35	6.36	-0.89	4.37	1540	315.15	312.75	43200

Table 6 shows the data of the climate files that were used for the stands in the Montafon case study. According to the elevation, the aspect, and the inclination, the climate files were assigned to each stand. Tmax is the average maximum temperature and Tmin the average minimum temperature. Tday is the average daily temperature. Prcp is the average annual precipitation, VPD the vapour pressure deficit. Srad represents the solar radiation and daylen stands for the average day length.

With increasing elevation, all three temperature values (Tmax, Tmin, Tday) and the vapour pressure deficit decreased, whereas the precipitation increased. Within each elevation group these values do not differ. The solar radiation has different values for each climate file, whereas the day length is the same for all files.

This shows that elevation has more influence on the climate files than the aspect or inclination, since most values for each elevation group stay the same.

3.3.2 Site specific parameters

The site characteristic parameters are additional input information to run the BIOME-BGC model. These specific parameters are the latitude, albedo, soil texture (the relative share of sand, silt and clay), effective soil depth (real soil depth reduced by the volume percentage of soil particles < 2 mm) and nitrogen fixation (kg m^{-2} yr^{-1}). The value of nitrogen fixation was set to 0.3 g N m^{-2} yr^{-1}. The albedo value depends on the land cover type and is usually set to 0.2 for coniferous forests (Pötzelsberger, 2008).

The numbers for nitrogen deposition were interpolated from a 1 km² nationwide raster of nitrogen deposition in 1995 (Schneider, 1998).

Data on soil were interpolated from the Austrian National Forest Soil Survey (WBZI; (Englisch et al., 1992). The numbers were taken from locations that are systematically distributed across the whole of Austria. For each location the longitude, latitude, elevation, slope, and aspect plus the soil characteristics for up to ten horizons were recorded. Originally, particle sizes were classified in 6 classes with a given percentage. For this study, however, they were reclassified to obtain sand, silt, and clay content as well as rock fraction. The effective soil depth was calculated by correcting the measured soil depth for the calculated rock fraction (Petritsch, 2008).The soil texture is expressed as a percentage of the soil fraction (sand, silt, clay). In addition, the interpolated soil fractions must add up to a total of 100% for each location.

Table 7 shows an overview of the site specific parameters for the Montafon region. Statistics of trees were produced with the inventory data presented in 3.2.1. A tree data set for the Montafon region was generated with the number of representative trees (N_{rep}). N_{rep} derives from the assumption that each tree with a DBH higher than 10.4 cm that was recorded in the inventory represents a basal area of 4 m², as in Austria a basal area factor of 4 is used within angle count sampling (Bitterlich, 1948). Therefore, the measured sample trees were multiplied with the N_{rep} to generate the amount of trees with the same DBH over the whole stand. The data set contained a total of 96,668 trees over all 53 stands. The mean DBH in the study region was 23 cm, with a standard deviation of 22 cm, a minimum of 3 cm and a maximum of 134 cm. 50% of the trees had a DBH between 7cm and 38 cm. The volume varied between 18 and 1125 m³ ha^{-1} with a mean of 448 m³ ha^{-1}.

The elevation of the stands ranges from 1151 m to 1752 m, with a mean of 1452 m. The average stand size was 4 ha and ranged from 1 ha to 11 ha. The mean share of sand was 17.89%, that of silt 40.91% and that of clay 41.20%. The effective soil depth was 46 cm on average. Due to the interpolation of the latter four, the deviation was very low.

Table 7 Mean, standard deviation, minimum (min), maximum (max), 25. percentile (25.p) and 75. percentile (75.p) of elevation, stand size, age, diameter at breast height (DBH), height, standing volume (Volume), crown competition factor (CCF), percentage of sand, silt and clay as well as effective soil depth in the study region Montafon

Stand characteristics	Dominating species: Norway Spruce (Picea abies)					
	mean	standard deviation	min	max	25.p	75.p
Elevation [m]	1452	163	1151	1752	1324	1556
Stand size [ha]	3.99	2.02	0.99	11.14	2.55	5.55
Age [years]	53	55	5	365	11	87
DBH [cm]	23	22	3	134	7	38
Height [m]	15	12	2	47	5	25
Volume [m3 ha -1]	448	264	18	1125	265	605
CCF	121	62	8	321	80	160
Sand [%]	17.89	0.08	17.75	18.06	17.83	17.94
Silt [%]	40.91	0.02	40.85	40.95	40.89	40.93
Clay [%]	41.20	0.09	41.00	41.37	41.15	41.26
Effective soil depth [m]	0.46	0.02	0.43	0.51	0.45	0.48

3.3.3 Eco-physiological parameters – Species specific parameterization

Species-specific parameters are needed as input data. For this study, the species-specific parameterization of the main Central European tree species of Pietsch et al. (2005) was applied. When simulating further treatments, the potential natural vegetation is relevant for the spin-up run, since the dominant species of a stand is the indicator for the selection the according file. As far as the Montafon region is concerned, the natural potential vegetation and the current vegetation require the use of the parameterization of “Highland Norway Spruce” for this study.

4 Results

In this part of the study, the results are presented. First, the results of the different ways how to estimate carbon from terrestrial input data are shown, regarding their application to a standardized tree data set. Second, the results of the application of these methods to the Montafon forest inventory data set are displayed. The third part contains the results of the model application to the Montafon region and the results of the comparison between those model carbon estimations and the estimations of the derived from terrestrial input data.

4.1 Carbon estimations for standardized tree data set

For the general comparison of the different methods that are utilized to calculate the aboveground carbon storage of forests (see section 2.2) a generated standardized tree data set was used (see section 3.1). The four methods using terrestrial input data that were analyzed are the:

- Austrian biomass function (ABF)
- Biomass function after Burger (Burger)
- Biomass expansion factor method (BEF)
- Biomass conversion and expansion factor method (BCEF)

4.1.1 Norway spruce

The aboveground carbon for each individual tree was calculated and plotted against the DBH in Figure 2. The numbers showed that all four methods, using a biomass function or a BEF, displayed results that were similar to each other until a DBH of 40 cm. The deviation in between the results of each method got bigger with an increasing DBH for all method, except the Burger function. The spread was higher for the two methods that use expansion factors (BEF, BCEF) than for the ABF. With an increasing DBH the differences between the different methods got also bigger. The Burger function showed higher results than the three other methods, while the results of the ABF, BCEF and BEF method overlapped over the whole DBH range.

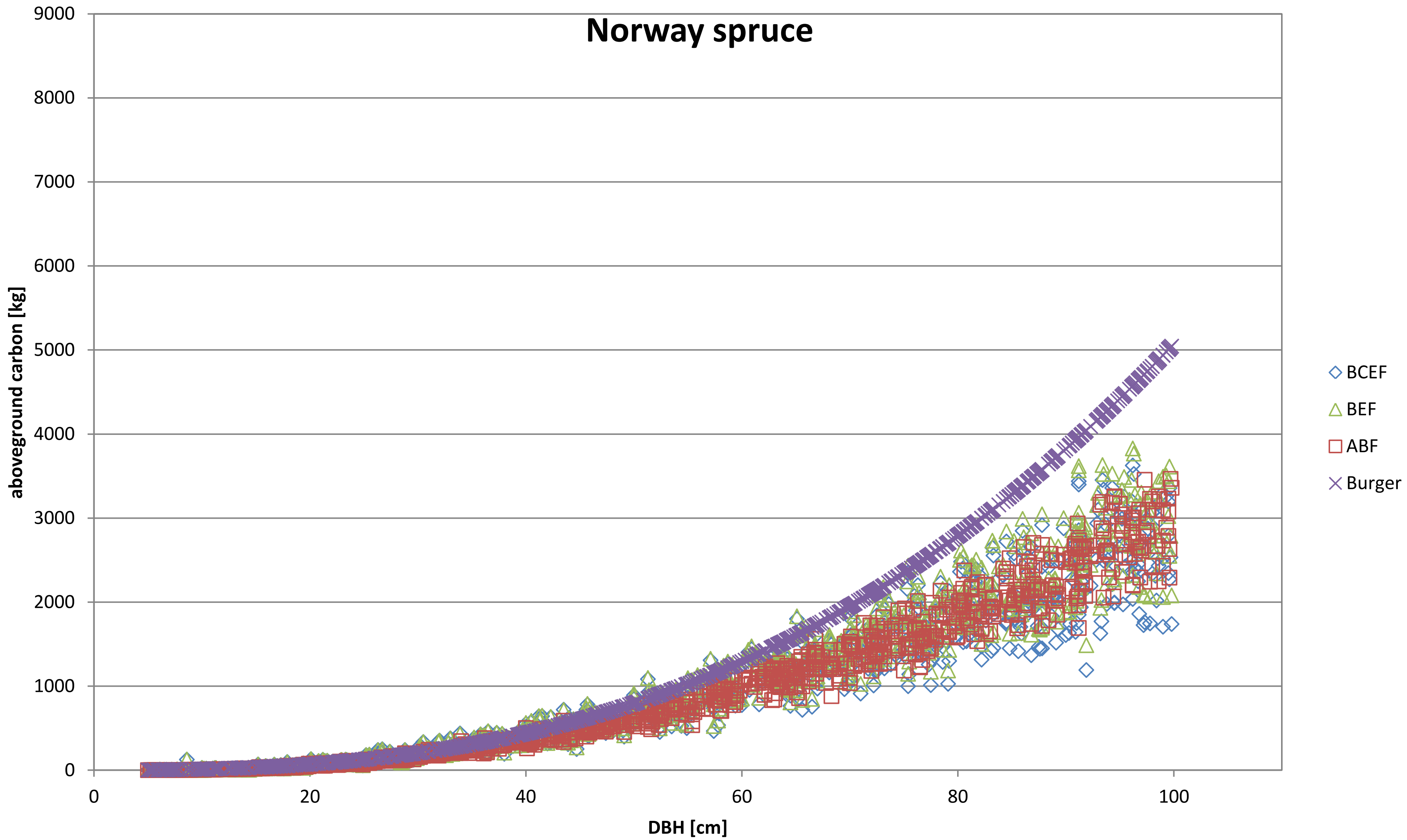

Figure 2 Carbon estimations for each tree of the standardized spruce tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

Furthermore Figure 2 shows, that if the DBH was 60 cm or above, the Burger function almost always showed the highest results. For a tree with an 80 cm DBH the results of the ABF, BCEF and BEF method ranged between 1,000 kg and 2,200 kg aboveground carbon, whereas the Burger function calculated a value of 2,700 kg for that tree. For a tree with a DBH of 100 cm the Burger function gave a value of 5,000 kg aboveground carbon, while the other three methods nearly showed results between 1,700 and 3,500 kg.

In Figure 3 the trees were compiled into DBH classes of 5 cm steps. The average aboveground carbon value of each function was calculated for each DBH class. The x-axis shows the average of the DBH class and the y-axis the aboveground carbon value in kilogram.

Here, the same trend as above became visible. Until a DBH class of 40 cm to 45 cm all four methods displayed similar results and after the DBH class of 60 cm to 65 cm the Burger function gave values that were above the values of the other three methods.

In the highest DBH class (95 to 100 cm), the Burger functions gave a value of around 4,700 kg aboveground carbon for the average tree of that DBH class, whereas the result of the BCEF method was 2,900 kg, the result of the ABF 2,800 kg and the one of the BEF method 2,600 kg aboveground carbon. Thus, the difference between the Burger function and the BEF method was 2,100 kg or, the value given by the Burger function was 1.8 times higher than the one of the BEF method. Compared to the ABF and the BCEF method, the value calculated with the Burger function was 1.67 times and 1.62 times higher, respectively.

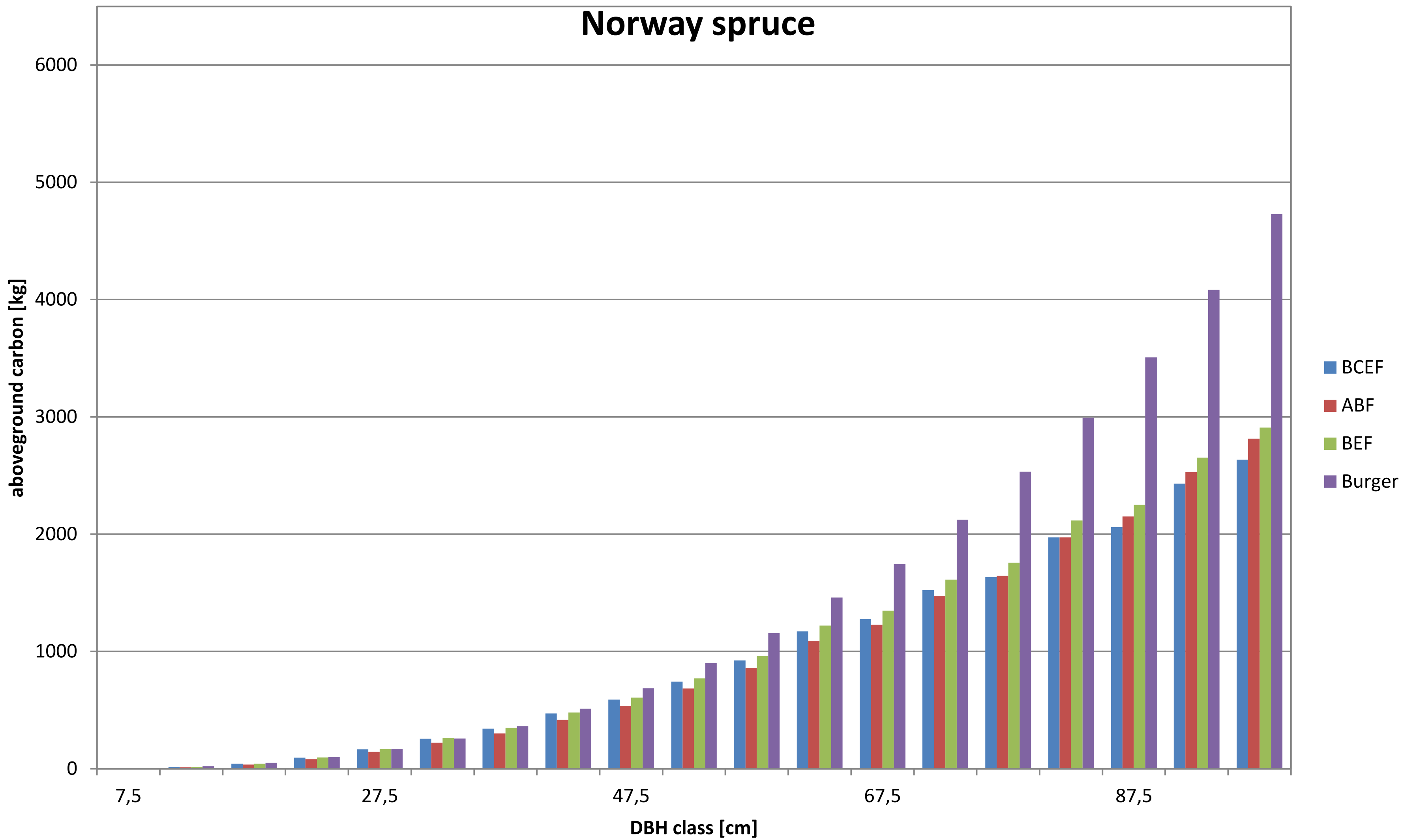

Figure 3 Average carbon estimations per 5 cm DBH class for the standardized spruce tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

Figure 4 shows the aboveground carbon content of each tree compartment. It is distinguished between stem carbon, branch carbon and carbon stored in foliage however, it has to be noticed that when using a BCEF, the stem biomass expands to the total aboveground biomass and thus, for this method it cannot be distinguished between branch and needle carbon. This is important to keep in mind, when looking at the branch carbon content in the middle graph of Figure 4, since only for the BCEF a combined value of the branch and needle carbon was used. The actual branch carbon of the BCEF method should actually be lower than the given value. Furthermore, only the ABF and the Burger function calculate the needle carbon separately. Thus, only the needle carbon content calculated with these two functions can be seen in the bottom graph.

For all four methods we can see that the stem had the highest share of the total aboveground carbon. In addition, it becomes obvious that the stem carbon followed the same trend as the total aboveground carbon. This means that until a DBH of around 50 cm to 60 cm the results of all four methods were similar. But with a DBH higher than 60 cm the Burger function gave values that were above those of the other three methods.

The values regarding the branch compartment were highest when calculated with a BCEF (see Figure 4, middle graph). This might be due to de fact that using a BCEF does not distinguish between branch and needle carbon and therefore, combines both. However, the values of all four methods were similar over all DBH classes. In contrast to the stem volume, the Burger function gave the lowest results over all DBH classes, as far as the branch compartment was concerned.

In the lower graph of Figure 4 the carbon content stored in the needles is shown. It can be seen that the values were very similar until the DBH class of 50 cm to 55 cm. With an increasing DBH, the values calculated with the ABF increased more than those of the Burger function. In the highest DBH class the ABF gave a value of around 450 kg, whereas the value of the Burger function was only 56 kg. Thus, the result calculated with the ABF was 8 times higher than that of the Burger function.

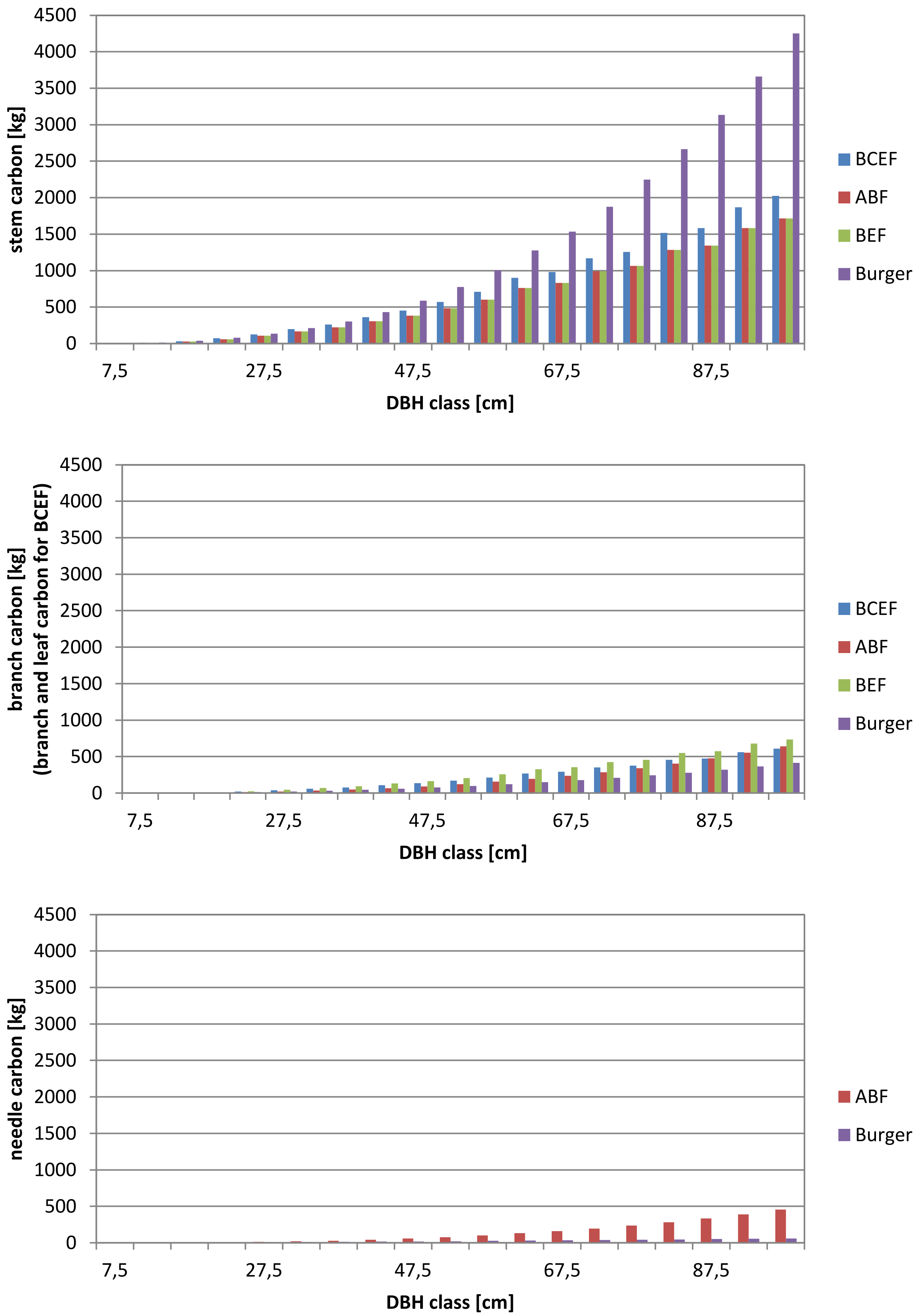

Figure 4 Average carbon estimations per 5 cm DBH class for the standardized spruce tree data set; stem carbon is displayed in the upper graph, branch carbon (and neelde carbon for BCEF function) in the middle graph and needle carbon in the bottom graph. Estimation derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

4.1.2 European beech

As for Norway spruce, the aboveground carbon content of each tree was calculated and plotted against the DBH, which can be seen in Figure 5.

For European beech we can see that all four methods showed similar results regarding trees with a small DBH. With an increasing DBH the deviation in between the results of each method as well as the deviation between the different methods amplified. When using a BEF the lowest values over almost the entire DBH range were obtained. The Burger function displayed results that lie between the results of the BEF and the BCEF method. The ABF and the BCEF method exhibited similar results over the whole DBH range, except in the upper end of the DBH range, in which the results of the ABF were above those of the BCEF method.

The highest difference in the amount of aboveground carbon measured for a single tree was detected for a tree with a DBH of 95.7 cm and a height of 20.3 m. For such a tree the aboveground carbon calculated with the ABF had a value of 8,796 kg. The Burger function generated a value of 3,508 kg and the BCEF and the BEF method calculated values of 2,955 kg and 1,867 kg, respectively. This means there was a difference of almost 7,000 kg carbon between the highest and the lowest calculated results.

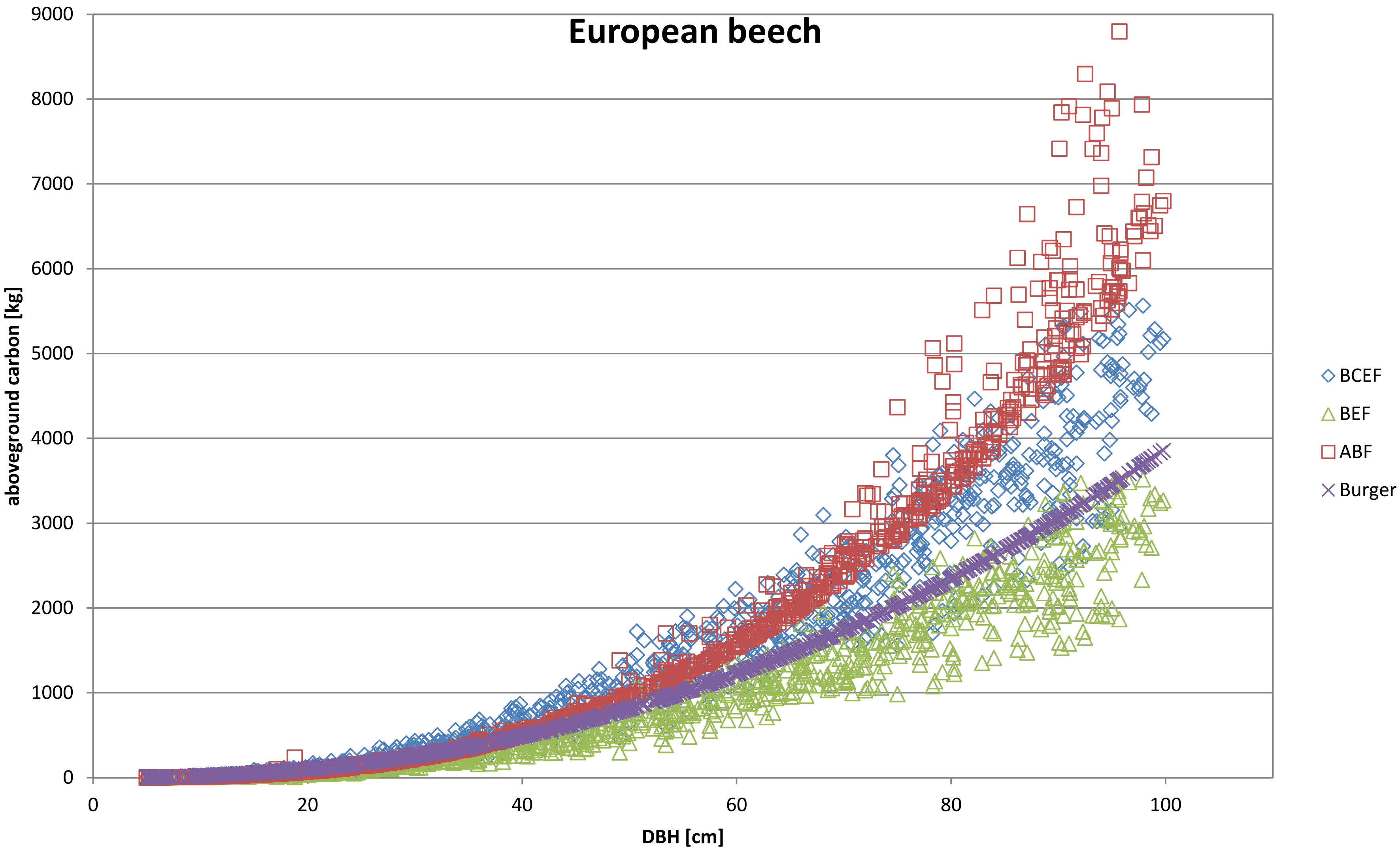

Figure 5 Carbon estimations for each tree of the standardized beech tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

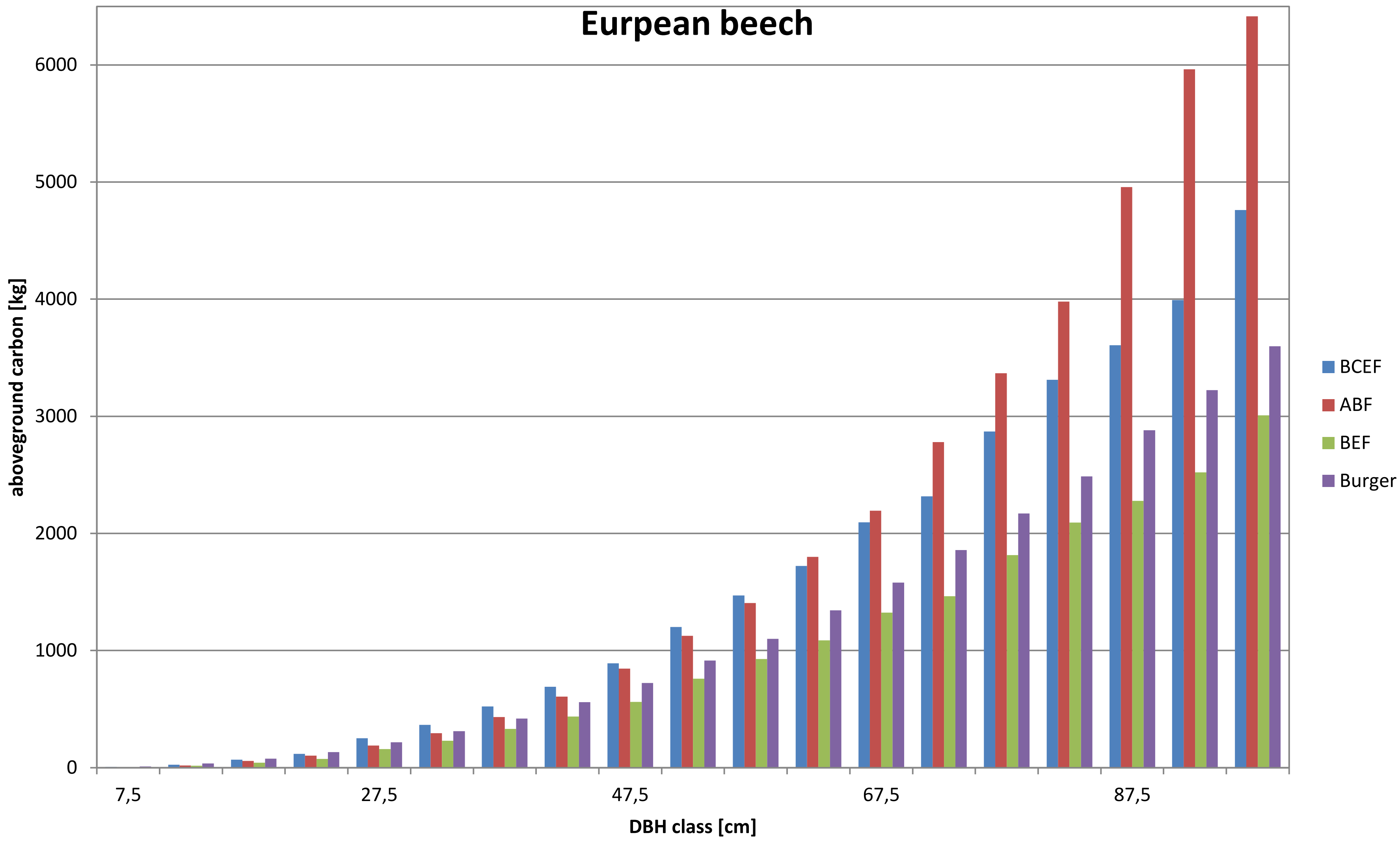

Figure 6 Average carbon estimations per 5 cm DBH class for the standardized beech tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

In Figure 6 the trees were compiled in DBH classes of 5 cm steps and the average aboveground carbon content was plotted against the DBH classes.

The graph shows that until the DBH class 40 cm to 45 cm the results of all four methods were similar. With an increasing DBH the BCEF method and especially the ABF generated elevated results compared to the other two methods. The BEF method and the Burger function displayed similar results over all DBH classes. Their results were lower than those of the ABF and the BCEF method. The average aboveground carbon content in the highest DBH class calculated was around 6,400 kg, when calculated with the ABF. For the same DBH class, the BCEF method gave a value of around 4,750 kg, the Burger function one of 3,600 and the BEF method one of 3,000kg. Thus, the value of the ABF function was around 2 times higher than the value of the BEF method.

In Figure 7 the average values of each tree compartment are displayed. Again, it has to be noticed that when using a BCEF it can only be distinguished between the stem carbon and the rest of the aboveground carbon. Therefore, the carbon stored in the branches and in the leaves was shown in the middle graph. Furthermore, it has to acknowledged that only the Burger function calculates leave carbon for broadleaf trees. The ABF does this only for conifers. As a consequence, the value of the Burger function is the only one displayed in the bottom graph of Figure 7, which regard the leaf carbon content.

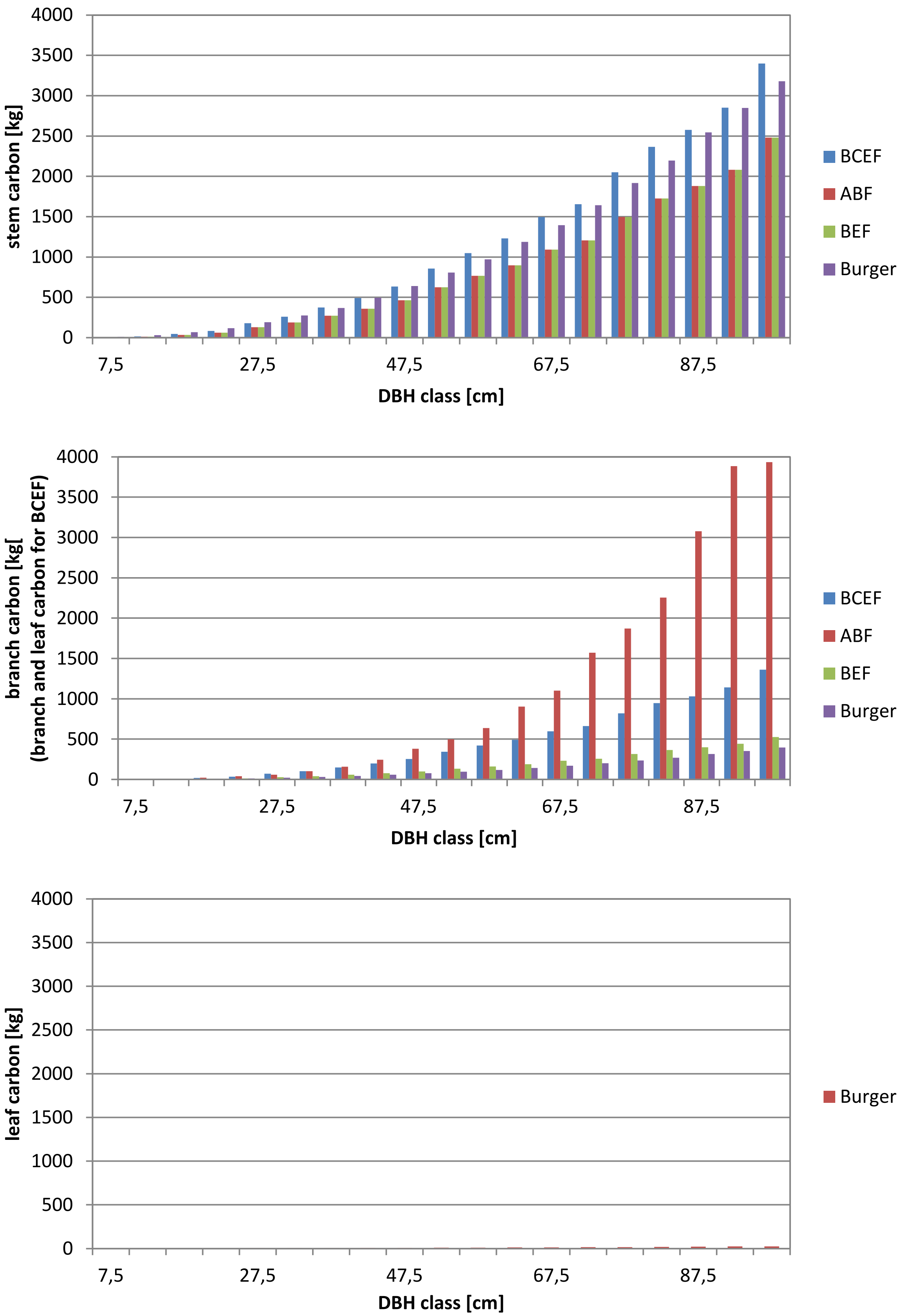

Figure 7 Average carbon estimations per 5 cm DBH class for the standardized beech tree data set; stem carbon is displayed in the upper graph, branch carbon (and leaf carbon for BCEF function) in the middle graph and needle carbon in the bottom graph. Estimation derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

Over all DBH classes, the stem carbon content was similar for all four methods. The BCEF method gave the highest results, followed by the Burger function and then by the ABF and BEF method. The middle graph displays the carbon stored in the branches (and for the BCEF method also the leaf carbon). For small DBH classes the difference between the four methods was not very high, but with an increasing DBH a vast difference became visible. The values of the Burger function and the BEF method were quite similar over all DBH classes. The results of the BCEF method were higher than those of the former two, whereas the ABF exhibited the highest results over all DBH classes. Especially for the ABF a high increase was detected with an increasing DBH. In the DBH class of 50 cm to 55 cm the ABF gave a value of 500 kg C stored in the branches, the BCEF method displayed a value of around 350 kg C and the BEF method and the Burger function one of 130 kg C or 100 kg C, respectively. In this DHB class the highest value (ABF) was around 5 times higher than the lowest value (Burger). In comparison to that, the value of the ABF was around 10 times higher than that of the Burger function regarding the highest DBH class.

Furthermore, it can be noticed that for the ABF the carbon stored in the branches was around 2 times higher than the stem carbon content in the DBH class of 90 cm to 95 cm. This stands in contrast to the results of the other three methods, for which the stem was the tree compartment with the highest share of carbon storage.
The quantity of carbon stored in the leaf mass was very low and only amounted to 30 kg carbon in the highest DBH class.

4.1.3 Scots pine

In the following section, the results of the carbon estimations of the four methods calculating carbon from terrestrial data regarding Scots pine are shown. In Figure 8 the carbon content of each tree was calculated and plotted against the DBH. In contrast to Norway spruce and European beech, the amount of Scots pine trees was smaller, since only trees with a DBH of up to 70 cm were used. This was done simply because trees with a higher DBH were not available.

The graph displays that all four methods exhibited similar results which overlapped over the whole DBH range. With an increasing DBH a greater deviation in between the results of each method as well as between the results of the compared methods was noticed. The highest difference for a single tree was observed for a tree with a DBH of 66.5 cm and a height of 40.3 m. For such a tree the method using a BEF calculated an aboveground carbon value of around 1,900 kg, whereas for the same tree the BCEF method gave a value of around 1,700 kg, the ABF one of 1,400 kg and the Burger function one of only 1,100 kg. Hence, the difference between the highest calculated value and the lowest was 800 kg, a discrepancy of around 70%.

Figure 8 reveals that the differences for single trees were relatively high, whereas the differences between the averages of each DBH class (see Figure 9) were not as high.

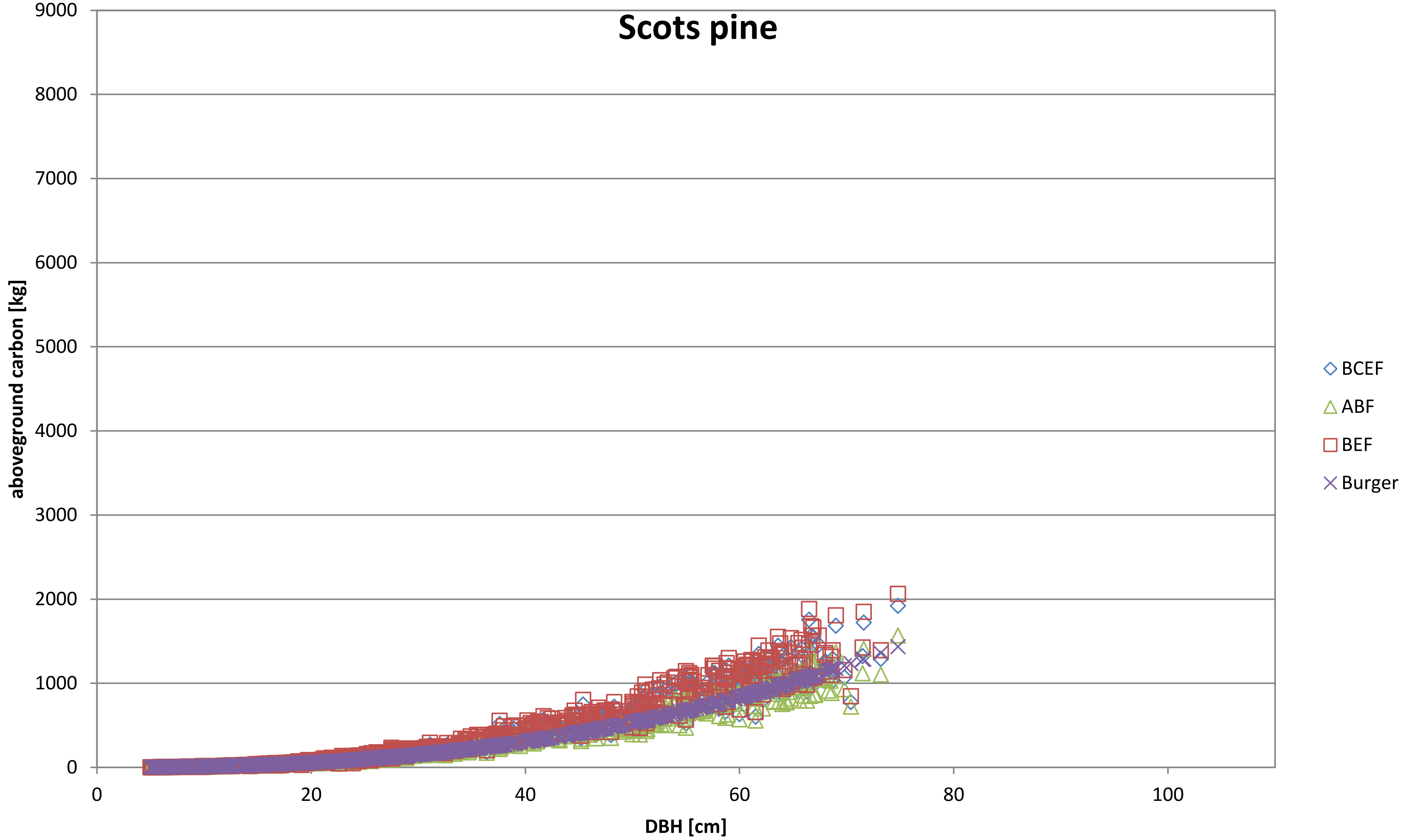

Figure 8 Carbon estimations for each tree of the standardized pine tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

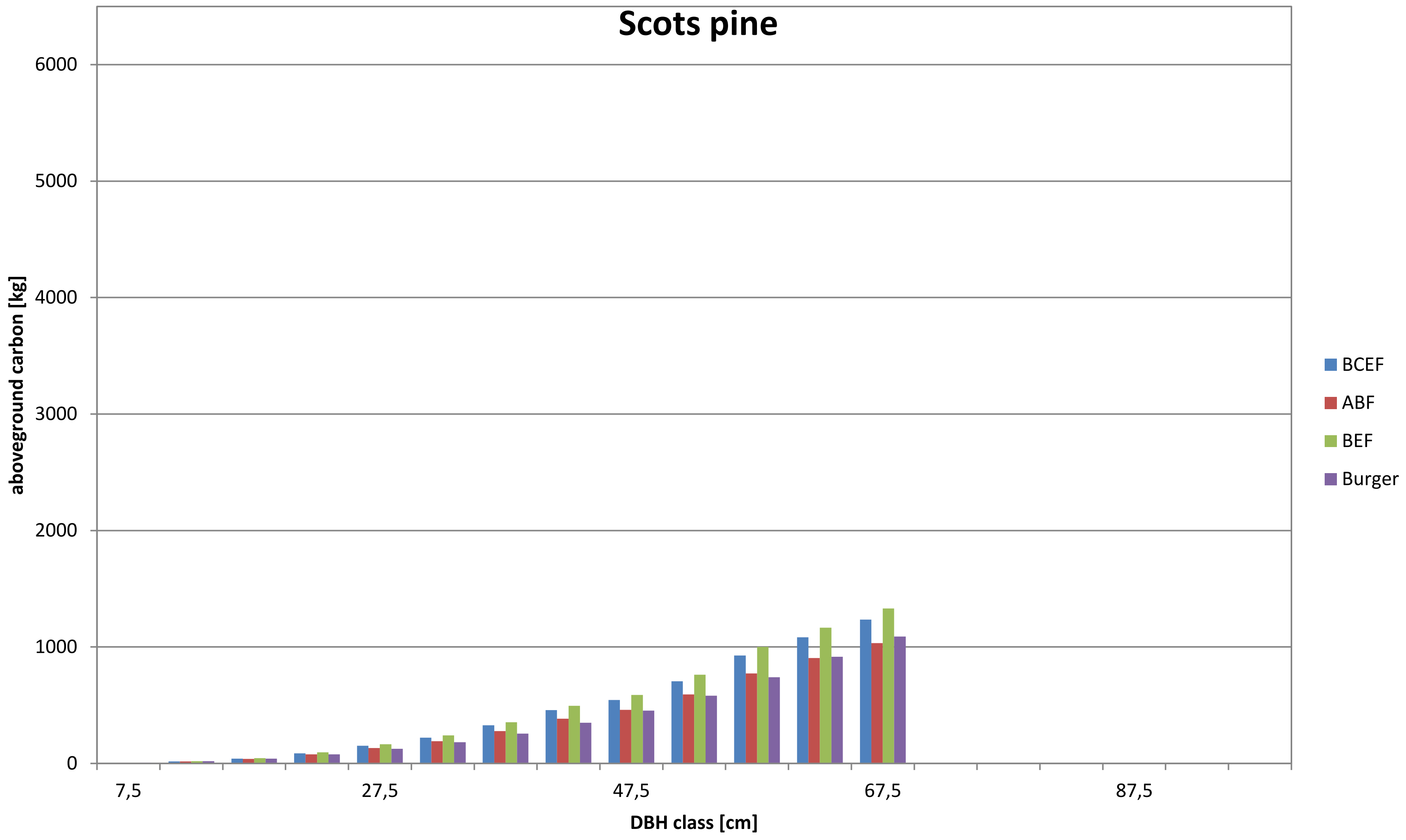

Figure 9 Average carbon estimations per 5 cm DBH class for the standardized pine tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

Figure 9 presents the averages of each DBH class. The results showed that the trends of the single tree calculations are also visible for the averages of each DBH class. Over all DBH classes, the BEF method displayed the highest results. The values of the BCEF method were very similar to that, whereas the values of the ABF and the Burger function were lower.

Figure 10 features the carbon content of each tree department. The results for carbon stored in the stem were very similar for each method over all DBH classes. It can be noticed that in small DBH classes the values obtained by the Burger function were the lowest, whereas in the highest DBH class this function gave the highest stem carbon content.

For the branch department, higher differences between the values of the four methods were detected. Again, it has to be noticed that using the BCEF method it cannot be distinguish between branch and needle carbon and as a consequence, the middle graph of the diagram shows values for the BCEF method that combine the carbon stored in the branches and the needles. The ABF and the Burger function showed very similar results for branch carbon over all DBH classes. The values of the BEF and the BCEF methods were also similar, but higher than the values of the other two functions for DBH classes above 25 cm. The maximum difference was detected in the highest DBH class, in which the carbon content calculated with the BEF method (around 400 kg) was around 4 times higher than the results of the ABF and the Burger function (both around 100 kg).

The bottom graph displays the carbon content of the needles, which only the ABF and the BCEF method calculate. Their results did not differ from each other. It was seen that the share carbon stored in the needles is very low compared to the total aboveground carbon stored in the tree.

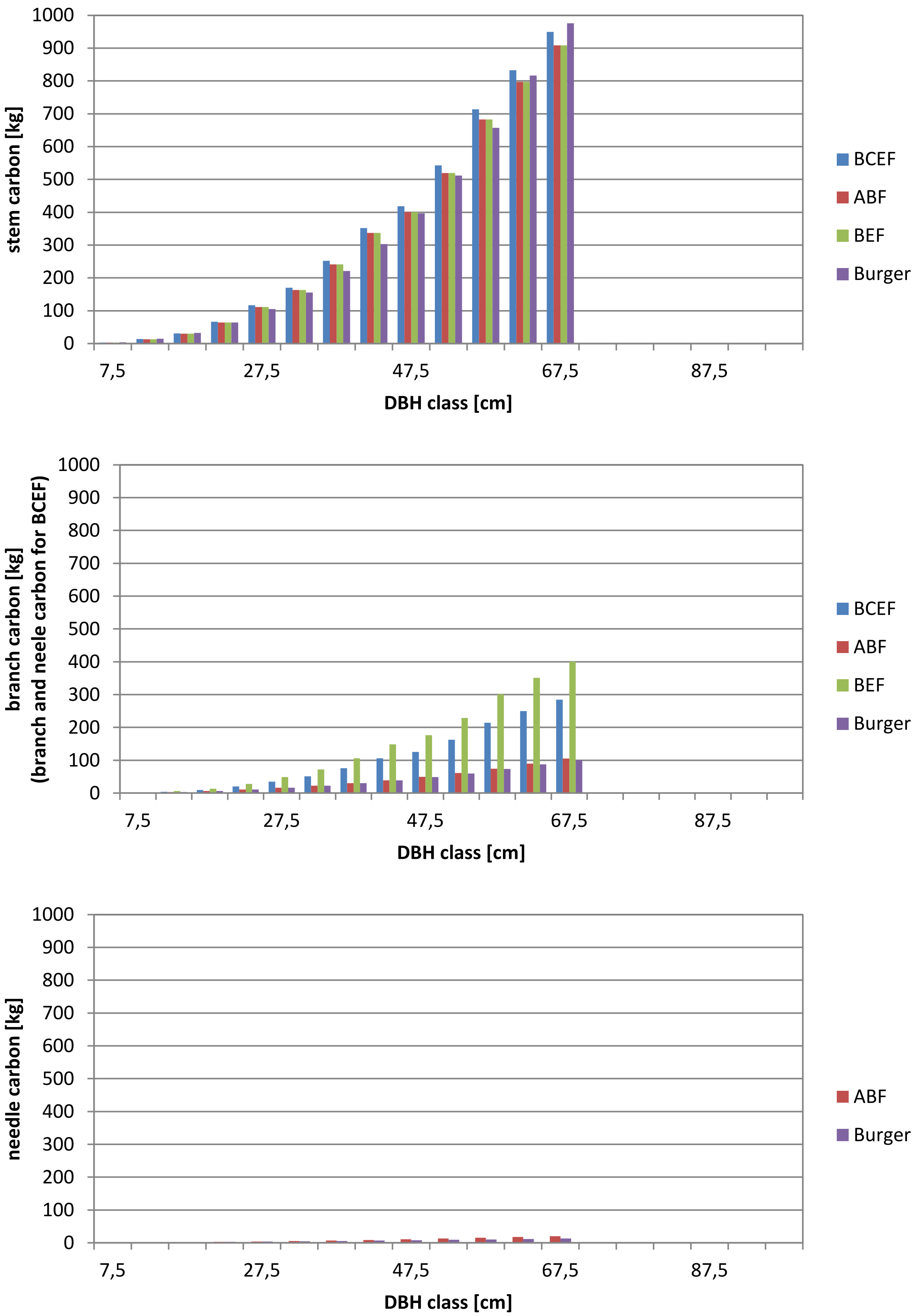

Figure 10 Average carbon estimations per 5 cm DBH class for the standardized pine tree data set; stem carbon is displayed in the upper graph, branch carbon (and neelde carbon for BCEF function) in the middle graph and needle carbon in the bottom graph. Estimation derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

4.2 Carbon estimations for the Montafon region

In this section the four carbon estimation methods were applied to the Montafon study region (see section 3.2) in order to detect possible local effects. In 4.2.1 the results of the methods are compared at a tree level and follow the same scheme as in 4.1. Due to the amount of the measured trees in the inventory process, this comparison was only carried out for Norway spruce. For other species the number of measured trees was so small that a bias could have been given. In section 4.2.2 a comparison regarding the whole forest area was carried out, to compare the carbon estimations derived from the four methods. For this comparison, the data set with the representative number of trees (see section 3.2.1) was used in order to have a realistic distribution of trees over the whole diameter range.

4.2.1 Tree level

For the tree level comparison the measured data from the forest inventory were used (see section 3.2). The carbon content of each tree was calculated and plotted against the DBH as shown in Figure 11.

The results regarding the Montafon area were very similar to those which were obtained by applying the estimation methods to the standardized tree data set (see section 4.1.1). For small diameter trees the methods showed very similar results. It can be stated that with an increasing DBH the deviation between the results of the different methods as well as the deviation between the results of each method amplified. The results of all the four methods overlapped until a DBH of around 40 cm. For trees with a DBH between 40 cm and 80 cm the results were still similar with the Burger function being on the upper end of the range and the ABF on the lower end. Figure 11 displays that with an increasing DBH the values obtained by the Burger function rose more rapidly than the values of the other three methods. For trees with a DBH around 120 cm the Burger function showed carbon values of around 8,000 kg. The results of the other three methods for trees with the same DBH measured between 4,000 and 5,000 kg aboveground carbon.

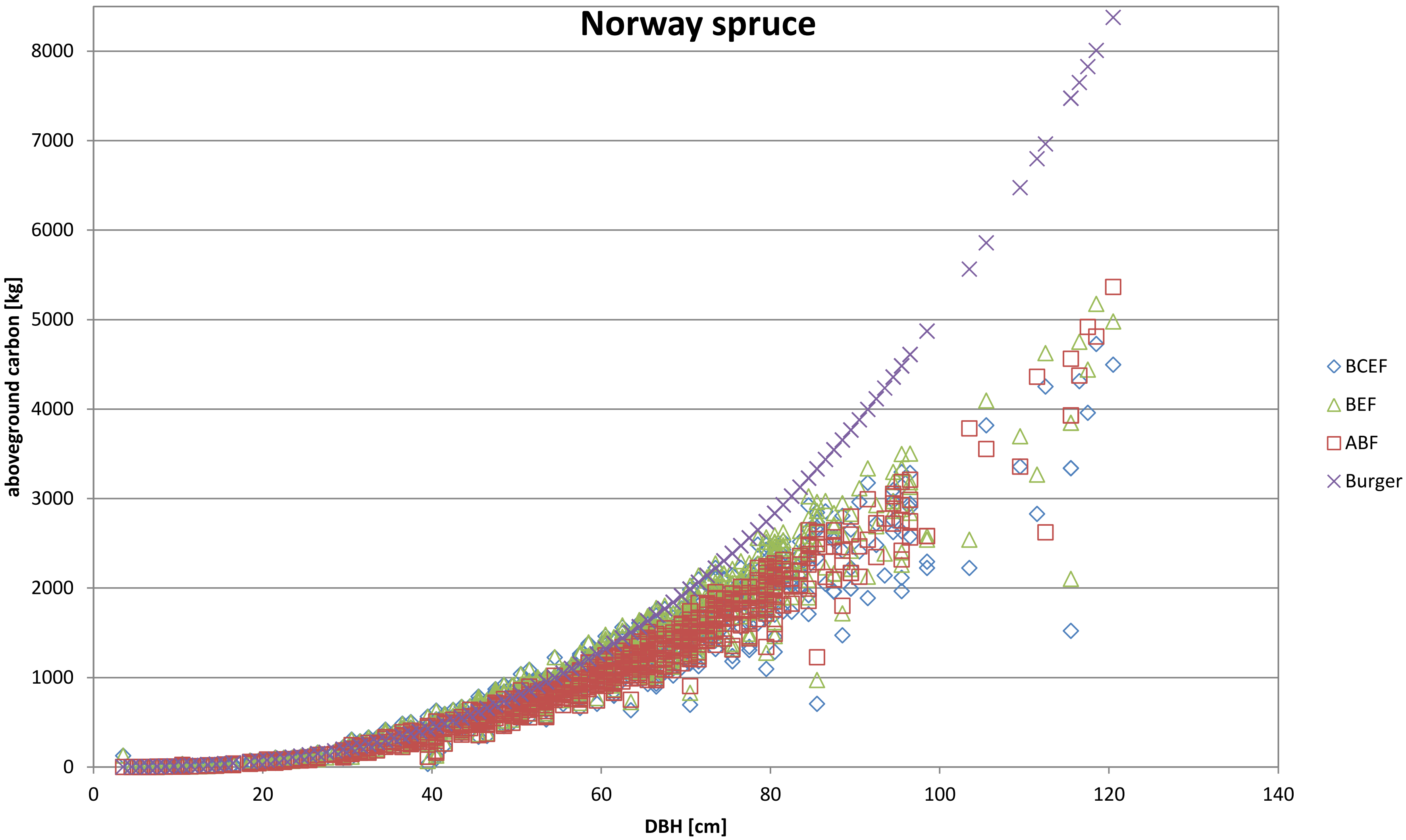

Figure 11 Carbon estimations for each tree of the Montafon forest inventory spruce tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

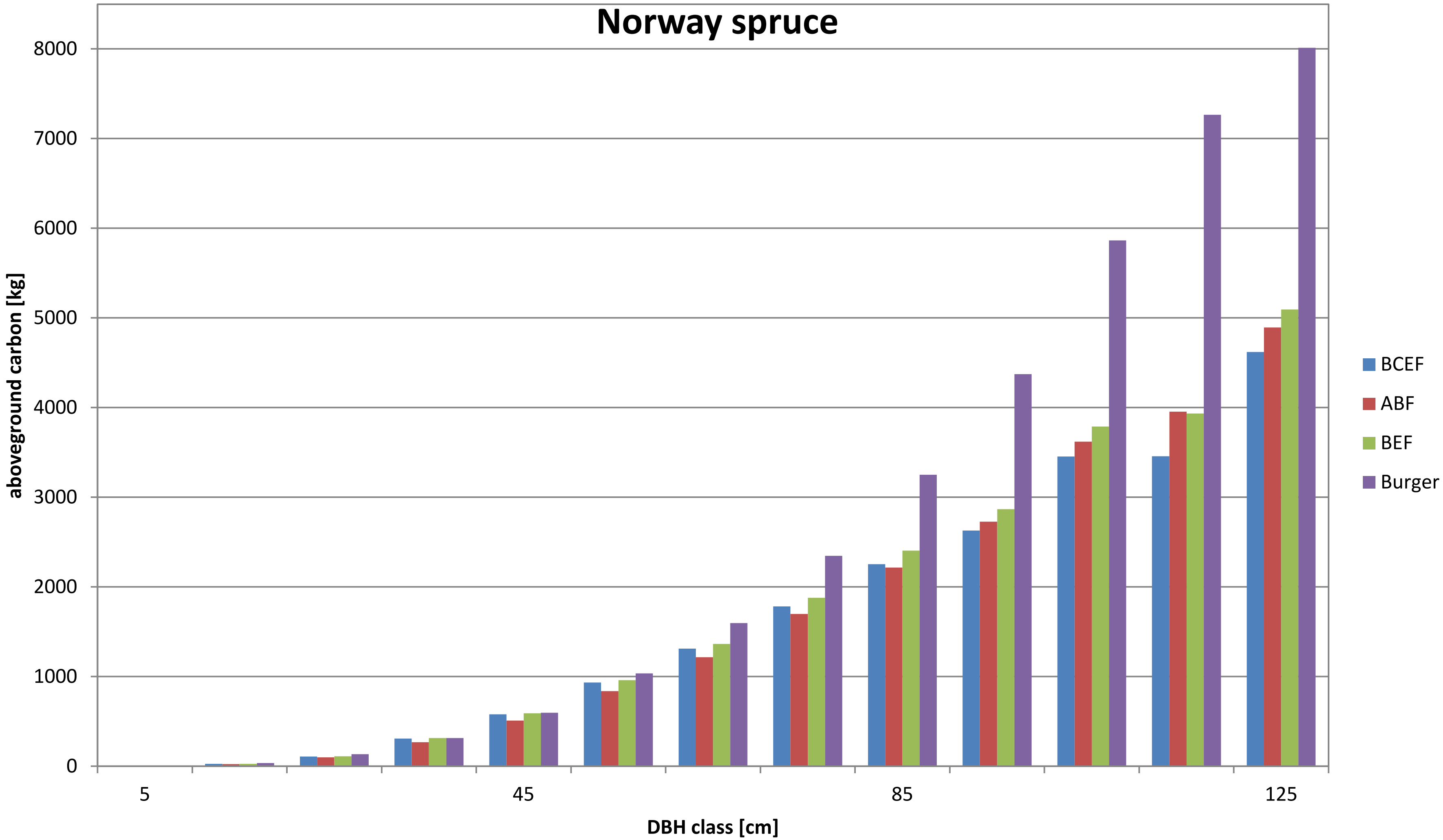

Figure 12 Average carbon estimations per 10 cm DBH class for the Montafon forest inventory spruce tree data set derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

Due to the fact that for the Montafon forest inventory more trees with a larger DBH were analyzed than for the standardized tree data set, the trees were compiled into 10 cm DBH classes for better clarity. Again, the average of the aboveground carbon content of each DBH class was plotted against the DBH class and the results are displayed in Figure 12. The bar chart shows that the results of the four methods estimating biomass from terrestrial data were very similar for small diameter classes (up to the diameter class of 70 cm to 80 cm). With an increasing DBH the results of the Burger function were above those of the other three methods. The highest difference was detected in the DBH class of 110 cm to 120 cm. In that section the values obtained by the ABF, the BCEF and the BEF method were in the range of 3,500 kg to 4,000 kg carbon, whereas the value of the Burger function was above 7,000 kg carbon. Just like for the single trees in Figure 11, it is also true for the averages of the DBH classes in Figure 12 that with an increasing DBH the values of the Burger function rose faster than those of the other three methods.

In Figure 13 the averages of each DBH class for each tree compartment are shown. The stem carbon content of each DBH class was very similar for each calculation method, as far as small trees are concerned. With an increasing DBH the results of the ABF, the BCEF and the BEF method still showed very similar results, while the results of the Burger function were above the others. For the DBH classes 90 cm and above the results of the Burger function were around 2 times higher than the results of the other three methods. For example, in the DBH class of 90 cm to 100 cm the Burger function showed an average stem carbon content of around 4,000 kg. Contrarily, using a BCEF to estimate the biomass generated a value of around 2,000 kg and the results of the ABF and the BEF method were around 1,800 kg carbon.

The middle graph of Figure 13 shows the carbon that is stored in the branches of the trees. Like stated above, the BCEF method only distinguishes between stem carbon and other aboveground carbon. Thus, the graph combines the branch and needle carbon for the BCEF method, whereas for the other methods only the carbon stored in the branches is displayed. Again, results of all four methods were similar, but in contrast to the stem carbon, the Burger function gave the lowest values compared to the other three. Even though the method using a BCEF includes branches and needles, its values were very similar to the ones obtained by the ABF and below those when calculated with a BEF.

The bottom graph of Figure 13 displays the carbon stored in the needles. Up to the DBH class of 40 cm to 50 cm both functions, the Burger and the ABF, displayed very similar results. With an increasing DBH the values of the ABF rose faster than those of the Burger function, which almost stayed at a constant level.

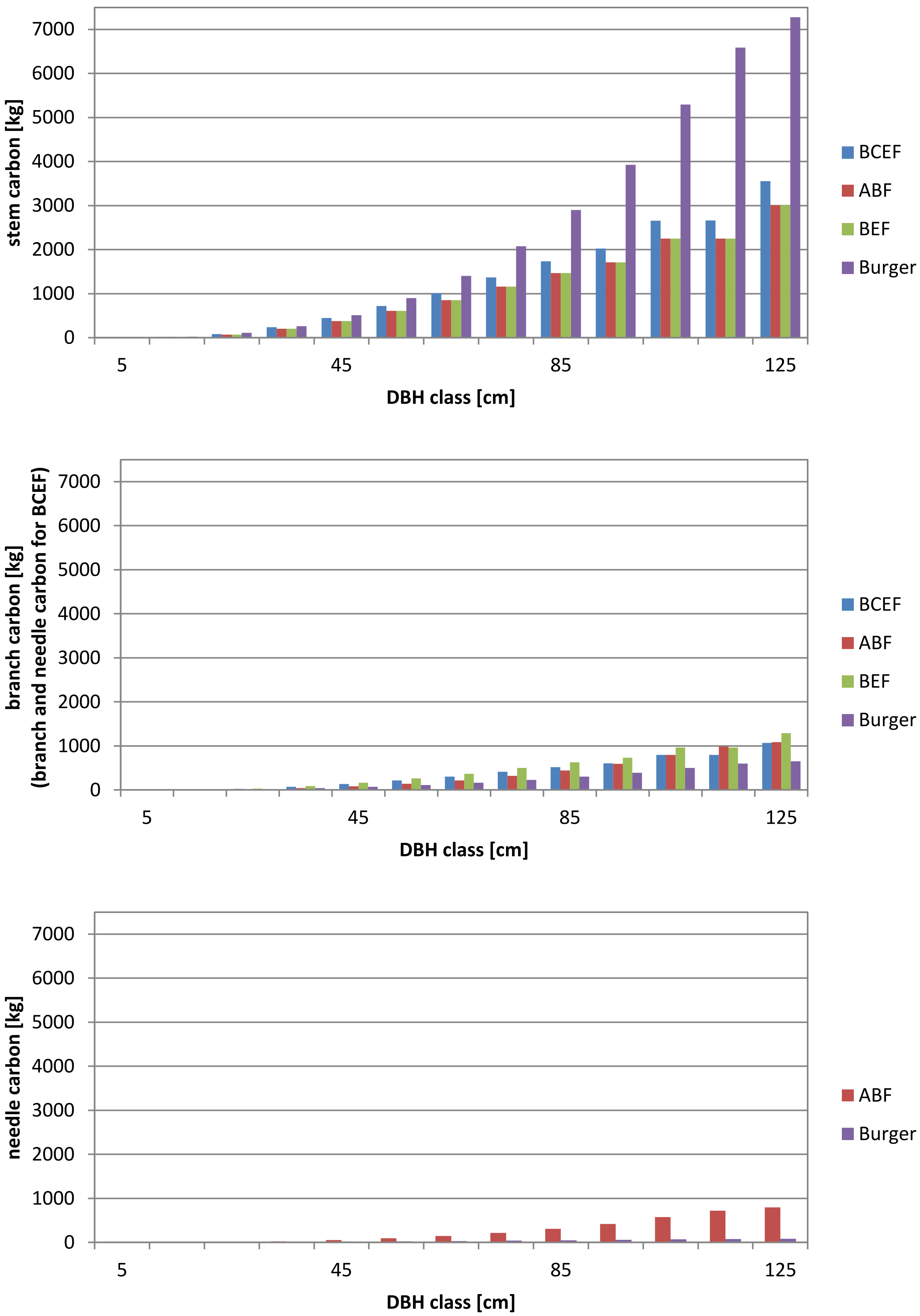

Figure 13 Average carbon estimations per 10 cm DBH class for Montafon forest inventory spruce tree data set; stem carbon is displayed in the upper graph, branch carbon (and neelde carbon for BCEF function) in the middle graph and needle carbon in the bottom graph. Estimation derived from the Biomass conversion and expansion factor (BCEF) and biomass expansion factor (BEF) method, from the Austrian biomass function (ABF) and the biomass functions after Burger (Burger)

The results of the Montafon study area are in line with the results obtained by applying the different calculation methods to the standardized tree data set (see Figure 4), since they also come to the conclusion that the most aboveground carbon is stored in the stem, followed by the amount in the branch and the needle compartment.

4.2.2 Area level

Next we were interested to study the total carbon stock per m² of the Montafon study area. The data used come from the forest inventory and represent the current situation of the area (see section 3.2).

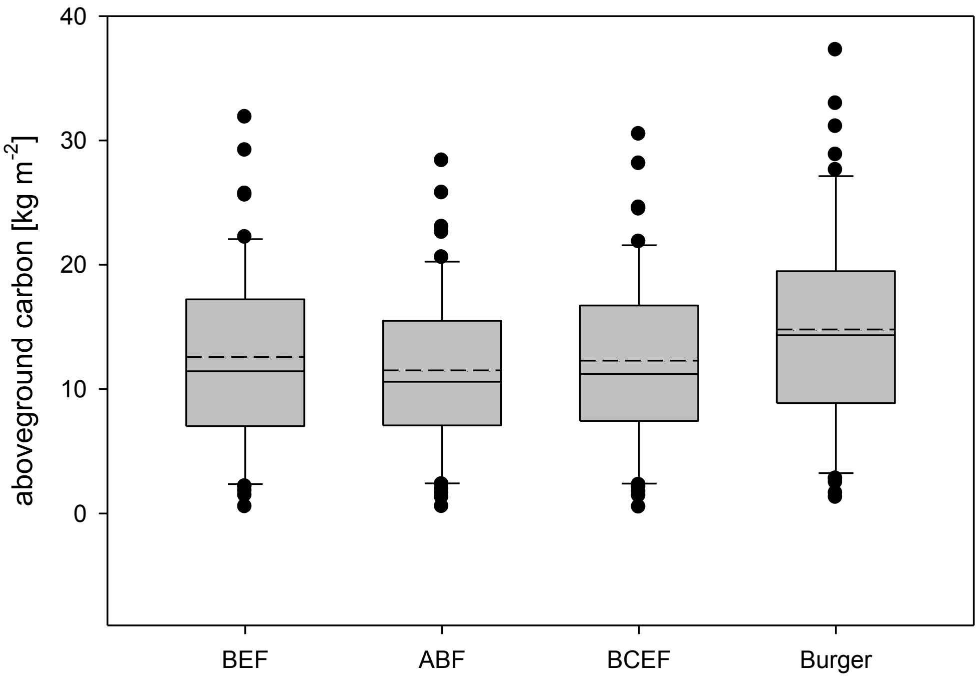

Figure 14 Average carbon estimations of the biomass functions for each of the 53 forest stands in the Montafon study region. The dashed line in the box plots shows the mean, the solid line the median. For calculation four methods were chosen: a method using a biomass expansion factor (BEF), a method using a biomass conversion and expansion factor (BCEF), the Austrian biomass function (ABF) and the biomass function after Burger (Burger)

The carbon stock per square meter of each of the 53 stands was calculated with each of the four biomass calculation methods. Figure 14 presents the box plots for each method in which the dashed line shows the mean over all stands and the full line the median. The highest average for the whole Montafon forest area was obtained by the Burger function with 14.79 kg C m^{-2}, followed by the method using a BEF with an average of 12.58 kg C m^{-2}. In both cases the median of each function was slightly lower with 14.33 kg C m^{-2} and 11.43 kg C m^{-2}, respectively. The method using a BCEF gave an average of 12.29 kg C m^{-2} and its median was 11.23 kg C m^{-2}.

The ABF showed the lowest results, both for the average and for the median with 11.05 kg C m^{-2} and 10.59 kg C m^{-2}.

The smallest difference between the average of the Burger function compared to the averages of the other methods (2.2 kg C m^{-2} between Burger and BEF) was higher than the highest difference between the averages of the other three methods (1.5 kg between BEF and ABF).

In terms of percentages, the Burger function gave a 17.6 % higher average than the BEF method, a 20.3 % higher average than the BCEF method and a 28.6 % higher average than the ABF. Furthermore, the BEF method showed a 2.2 % higher average than the BCEF method and compared to the average given by the ABF the average of the BEF method was 8.6 % higher. Moreover, the method using a BCEF calculated an average that is 6.5 % above the one of the ABF.

4.3 Carbon estimations by the BGC-model

In the following section, the model's carbon stock estimations for the Montafon study area are presented. The BIOME-BGC model was applied to all 53 stands of the study area. The input data have been described in section 2.3.1.1 and site specific information were given in section 3.3. The model results were compared to those obtained by the BCEF method to check if the model gives realistic results for the Montafon region. The BCEF method was chosen because it is the one that is used to calculate the carbon stock of all countries that participate in the ARANGE project. The BIOME-BGC model's predictions for the carbon stock per m^2 were then compared to the estimations based on terrestrial data from all the four methods used before in order to see how they relate to one another.

4.3.1 Application of the BIOME-BGC model to the Montafon study area

The application of the BIOME-BGC model to the Montafon study area follows the procedure described in section 2.3.1.2.

4.3.1.1 Spin up

As a first step, the potential aboveground carbon stock of a fully stocked stand (virgin forest) was simulated (see 2.3.1.2.1).

Figure 15 gives an account of the box plots of the model predictions for the spin-up and the calculated values for the present forest stands of the Montafon study region. The predicted value is the mean of the last completed mortality cycle (300 years) of the spin up run (see section 2.3.1.2.1). The comparison was carried out in order to see how much the potential forest carbon stock differs from the actual forest carbon stock. The mean of the model predictions was 14.54 kg C m^{-2}, the mean of the BCEF method values was 12.29 kg C m^{-2}. Thus, a difference of 2.25 kg C m^{-2} between the potential and the actual carbon stock was observed. In addition, a larger deviation in the calculated values compared to the model predictions was detected.

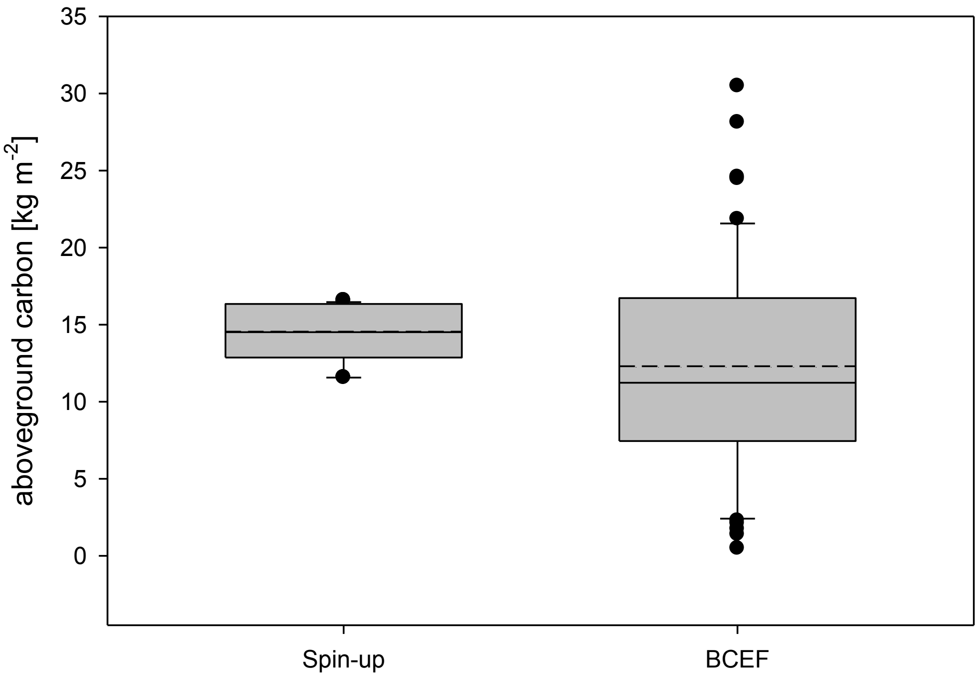

Figure 15 Average aboveground carbon predictions obtained by the BGC-model for the spin-up run and the results obtained by the BCEF method (BCEF) for the present forest stands in the Montafon study region

4.3.1.2 Management assumptions

As a second step, the effect of management was taken into consideration for our simulations. The crown competition factor (CCF) of each stand was calculated (see section 2.1.3) to see if there is a difference in the stand density. It was assumed that stands with a lower CCF have had a more recent management activity (thinning) than stands with high CCF values.

After the CCF was calculated for each stand, the CCF was plotted against the standardized residuals of the model predictions minus the calculated values to see if a trend in the model predictions, regarding the stand density, can be seen.

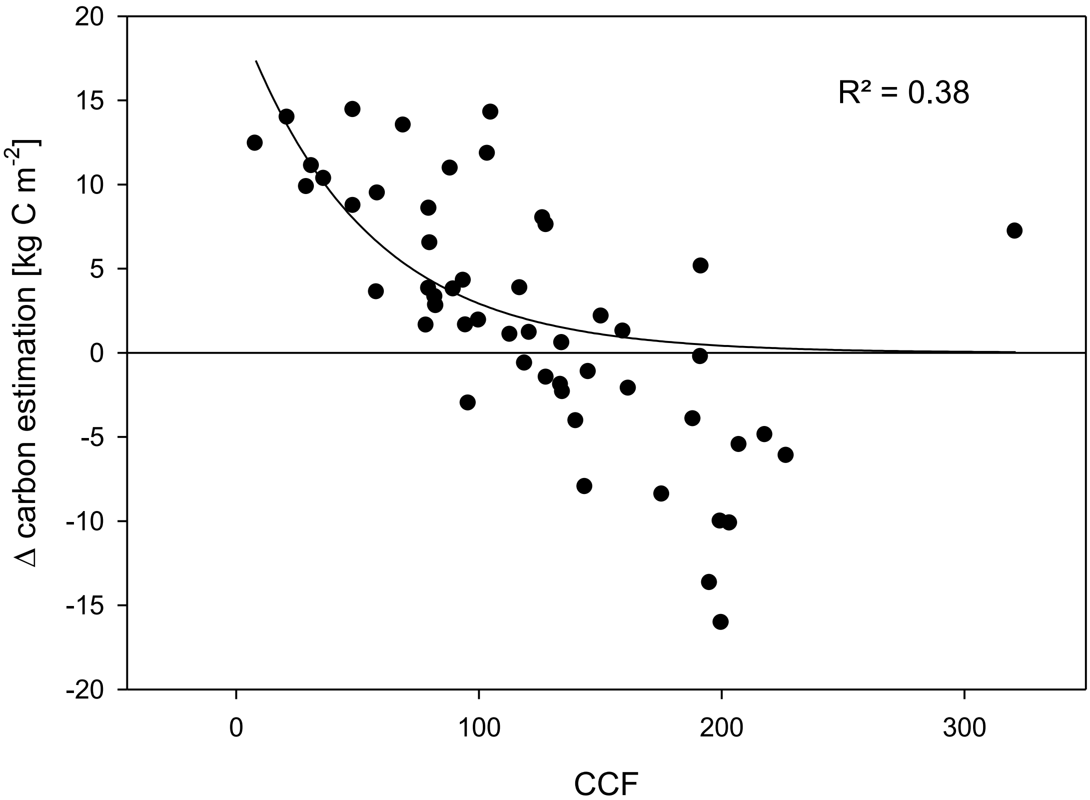

Figure 16 Trend in the differences (Δ carbon estimations) of the predicted (spin-up) values minus the calculated values (BCEF) of aboveground carbon plotted against crown competition factor (CCF) of each stand in the Montafon study region

Figure 16 gives the difference in carbon estimations (Δ carbon estimations) vs. the crown competition factor (CCF) plus the corresponding nonlinear trend line. A significant (R^2=0.38, $t_{n=53;\alpha=0.05}$=3.8*) density related trend is evident. For stands with low density, the model gives higher values than the BCEF function, whereas for stands with a high CCF the opposite is the case. The BIOME-BGC model assumes fully stocked stands and thus, tends to overestimate stands with lower density and to underestimate stands with higher density (overstocked).

The differences of the model predictions minus the calculated values were plotted against the elevation. This was done in order to see if elevation is correctly taken into account by the model, since it is a very important stand parameter for forest growth. Figure 17 displays that there is no significant (R^2=<0.01, $t_{n=53;\alpha=0.05}$=4.03E-122) trend related to the elevation of the plots. Consequently, it can be assumed that the model considers elevation correctly.

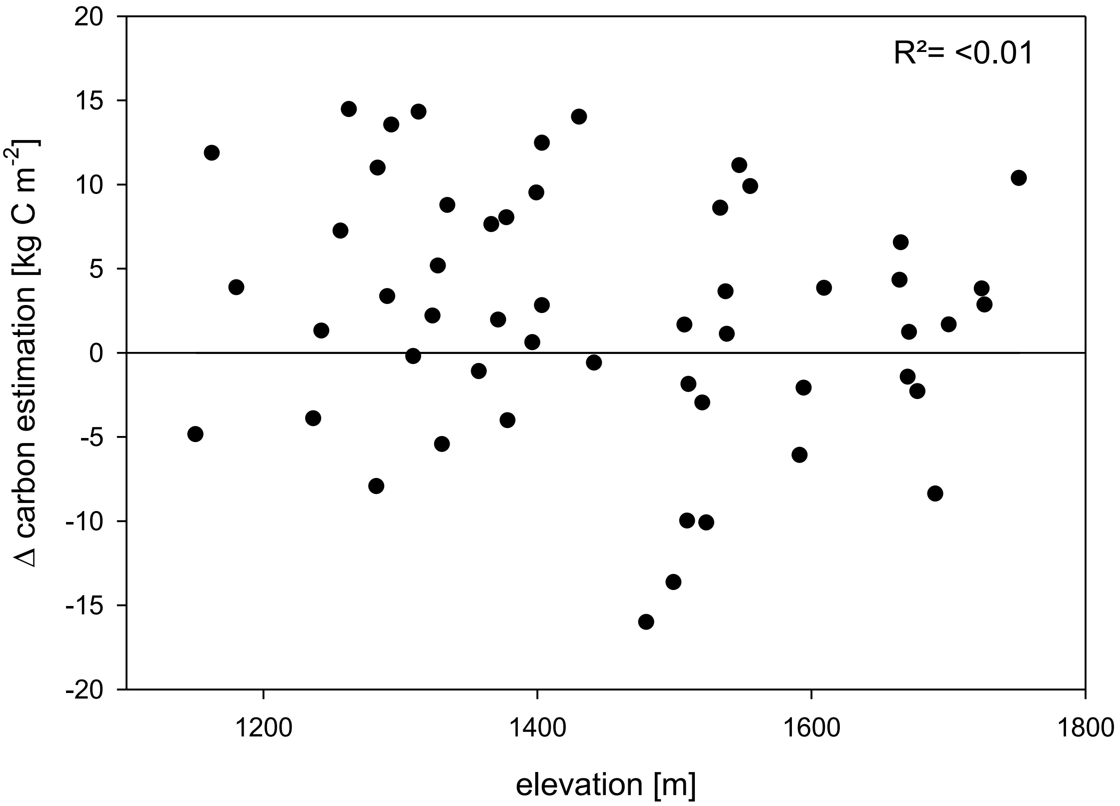

Figure 17 Trend in the differences (Δ carbon estimations) of the predicted (spin-up) values minus the calculated values (BCEF) of aboveground carbon plotted against altitude of each stand in the Montafon study region

4.3.1.3 Land use and thinning

In the Montafon region, the stands are managed extensively. Cable yarding is a common practice. Along the cable lines clear cuts take place. However, these clear cuts only affect parts of the stands, since not the whole stand is cleared at once. Thus, no clear cut in the common sense was applied in the management history of the model, just thinning.

The timing of the thinning was determined by the CCF. The plots were divided in three groups (each class by 80 CCF) from 0 to 240 (only one value was outside that range) (see Figure 16) and past management was considered accordingly. All stands were assumed to be treated in the same way; only the starting point of the interventions differed. The CCF was used to assign the starting point of the management intervention regarding each stand. Stands with a low CCF had the most recent thinning, whereas stands with a high density had the longest time without a thinning.

In this study, a thinning was assumed in which the bole of the trees were removed, but the branches, leaves and roots remained on site. Thus, 90 percent of the wood carbon was removed and 10 percent of the wood carbon (branches) was transferred to the coarse woody debris pool. The leaf carbon from removed trees shifted into the litter carbon pool, as did the carbon from fine roots. The carbon from roots, moved into the coarse woody debris pool.

Due to the fact that the historic land use was not a typical clear cut planting harvesting regime, thinning was applied over two complete rotations of managed Norway spruce forests (240 years).

Through expert guess a thinning intensity of 15 percent aboveground carbon in every decade was applied. Thus, every 10 years a thinning of 15 percent of the aboveground carbon was assumed, which resulted in the removal of 13.5 % of the stem carbon pool for each stand. In addition to that, 1.5 % of the stem carbon (branches etc.) was allocated to the litter carbon pool. Moreover, 15 % of the leaf carbon as well as 15 % of fine root carbon were allocated to the litter carbon. The root carbon pool was allocated to the coarse woody debris carbon pool.

The results of the spin-up, the model predictions (including the effects of management) and those of the BCEF method are illustrated in Figure 18. It can be seen that the model predictions, including harvest activities, do not differ much from the calculated values. After applying thinning to the simulation, the mean of the predicted values was 12.02 kg m^{-2} aboveground carbon compared to the mean of the calculated values of 12.29 kg m^{-2} aboveground carbon.

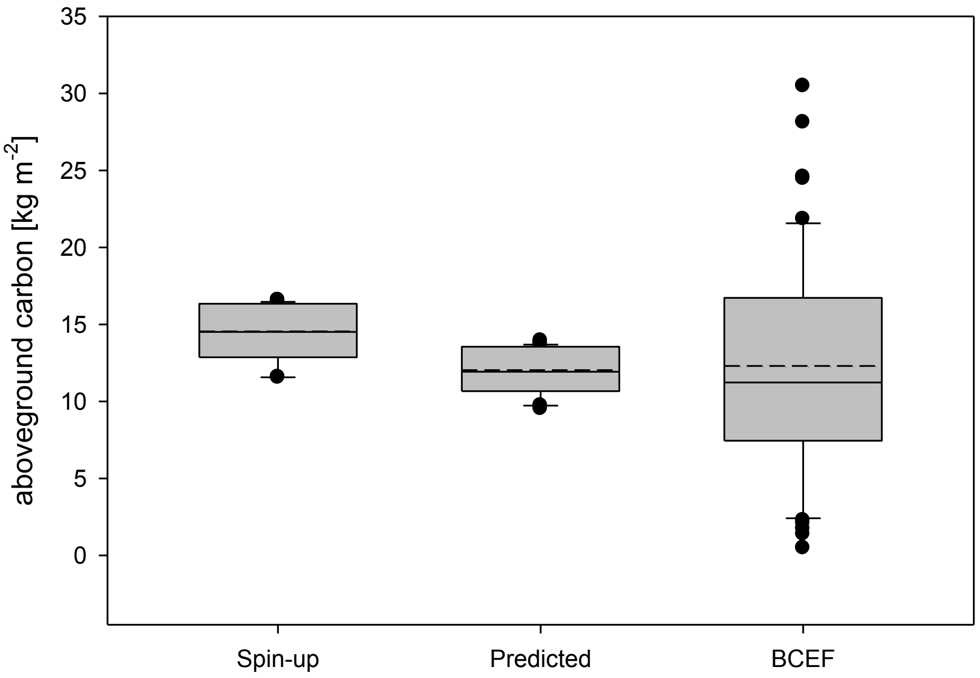

Figure 18 Model predictions for the spin-up, model predictions after incorporation of management (predicted) and the results of the BCEF method (BCEF) where the dashed lines show the mean, the solid lines the median; assumed management for modeling: 15 percent reduction of aboveground carbon every 10 years over the last 240 years (two rotation periods of Norway spruce)

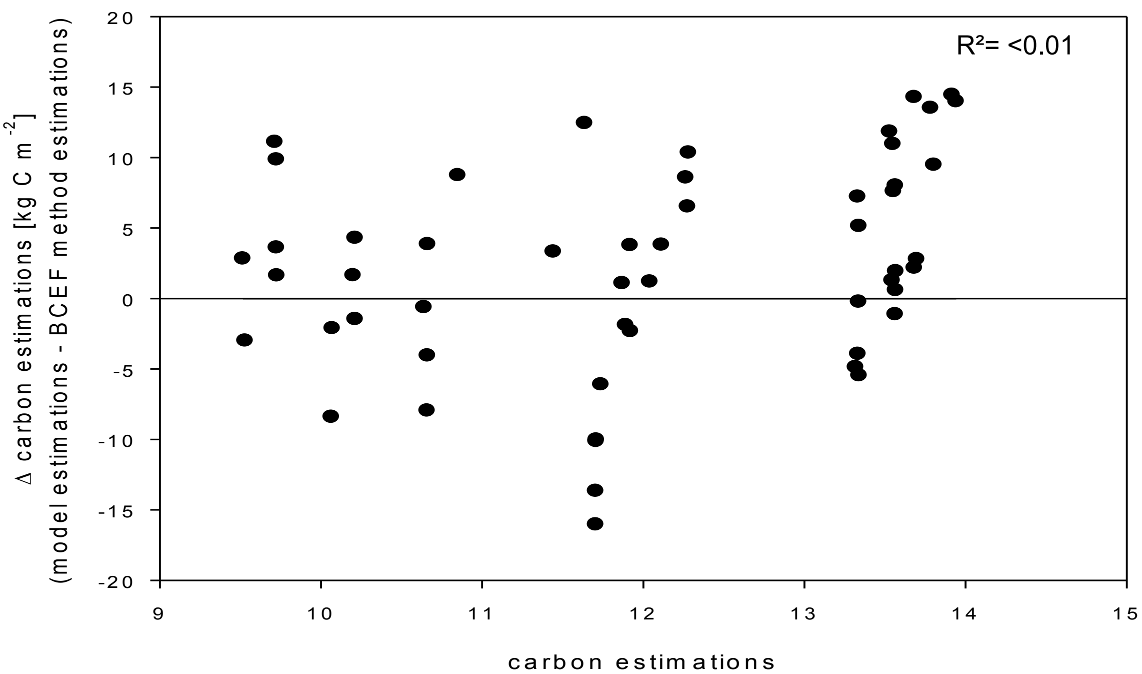

Figure 19 Standardized residuals of model predictions (after management) minus the calculated values of the BCEF method for aboveground carbon of each forest stand in the Montafon study region plotted against the predicted carbon estimations

To investigate if the model estimations exhibit a bias, the difference between the results of the model and the BCEF was calculated and plotted against the model's carbon estimations (Figure 19). Figure 19 reveals that no bias (R^2=<0.01, $t_{n=53;\alpha=0.05}$=<0.0001) in the model estimations is evident. As a consequence, it can be assumed that the model predicts the carbon content without a bias for the Montafon study area.

4.3.2 Model estimations vs. calculated estimations from terrestrial data

Finally, the results of the model estimations were compared to the estimations obtained by the methods using terrestrial input data. Figure 20 shows the box plots of each estimation method, where the dashed line shows the average carbon per square meter over all 53 stands, the solid line the median.

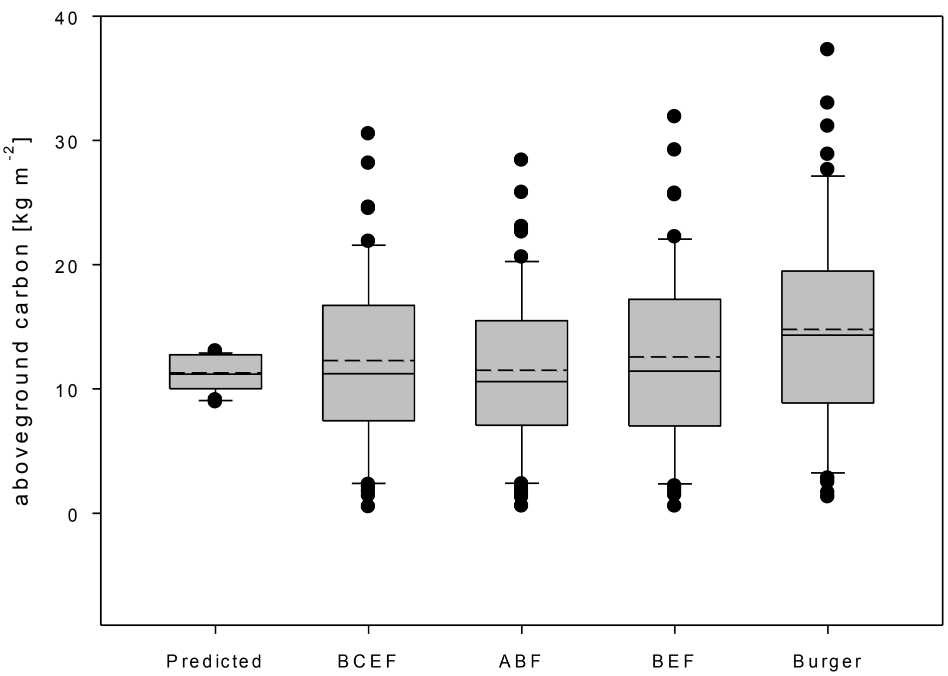

Figure 20 Model predictions after incorporation of management (predicted) and the results of the BCEF function (BCEF), the Austrian biomass function (ABF) the BEF function (BEF) and the Burger function (Burger) where the dashed lines show the mean, the solid lines the median; assumed management for modeling: 15 percent reduction of aboveground carbon every 10 years over the last 240 years (two rotation periods of Norway spruce)

The highest average for the whole Montafon forest area was obtained by the Burger function with 14.79 kg C m^{-2}, followed by the method using a BEF with an average of 12.58 kg C m^{-2}. The method using a BCEF gave an average of 12.29 kg C m^{-2} and is close to the mean of the predicted value obtained by the model with 12.02 kg m^{-2}

aboveground carbon. The ABF showed with an average of 11.05 kg C m^{-2} the lowest results.

With -2.78 kg C m^{-2} the highest difference was shown comparing the average of the model estimations with the one of the Burger function. The means of the estimations of the other three calculation methods only differ between -0.56 kg C m^{-2} (BEF) and 0.52 kg C m^{-2} (ABF). The smallest difference of 0.28 kg C m^{-2} was given, when the model predictions were compared to value of the method using a BCEF. The model shows much less deviation within its own results than the other four calculation methods.

5 Discussion

General trends in the results of carbon estimations obtained from terrestrial input data applied to a standardized species specific tree data set

All four methods estimating carbon from terrestrial data used in this study show similar results for the three tested species and for trees with a DBH of up to 40 cm to 50 cm. This trend was visible for single trees (Figure 2, Figure 5, Figure 8) as well as for the averages of the DBH classes (Figure 3, Figure 6, Figure 9). As we can see for the development of the ABF coefficients (Table 1), the DBH of the analyzed trees ranged from 8 cm to 50 cm, depending on the species. The coefficients used for the BEF function are also based on data of trees with a DBH of up to 40 cm to 60 cm (Hager, 1988; Hochbichler et al., 1994; Sekot, 1982). The high similarity between the results of the different functions regarding small diameter classes can be explained by the fact that the data which were used to develop those functions involved a similar DBH range in most cases.

With an increasing DBH the deviation in between the results of each method and between the results of the different methods amplified. A reason for that might be that the BEFs or the coefficients used in the biomass functions were not based on trees with a DBH higher than 60 cm. Thus, the different methods were applied outside their tested range. This is in line with the findings of Zell (2008), who states that with an increasing size of the estimator (e.g. DBH) an increased standard error should also be used, in order to obtain more realistic results from biomass equations.

The Burger function showed results above the results of the other three methods, when applied to spruce (Figure 3) and the ABF when applied to beech (Figure 6).

The higher values of the Burger function for spruce might be due to the methodology of the function (see section 2.2.2). It is an allometric function which calculates the tree biomass directly from the DBH. As the DBH is the only independent variable, the height of the tree is not accounted for. An increase in the DBH of a tree will lead to an exponential increase of the tree biomass. Thus, unlimited growth in height is assumed, which does not reflect nature. Height growth is determined by site quality and its function follows an asymptotic shape (Marschall, 1975). Looking at the different tree compartments, in which carbon is stored, one can see that carbon stored in the stem of the trees was the highest in greater DBH classes. For the branch and the needle compartment, the results of the Burger function do not differ as much from the results of the other methods, as they do regarding the results of the stem carbon (Figure 4). A reason might be that Burger's research focused on the branch and needle compartment of different tree species, rather than the stem compartment (Burger, 1953; Fehrmann, 2006).

Compared to the findings of other authors, it seems that the values for spruce trees obtained by the Burger function are too high. Zell (2008) developed a generalized allometic biomass function for spruce and beech based on data from the German NFI. His carbon estimations regarding trees with the same DBH are very similar to the results obtained by the method that used a BCEF. Comparable results can also be found in Muukkonen (2007), who developed a generalized biomass equation for spruce trees in Europe. Their findings are in line with the results of the BCEF method. They are also closer to those of the ABF and BEF method, than to the results of the Burger function.

By looking at the carbon storage in each tree compartment regarding beech, one can see that, in contrast to spruce, the results for the stem carbon are similar for all functions (Figure 7). The greatest differences between the methods were detected regarding the branch compartment for which the ABF calculated values that are around 8 times higher than those of the BEF method or the Burger function (Figure 7). The BCEF method does not distinguish between branch and leaf carbon. This might explain why its results are higher than those of the BEF method and the Burger function. However, the results of the BCEF method are much lower than those of the ABF. When calculated with the ABF, the carbon stored in the branches exceeded the carbon stored in the stem in DBH classes from 60 cm to 65 cm and onwards. For the ABF the branch carbon value was around 40% higher than that of the stem carbon in the highest DBH class. This stands in contrast to the findings of other authors who developed biomass equations for beech. Bartelink (1997) developed biomass equations for beech based on data from the Netherlands, Cienciala et al. (2005) based on data from the Czech Republic and Skovsgaard and Nord-Larsen (2011) on trees from Denmark. All three authors showed that the most carbon is stored in the stem over all DBH classes. This assumption is also in line with the results of the other three carbon estimation methods used in this study. Furthermore, the results of Bartelink, Cienciala et al. and Skovsgaard and Nord-Larsen, regarding the whole aboveground biomass, were closer to the results of the BCEF and BEF method as well as the Burger function, than to those of the ABF. The higher results of the ABF compared to those of the other three methods might be rooted in the use of the function outside its tested range. As shown in Table 1 the DBH of the observed trees that Hochbichler et al. (2006) used ranged from 6.6 cm to 52 cm. Thus, if the function is prolonged outside the tested range, the obtained results cannot be verified with observation and therefore, the extent of the error is unknown.

It can be pointed out that the highest deviations for spruce and beech occurred when allometric functions (ABF for beech, Burger for spruce) were used. Vague results can be obtained if allometric functions are applied to trees with a DBH that is outside their tested range because predictions are not verified by observations (Wirth et al., 2004). In general, biomass functions should only be applied to trees that have a DBH within the range of the test data. Unfortunately, the original data that were used to develop the biomass equations has rarely been published in most cases (Fehrmann, 2006; Wirth et al., 2004). Often the applicable range of the functions has neither been identified (Fehrmann, 2006), which makes it hard to determine whether their application is adequate for different DBH classes or not.

Joosten and Schulte (2002) state that general predictions obtained by the BEF function are less precise than those of allometric biomass functions and that their statistical error is often unknown. As a consequence, Joosten et al. (2004) claim that allometric biomass functions should be preferred. The results of our study do not back up those claims. The ABF showed the highest deviation from the results of the other three functions for beech, as did the Burger function for spruce. The results obtained by the BCEF method are those that are most similar to the findings of other authors (for spruce:(Muukkonen, 2007; Zell, 2008); for pine: (Cienciala et al., 2006; Grote et al., 2003); for beech: (Bartelink, 1997; Cienciala et al., 2005; Joosten et al., 2004). Therefore, the results of this study do not confirm that allometric functions are generally better suited to calculate carbon stocks then the BEF methods.

An advantage of using a biomass expansion factor is that merchantable timber volume usually serves as the input for such methods. Volume equations have a long history in forestry and thus, many well tested functions to obtain the timber volume are available even for large trees (Zeide, 1993). As a result, the reduced growth of old trees can be taken into account with this method.

A disadvantage of BEFs, however, is that merchantable timer can only be calculated for trees with a DBH of above 10 cm, which is the margin of merchantable timber. Thus, the biomass of trees with a DBH smaller than 10 cm can usually not be calculated with this method.

The last point worth mentioning in regard to the results is that by comparing the carbon estimations per DBH class for each species (Figure 3, Figure 6, Figure 9), it can be seen that the values are very similar to each other. This is especially true for trees with a DBH of up to 70 cm. It does not matter which tree species is chosen if the management goal simply is to increase the carbon stock of a forest.

Regional influence on trends of carbon estimations obtained by biomass functions using terrestrial input data

To see if the results obtained by the biomass calculation methods differ, when applied to a specific region, the four methods were used to calculate the carbon content for spruce trees taken from the forest inventory of the Montafon study area.

The results for the Montafon region, concerning single trees (Figure 11), the averages of the DBH classes (Figure 12) and the tree compartments (Figure 13), are very similar to the results of the estimations for the standardized tree data set (Figure 2, Figure 3, Figure 4). The same trends as before are visible. Similar results were obtained by all four calculation methods for trees with a DBH of up to 50 cm. For bigger trees the Burger function shows values that are above the values of the other three methods.

Thus, no noticeable regional influence could be detected. A reason might be that the trees from the forest inventory of the Montafon region do not differ much from the trees used in the standardized tree data set.

Zianis and Mencuccini (2003) state that inaccurate estimations may be obtained if generalized equations are applied to a specific stand. Even though this might be true for small stands, our results indicate that the BCEF method, which uses generalized coefficients, displays comparable results to those of the other functions, despite being applied to a specific area.

Carbon estimations by the BIOME-BGC model for the Montafon study region

The carbon estimations obtained by the BIOME-BGC model for the Montafon region show that the model results are very similar to the results calculated with the BCEF method (Figure 18). In addition, the residual plot of the model predictions minus the calculated values of the BCEF method does not exhibit a trend (Figure 19). Thus, it can be assumed that the model gives unbiased results for the carbon that is stored in the Montafon forests.

It has to be acknowledged that the spin-up run only uses pre-industrial values for atmospheric CO2 and nitrogen. As a consequence, the result displays the potential of a fully stock forest stand in pre-industrial times. Today, the potential would be higher, due to almost 250 years of an increased atmospheric CO2 and nitrogen deposition (IPCC WGI, 1996). The spin-up run, however, only ends once an equilibrium stage in all pools of the model is reached. Therefore, it is not possible to exactly simulate the potential of a contemporary forest exactly, since pools are still increasing and it would take many years before an equilibrium is reached (if ever due to still increasing values).

Through a comparison between the calculated carbon values and the model results the sparse variation within the latter becomes obvious. There is almost no variation within the model results, due to the input data that were used. The information about the soil and the climate were interpolated (see sections 2.3.1.1 and 3.3). As a consequence of the interpolation, good estimates for the average values can be obtained, whereas a lot of local variation gets canceled out. The average of the BGC-model and the average of the calculated values, therefore, exhibit comparable values, while it is not possible to obtain extreme values from the BGC-model realistically when using such interpolated input data.

Measures of density and competition such as the crown competition factor or the stand density index are very suitable to determine the timing of a thinning, especially when the management history is unknown or vague. This is a reason why other authors have referred to these measures in this context as well (Hasenauer et al., 2012; Petritsch et al., 2007). Furthermore, the results of the BIOME-BGC model confirm that this is a good way to determine past management even though only very little is known about historic forest treatments, as the integration of the assumed management activities led to realistic results.

Comparing carbon estimations obtained by calculation methods using terrestrial data and by mechanistic model predictions

Figure 20 shows that the model predictions are very similar to the results obtained by the four methods that calculate biomass based on terrestrial input data. The mean of the model estimations differs from the means calculated by the ABF, the BEF and BCEF method in a range of ± 0.5 kg C m-2. The mean carbon value of the Burger function is 2.78 kg C m-2 higher than the model predictions. This can be explained by the high share of species in the Montafon study region. The Burger function exhibits higher values than the other three biomass calculation methods when applied to the standardized spruce tree data set and to the Montafon inventory data set. In addition to that, the average of the carbon estimations for the whole study area obtained by the Burger function was higher than the averages of the other three methods. It is interesting to see that when the mean calculated with the Burger function and the mean of the spin-up are compared both display very similar values (see Figure 20). The mean of the spin-up is even 0.25 kg C m-2 lower than the mean of the Burger function.

6 Conclusion

Our results suggest that for trees with a DBH range of up to 60 cm it does not matter which carbon estimation method is chosen, since their results are all alike for trees within this DBH range. As a consequence, one can conclude that the two different systems of how biomass functions work, using allometric relationships or a biomass expansion factor, produce comparable results.

Second, our study reveals that generalized coefficients in biomass calculation methods (here the BCEF) can be utilized to estimate the tree carbon content of a specific area, without showing different results than biomass calculation methods using nationally developed coefficients (here the ABF and the BEF function). Thus, our findings indicate that it makes no difference whether generalized or nationally tested coefficients are used. Our study, however, is just based upon data from one study area in Austria and therefore, further studies need to be conducted in order to confirm or disprove our assumption.

Third, the results of the BIOME-BGC model's application to the Montafon study area point out that mechanistic modeling produces accurate estimations for a forest's carbon content. Furthermore, the use a mechanistic models such as the BIOME-BGC model holds several advantages over the use of carbon estimation methods based on terrestrial data such as they are less labor intensive since they are not based on forest inventory data, besides carbon estimations around 600 additional output variables can be produced in just one simulation and climate change scenarios can be incorporated, leading to predictions about possible future climate change effects.

Fourth, it has to be noticed that most biomass functions and BEFs are only developed and tested for a DBH range from 0 ~ 60 cm. If carbon estimations are made for trees with a DBH that lies outside this range, unrealistic results may be obtained. This was the case when the Burger function was used to estimate the carbon content of spruce trees and when the ABF was utilized to estimate that of beech trees. Thus, further biomass studies need to be carried out for trees with a higher DBH than 60 cm, in order to adapt those functions so that more realistic results for high diameter classes can be obtained.

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7.1 List of tables

7.2 List of figures

8 Appendix

Table A 1 Species specific parameters for calculating tree height according to Prodan's "Einheitshöhenkurve" (Schmidt, 1956)

Species	a0	a1	a2
Spruche and other NL	20,172	0,110	0,023
Fir	82,199	1,464	0,034
Ash	1,999	0,489	0,059
Alder	1,999	0,489	0,059
Beech	-0,229	1,176	0,023
Mountain-ash	1,999	0,489	0,059
Other BL	1,999	0,489	0,059

$$h_{Prodan} = \frac{DBH^2}{a0 + a1 * DBH + a2 * DBH^2} + 1.3 \qquad (1)$$

Table A 2 Estimates by tree species for computing tree volume (V) according to Kennel (1973). Where *other NL* refers to all remaining needle tree species and *other BL* to all other broad leaf species, respectively.

Species	a0	a1	a2	b0	b1	b2	c0	c1	c2
Spruce	-3,59624	1,80213	-0,28824	1,06247	-0,12899	0,03534	0,14226	-0,05826	0,00460
Fir	-7,41365	3,33667	-0,42642	4,00998	-1,39533	0,16520	-0,32161	0,14401	-0,01655
Larch	-9,26182	4,75438	-0,67250	5,17159	-2,27654	0,31163	-0,55538	0,30280	-0,04125
Pine	-5,80915	3,38700	-0,49439	3,67116	-1,83211	0,27400	-0,45928	0,29989	-0,04449
Douglas Fir	-12,50170	6,62441	-0,91119	7,27277	-3,58346	0,48915	-0,87715	0,51559	-0,07144
other NL	-3,59624	1,80213	-0,28824	1,06247	-0,12899	0,03534	0,14226	-0,05826	0,00460
Alder	-5,98031	2,85905	-0,33740	3,78395	-1,47316	0,13366	-0,54096	0,29696	-0,03852
Ash	-2,72840	0,83756	-0,10534	1,62283	-0,21481	0,02893	-0,08797	0,03257	-0,00446
Beech	-2,72840	0,83756	-0,10534	1,62283	-0,21481	0,02893	-0,08797	0,03257	-0,00446
other BL	-2,72840	0,83756	-0,10534	1,62283	-0,21481	0,02893	-0,08797	0,03257	-0,00446

$$V_{Kennel} = DBH_i^2 * \frac{\pi}{4} * fh_i \qquad (2)$$

$$fh_i = e^{a + b * \ln(h_i) + c * ln^2(h_i)} \qquad (3)$$

$$a = a_0 + a_1 * \ln(dbh) + a_2 * ln^2(dbh) \qquad (4)$$

$$b = b_0 + b_1 * \ln(dbh) + b_2 * ln^2(dbh) \qquad (5)$$

$$c = c_0 + c_1 * \ln(dbh) + c_2 * ln^2(dbh) \qquad (6)$$

Table A 3 Species specific coefficient for calculating Crown Width (CW) according to Hasenauer (1997). Where other NL refers to all remaining needle trees and other BL for all remaining broad leaf trees, respectively.

Species	b0	b1	b2
Spruce and other NL	-5,04936	2,73927	-0,08860
Pine	-3,28558	2,16843	-0,14726
Beech and other BL	-3,54015	3,93514	-1,59363
Oak	-3,85999	3,19260	-0,75400

$$\ln(CW) = a + b * \ln(dbh) \quad (9)$$

Table A 4 Fraction of merchantable timber (MT), dry matter carbon fraction (CC) and fresh weight dry matter fraction (1-WC) as well as timber density (WD) by tree species, where other NL refers to all remaining needle tree species and other BL to all remaining broad leaf species, respectively.

Species	Merchantable timber fraction	Dry matter carbon fraction (CF) (kg C / kg)	Fresh weight dry matter fraction (1-WC) (kg/kg)	Timber desity (D) (kg/m³)
Spruce and other NL	0,700	0,503	0,440	800
Pine	0,694	0,500	0,500	820
Larch	0,850	0,503	0,440	800
Oak	0,760	0,504	0,500	1000
Beech and other BL	0,825	0,486	0,440	950

Values for Beech (*Fagus sylvatica*) were taken from Hochbichler et al. (1994), for Oak (*Quercus robur/petraea*) from Hochbichler (1993), for Pine (*Pinus sylvestris*) from Sekot (1982) and for Larch (*Larix decidua*) and Spruce *(Picea abies*) from Hager (1988).

$$dsm = Vol_{Kennel} * D * (1 - WC) \quad (11)$$

The aboveground carbon content with the BEF method is then calculated using equation (17) where the stem biomass (*dsm*) is calculated according to equation (11) and the dry needle biomass (dbm) is calculated according to equation (12):

$$C_{aboveground} = \frac{dsm * CF}{MT} + dnm * CF \quad (17)$$

Table A 5 Parameters for calculating the dry mass of branches according to Hochbichler et al. (2006) for spruce and all other needle trees (other NL), pine, beech and all other broad leaf trees (other BL) as well as oak.

Species	b0	b1	b2
Spruce and other NL	-5,16890	2,69049	
Pine	-3,34766	2,04663	
Beech and other BL	-3,54015	3,93514	-1,59363

$$dbm \ = e^{(b_0+b_1*\ln(DBH)+b_2*\ln\,(H))} \tag{12}$$

Table A 6 Parameters for calculating the dry mass of needles according to Hochbichler et al. (2006) for spruce and all other needle trees (other NL) and pine.

Species	b0	b1
Spruce and other NL	-6,17165	2,83519
Pine	-3,78862	1,78458

$$dbm\ [dnm] = e^{(b_0+b_1*\ln(DBH))} \tag{13}$$

Table A 7 for conversion of merchantable timber volume to abovground tree biomass (BEF2), basic wood desity for tree species (D) and dry matter carbon fraction (CF) according to (IPCC, 2003)

	D		CC
Spruce	0,41	**Broadleafes**	0,48
Fir	0,40	**Conifer**	0,51
Larch	0,46	**default**	0,50
Pine	0,42		
Douglas Fir	0,45		
Beech	0,58		
Other BL	0,45		**BEF2 (default)**
Mountain-ash	0,58	**Temperate conifers**	1,30
Poplar	0,35	**Temperate broadleaf**	1,40
Maple	0,52	**Boreal conifers**	1,35
Ash	0,57	**Boreal broadleaf**	1,30

$$C_{aboveground} = (Vol_{Kennel} * D * BEF2) * CF \qquad (18)$$

Table A 8 Parameters for calculating the dry mass of the stem according to Burger (1953) for spruce and all other needle trees (other NL), fir, pine, beech and all other broad leaf trees (other BL) as well as for alder, rowan and maple

species	a	b
spruce and other NL	0,03007189	2,74001367
fir	0,03007189	2,74001367
pine	0,04750124	2,52715533
beech and other BL	0,22225	2,2503739
alder	0,22225	2,2503739
rowan	0,22225	2,2503739
maple	0,22225	2,2503739

$$dsm[dbm] = a * DBH^b \qquad (15)$$

Table A 9 Parameters for calculating the dry mass of the branches according to Burger (1953) for spruce and all other needle trees (other NL), fir, pine, beech and all other broad leaf trees (other BL) as well as for alder, rowan and maple

species	a	b
spruce and other NL	0,022	2,3
fir	0,022	2,3
pine	0,036	2,0534
beech and other BL	0,022	2,3
alder	0,022	2,3
rowan	0,022	2,3
maple	0,022	2,3

$$dsm[dbm] = a * DBH^b \quad (15)$$

Table A 10 Parameters for calculating the dry mass of the foilage according to Burger (1953) for spruce and all other needle trees (other NL), fir, pine, beech and all other broad leaf trees (other BL) as well as for alder, rowan and maple

species	a	b	c	d
spruce and other NL	1,385	0,3	0,23	1,56
fir	1,206	0,3	0,23	1,56
pine	1,431	0,3	0,17	1,4
beech and other BL	1,206	0,3	0,06	1,7
alder	1,385	0,35	0,1	1,43
rowan	1,385	0,35	0,08	1,43
maple	1,385	0,3	0,06	1,7

$$dnm = a * b * c * DBH^d \quad (16)$$