Tree volume and biomass equations for *Picea abies* and *Larix decidua* in South Tyrol

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Abstract

In this article we present predictive equations for above and below ground biomass of *Picea abies* and *Larix decidua* based on sample trees collected in the Province of Bolzano - South Tyrol (Italy). Sample trees have been selected in the plots of the Italian National Inventory of Forests and Carbon Stocks and measured with the technique of the randomized branch sampling.
This set of equations ultimately constitutes a tool for the estimation of biomass and standing volume for single trees and forest stands. This activity aims to the estimation of the carbon content and annual fluxes in the different compartments of the typical forest ecosystems of the Province.

Key words: tree phytomass, prediction models, woody biomass.

1. Introduction

Till the last decades the quantification of the forest biomass mostly aimed to the wood market and therefore was limited to the estimation of the timber volume per tree or stand (yield and volume tables). Nowadays, the woody biomass has gained a broader socio-economic relevance as important compartment for the storage of carbon on land.
For this reason there is an increasing need of validated statistical methods and tools to assess the amount and distribution of the forest biomass in the different ecosystem compartments, quantify its carbon content and in general the capacity of forest ecosystems to exchange and accumulate organic carbon above and belowground.

The estimation of biomass equations from sample trees is part of a project started in 2005, aiming to the quantification of the carbon fluxes and pools of the most important forest ecosystems of South Tyrol.
The methodological approach (Fig. 1) − based on the integration of biometric models and experimental observations collected at sample plots (e.g. soil and wood samples, hemispherical photograph, etc.) with remote sensing and environmental data (e.g. forest types, topography) − aims to the up-scaling of the following parameters:

1) Total biomass of the main forest tree species
2) Ecosystem carbon *pools* separated in the following compartments:
    - aboveground biomass,
    - belowground biomass,
    - litter,
    - deadwood,
    - soil organic matter,
3) Net Ecosystem Productivity (NEP) or carbon-sink.

For this purpose, a statistical representative sample of model trees has been defined on the basis of the data collected during the Italian National Inventory of Forests and Carbon Stocks (INFC, 2003-2006). Both the spatial distribution of the different forest types and the distribution of trees in diameter classes have been considered to identify an unbiased set of sample trees.

This work complements the analogous activity carried out in the nearby Province of Trento (1) and extends the methodology to the estimation of below ground tree biomass

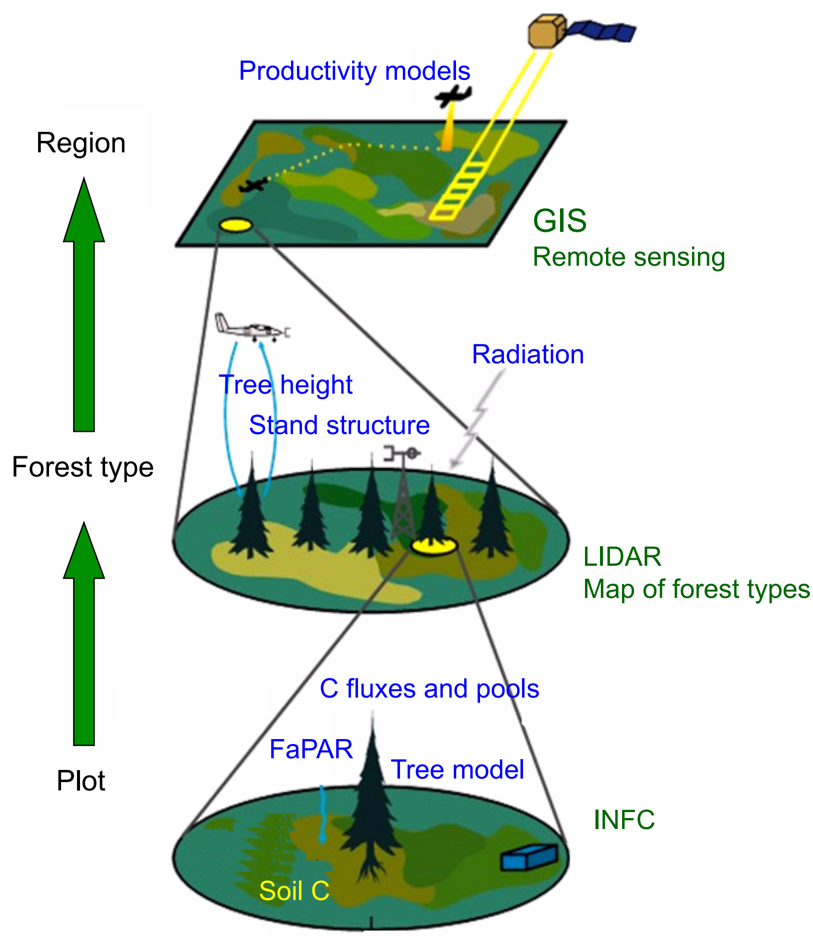

Fig 1 – Data and tools used for the spatial integration of the target variables.

2. Sampling sites

The selection of sites suitable for the collection of sample trees was based on the experimental plots of the 2nd phase of the INFC (Fig. 2) and consequently the areas are randomly distributed in the territory of the Province.
Sample plots were selected using GIS queries that accounts for raster and vector layers (altitude, accessibility, DEM) and plot attributes collected during the INFC (topography, land property, etc.). The sampling was finally designed to consider the following criteria:

- Distribution of sample trees of the main forest species in the three bio-geo-ecological sectors of the Province (West, Centre-South, East);
- Distribution of sample trees in altitude classes (e.g. for Norway spruce in the two altitudinal bands 1000-1600 m a.s.l. and higher than 1600 m a.s.l.);
- Exclusion of plots in private land property;
- Occurrence of suitable sample tree (see chapter 3 – Tree sampling) located within 100 m from the centre of the inventory plot (in homologous environmental conditions), but outside the boundaries of the INFC sample area;
- Distance from forest road between 20 and 50 m to facilitate access and avoid major edge effects (Fig. 3);
- Equal distribution of the plot in geographic homogeneous clusters (Fig. 5).

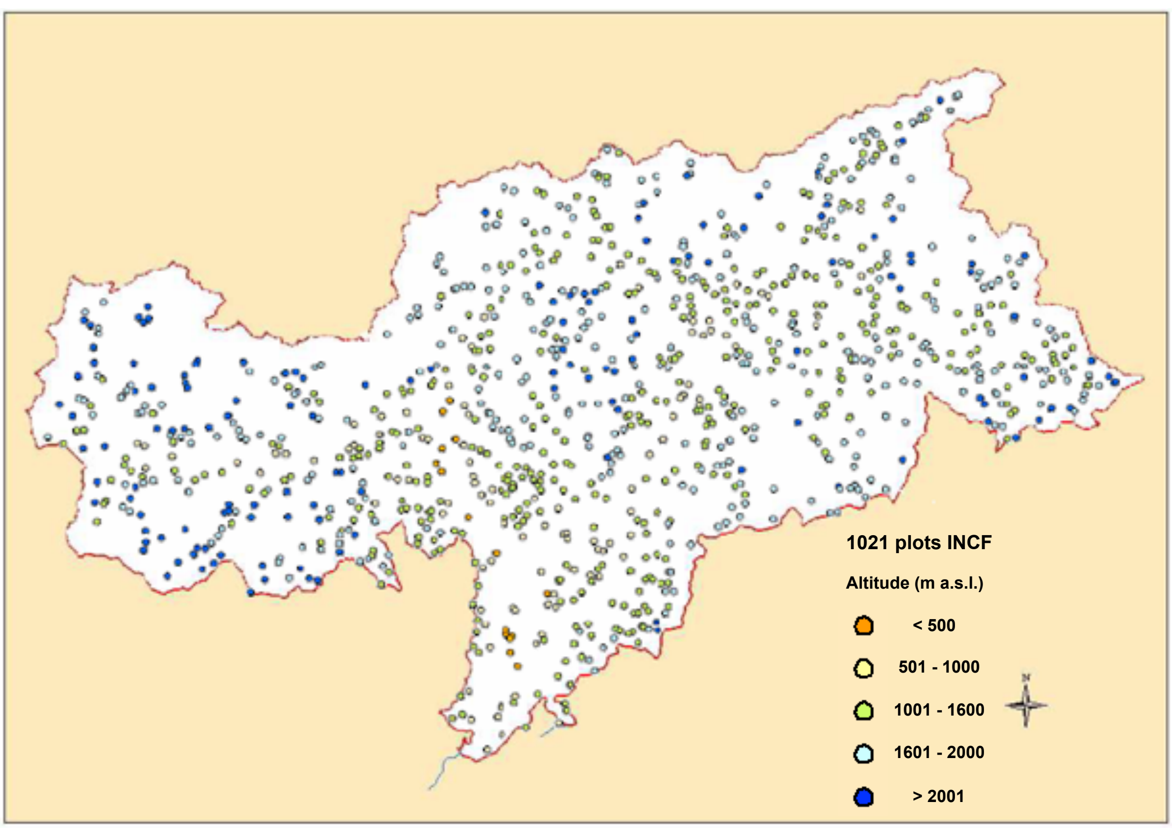

Fig. 2 – The 1021 plots of the 2nd phase of the INFC.

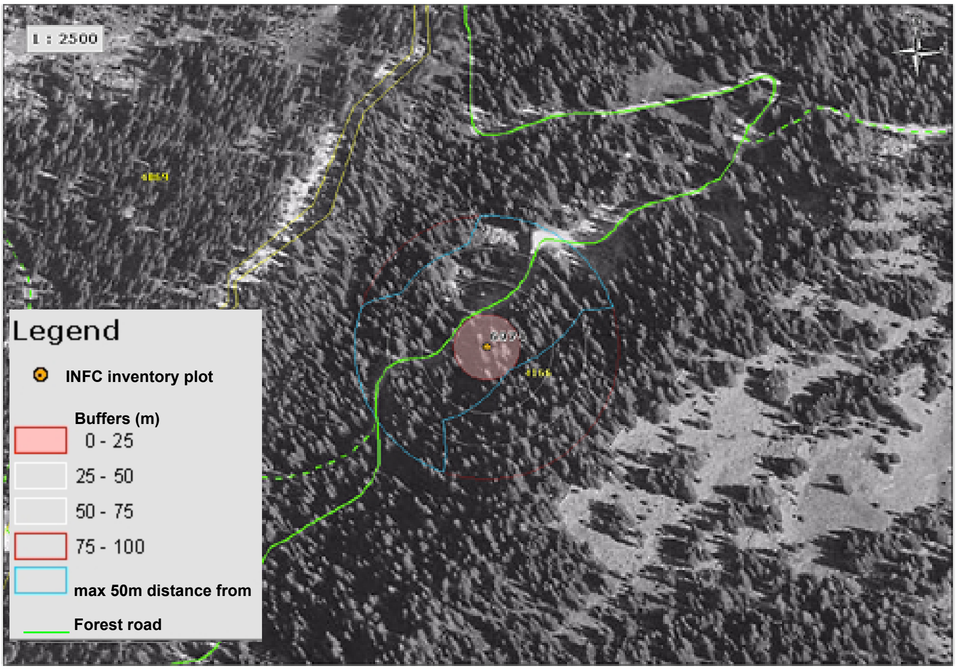

Fig. 3 – Example of sampling site located at the INFC plot with buffer areas for the selection of sample trees.

Following the selection criteria a total of 98 inventory plots were selected (Table 1, Fig. 4)

PLOT NUMBER	ALTITUDE (M A.S.L.)	ZONES
47	> 1601	sub-alpine
38	1001 - 1600	montane
10	501 - 1000	sub-montane
3	< 500	lowland

Tab. 1 – Distribution of sample plots in altitudinal belts.

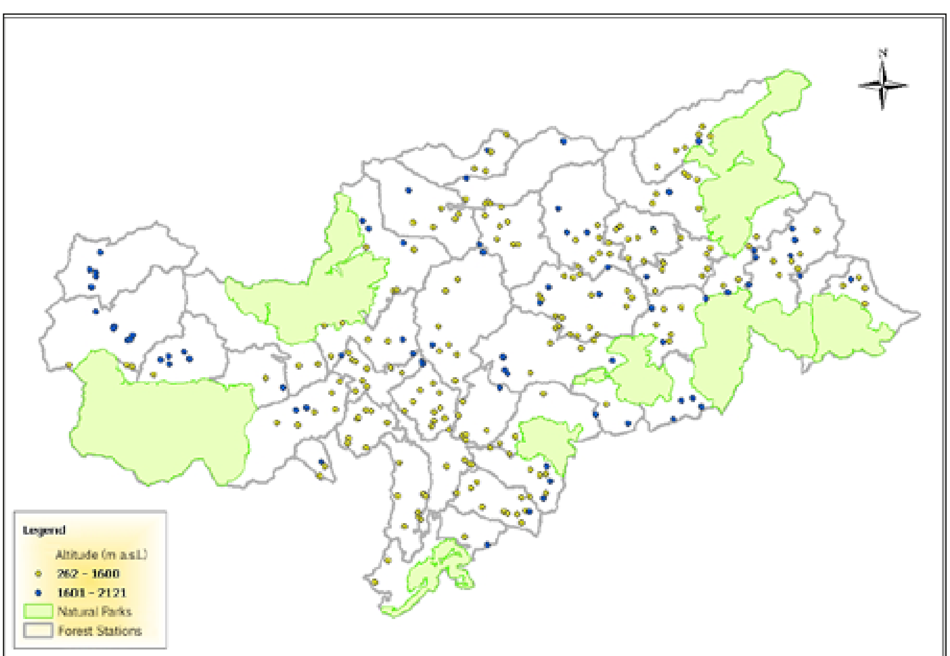

Fig. 4 – Map of the 98 sites selected for the tree sampling.

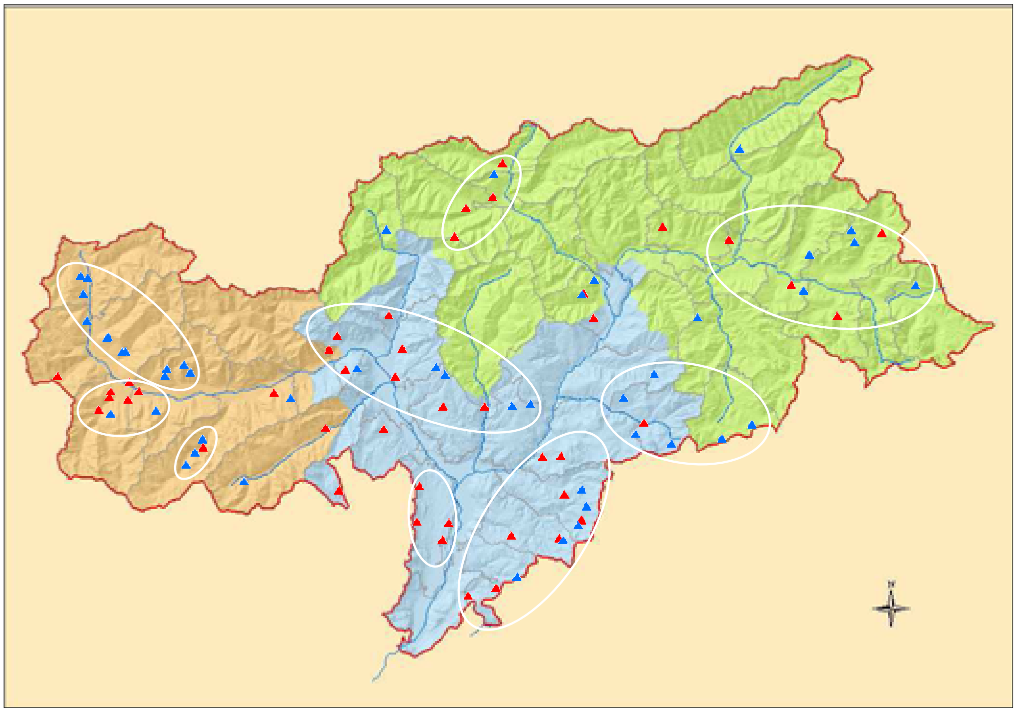

Fig. 5 – Clusters of plots selected for the sampling of Norway spruce (Picea abies).

3. Tree sampling

Trees were uniformly selected in diameter classes (range 5-100 cm of diameter at 1,30 m, *dbh*) including bifurcated or partially rotten trees. On the contrary, trees with major anomalies (e.g. stem breakage, leafless, dead trees, etc.) were excluded. In total 120 sample trees were harvested and processed for aboveground biomass and 21 for belowground biomass (°). The distribution of sample trees between species and geographic sectors is summarized in Table 2.

The limited sample size for Norway spruce and European larch was compensated by integrating the dataset with that of the nearby Trento Province. For the other conifers such as for broadleaves, giving the limited sample size, the use of the biomass equations estimated for the Trento Province is recommended (1).

(°) As a consequence of the economic cuts to the foreseen personnel costs (decree 23.12.2005, n° 266/213) the number of sample trees for the aboveground biomass (both conifers and broadleaves) was reduced from 175 to 120 and the sub-sample for the belowground biomass from 60 to 21 sample trees.

Tab. 2 – Distribution of sample trees by species and sector.

SPECIES / Geographic sector		WEST	CENTRE SOUTH	EAST	TOTAL
Picea abies	Sub-alpine	8	25	10	43
	Montane	4	10	10	24
Larix decidua		7	7	6	20
Pinus sylvestris		3	4	4	11
Pinus cembra		5	5	5	15
Abies alba			6	1	7
Broadleves spp.					0
					120

3.1. Sampling methodology

The biomass of sample trees has been divided into different compartments (Tab. 3, Fig. 6), according to the sampling scheme of the project RISELVITALIA (2). The belowground biomass has been analysed with an original procedure described in the following paragraphs. Tree sampling was performed during the summer season in the years 2006-2009 in order to quantify the leaf biomass at the peak of the growing season.

Tab. 3 - List of biometric variables collected for each sample trees and related acronym.

Acronym	Unit	Description
dbh	cm	Diameter at 1,30 m
h	m	Height
a	year	Age
S_VOL	dm^3	Stem volume (up to 5 cm ∅)
L_DW	kg	leaf biomass (dry weight)*
B_DW	kg	biomass of living branches (dry weight)
D_DW	kg	biomass of dead branches (dry weight)
S_DW	kg	Stem biomass up to 5 cm ∅ (dry weight)
AG_DW	kg	Total aboveground biomass (dry weight)
R_DW	kg	Root biomass (dry weight)*

* limited to a subsample of trees

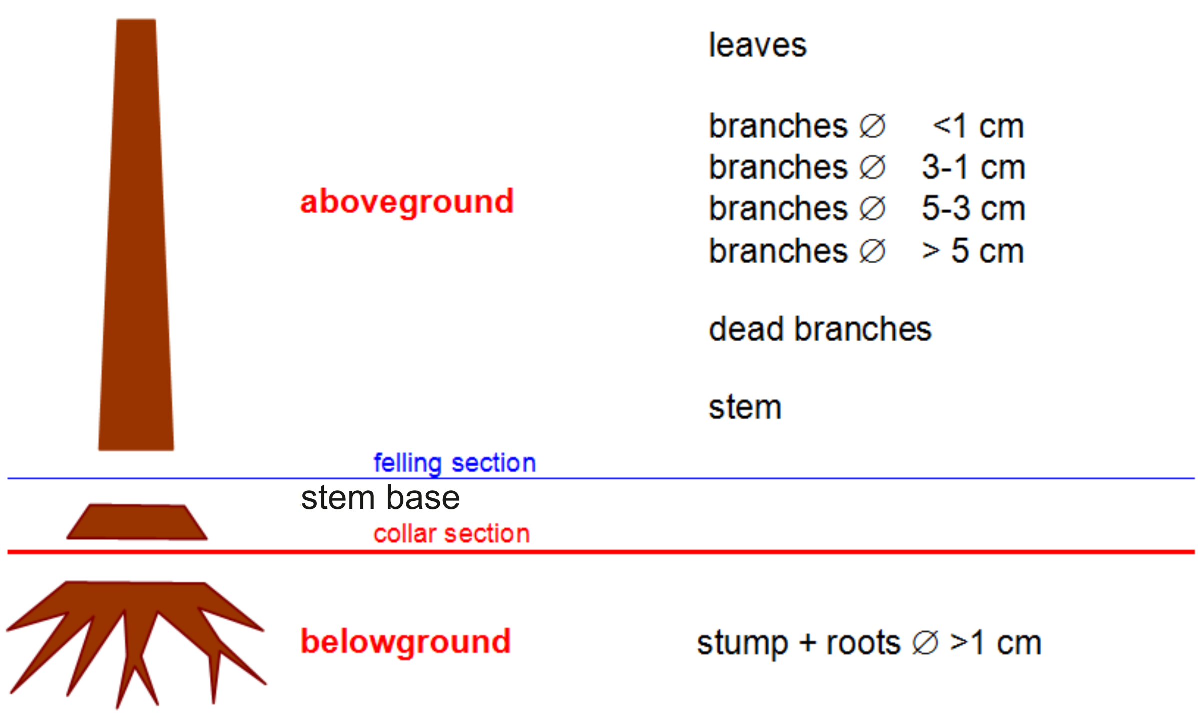

Fig. 6 – Partitioning of the tree biomass in the different compartments.

3.2. Aboveground biomass

The biomass of the stem and of the thicker branches (∅ larger than 5 cm) was derived from the estimate of the volume (by section analysis) in order to preserve the commercial value of the wood and to obtain in parallel the stem volume. All other tree compartments were estimated by direct weighting the biomass or a subsample of it.

Crown biomass was estimated using the statistical method know as Randomized Branch Sampling (RBS, 3). RBS is a multistage sampling method that minimizes the experimental effort and provides unbiased estimators of the average and variance of the target variables.

Since the sampling scheme adopted in the nearby Province of Trento was not based on RBS, the joint analysis of the datasets collected in the two Provinces was therefore limited to the biomass and volume of the stem and to the biomass of the dead branches.

3.3. Belowground biomass

Given the complexity of the experimental assessment of belowground tree biomass, this variable has been rarely considered in forest inventories and the availability in the literature of biomass equations for root biomass is rather limited. For this reason a novel sampling technique has been developed in order to reduce the experimental effort while maintaining the representativeness of the sample in the statistical analysis.

The experimental plots for the assessment of belowground biomass were selected by subsampling the plots used for the analysis of the above ground biomass according to the following criteria:

- Representativeness of the sample tree in the diameter distribution of the species;
- Regular micro-topography of the terrain (flat surface, loose soil, absence of outcropping rocks) to assume the symmetric development of the root system (Fig. 7);
- Minimum slope to facilitate the use of high-pressure water jets during the excavation of the roots.

The details of the sampling methodology developed in this study for the estimation of the root biomass is reported in Appendix A.

Belowground biomass equations have been estimated for 11 and 4 sample trees for Norway spruce and European larch, respectively. Despite the limited sample size the biomass equations well represents the distribution of the root biomass as a function of the two predictors (tree diameter and height for R_DW in Tab. 4-5 and Fig. 8f-9f).

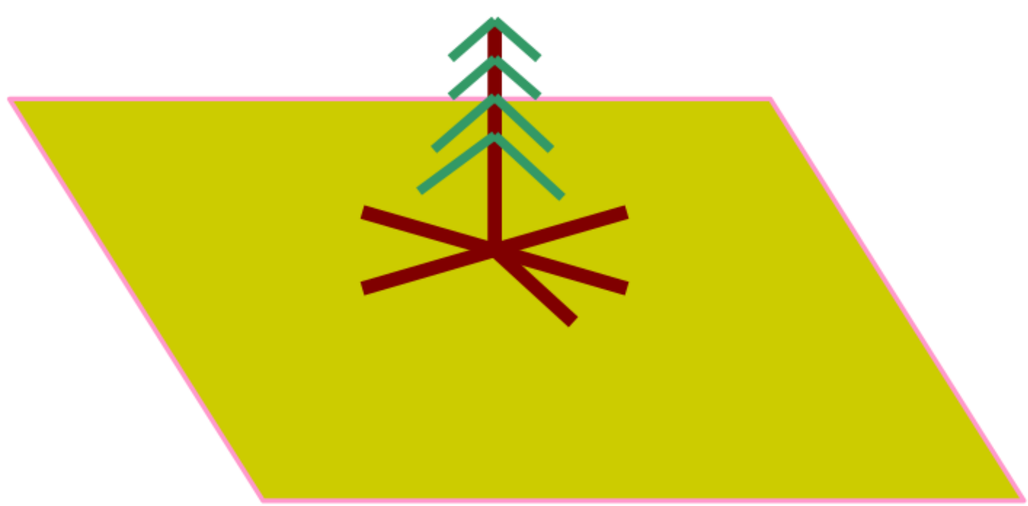

Fig. 7 – In the selection of the sample tree, regular topography and gently sloping terrain are preferred.

4. Biomass equations

The total tree dry biomass is estimated by a modular predictive model given by the sum of the biomass equations related to the different tree compartments. The model is equivalent to a regional two-entry biomass table using tree diameter and height as predictors.

All equations are estimated with the analytic least square method for multiple linear forward step-wise regressions of the following general form, and include all terms with regression coefficients significantly different from zero at *t* test ($p<0.05$):

$$DW = \mathbf{b_1}d + \mathbf{b_2}h + \mathbf{b_3}dh + \mathbf{b_4}d^2h + \mathbf{b_5}dh^2 + \mathbf{b_6}d^2h^2 ,$$

where:

DW dry weight (kg) or VOL = volume (dm^3)
d stem diameter at 1.30 m height (cm)
h tree height (m)
b_i regression coefficients

The use of the product $\mathbf{dh^2}$ among the predictors linearizes the relationships, while the inclusion of tree height explains the variability due to the various tapering of trees growing at different altitudes and stand densities.

In the following tables 4 and 5, the equations for the different biomass compartments (leaves, branches, dead branches, stem, belowground) are summarized. Equations refer to Norway spruce (67 and 83 model trees) and European larch (20 and 33 model trees) in the Provinces of Bolzano and Trento, respectively. Regression coefficients are reported together with the standard error of the estimates and the results of the *t* test.
Giving the different partitioning in biomass compartments used for the model trees collected in the Province of Trento, the leaf biomass is aggregated with the fine branches (< 5 cm) and therefore the equations referring to the total sample (Bolzano + Trento) is limited to the estimate of the following compartments: stem biomass and volume, branch biomass and dead branches ($\_DW_{BZ+TN}$ in Tab. 4 e 5).
Biomass equations for the other tree species are available in Fattorini *et al*. (2004). The biometric models estimated by Fattorini et al. (2004) for the total aboveground biomass are resumed in Table 6.

Tab. 4 – Biometric equations for **Norway spruce**: regression coefficients and related statistics for the different compartments.

Compartment		Equation	b_i	Std. Err.	t	p-level	Adj. r^2	No. of cases
L_DW_{BZ}	leaves	$b_1\,\mathbf{d^2} + b_2\,\mathbf{d^2h}$	0.043738	0.005044	8.67133	0.000000	0.90	67
			- 0.000544	0.000157	-3.46560	0.000942		
B_DW_{BZ}	branches	$b_1\,\mathbf{d^2} + b_2\,\mathbf{dh}$	0.171182	0.024573	6.96619	0.000000	0.89	67
			- 0.119155	0.047228	-2.52297	0.014093		
D_DW_{BZ+TN}	dead branches	$b_1\,\mathbf{d^2} + b_2\,\mathbf{dh^2}$	0.017373	0.002210	7.86251	0.000000	0.67	150
			- 0.000407	0.000123	-3.31075	0.001169		
S_DW_{BZ+TN}	stem	$b_1\,\mathbf{d^2h} + b_2\,\mathbf{dh}$	0.008272	0.000437	18.92001	0.000000	0.98	150
			0.234490	0.024077	9.73938	0.000000		
R_DW_{BZ}	roots	$b_1\,\mathbf{d^2h}$	0.006320	0.000173	36.45965	0.000000	0.99	11

S_VOL_{BZ+TN}	stem volume ∅ >5cm	$b_1\,\mathbf{d^2h}$	0.032473	0.000327	0.000327	0.000000	0.98	149

Tab. 5 – Biometric equations for European larch: regression coefficients and related statistics for the different compartments.

Compartment		Equation	b_i	Std. Err.	t	p-level	Adj. r^2	No. of cases
L_DW_{BZ}	leaves	b_1 **dh**	0.009514	0.000849	11.210976	0.000000	0.86	20
B_DW_{BZ}	branches	b_1 **d²**	0.068074	0.005901	11.535233	0.000000	0.87	20
D_DW_{BZ+TN}	dead branches	$b_1 \mathbf{d^2} + b_2 \mathbf{dh} + b_3 \mathbf{h^2}$	0.030292	0.004836	6.263450	0.000000	0:76	53
			-0.081967	0.022539	-3.636682	0.000653		
			0.064423	0.025859	2.491330	0.016090		
S_DW_{BZ+TN}	stem	$b_1 \mathbf{d^2h} + b_2 \mathbf{dh}$	0.011560	0.000879	13.145712	0.000000	0.98	53
			0.169109	0.056597	2.987952	0.004311		
R_DW_{BZ}	roots	$b_1 \mathbf{d^2h^2}$	0.000403	0.008799	113.63904	0.000002	0.99	4
S_VOL_{BZ+TN}	stem volume ∅ >5cm	$b_1 \mathbf{d^2h} + b_2 \mathbf{dh^2}$	0.021609	0,001792	12,056517	0,000000	0.99	53
			0,017364	0,004017	4,322353	0,000072		

Tab. 6 – Biometric models and regression coefficients for the aboveground biomass AG_DW of the main forest species for the Province of Trento as reported in Fattorini et al. (2004).

Species	Equation	b_1 / Std. Err.	b_2 / Std. Err.	b_3 / Std. Err.
Picea abies	$b_1 + b_2 \mathbf{d^2h} + b_3 \mathbf{dh^2}$	8.8297	$1.8760\cdot10^{-2}$	$-8.5316\cdot10^{-5}$
		$8.5243\cdot10^{-1}$	$2.0997\cdot10^{-3}$	$2.6360\cdot10^{-3}$
Larix decidua	$b_1 + b_2 \mathbf{d^2h} + b_3 \mathbf{d}$	$1.3245\cdot10$	$1.8785\cdot10^{-2}$	$2.1401\cdot10^{-3}$
		8.6570	$2.1401\cdot10^{-3}$	1.1164
Pinus sylvestris	$b_1 + b_2 \mathbf{d^2h}$	2.7081	$2.3724\cdot10^{-2}$	-
		2.4017	$1.3878\cdot10^{-3}$	-
Pinus nigra	$b_1 + b_2 \mathbf{d^2h} + b_3 \mathbf{d^2}$	$-1.2958\cdot10$	$1.3807\cdot10^{-2}$	$2.0206\cdot10^{-1}$
		2.5941	$2.7837\cdot10^{-3}$	$3.4292\cdot10^{-2}$
Pinus cembra	$b_1 + b_2 \mathbf{d^2h} + b_3 \mathbf{d^2}$	-3.4268	$1.0256\cdot10^{-2}$	$1.4144\cdot10^{-1}$
		1.3511	$1.7403\cdot10^{-3}$	$2.7527\cdot10^{-2}$
Abies alba	$b_1 + b_2 \mathbf{d^2h} + b_3 \mathbf{d^2}$	3.3424	$1.6487\cdot10^{-2}$	$8.1355\cdot10^{-2}$
		3.6804	$2.6407\cdot10^{-3}$	$5.2771\cdot10^{-2}$
Fagus sylvatica	$b_1 + b_2 \mathbf{d^2h} + b_3 \mathbf{d^2}$	$-1.0798\cdot10$	$1.8017\cdot10^{-2}$	$2.5888\cdot10^{-1}$
		7.8180	$7.6765\cdot10^{-3}$	$1.3606\cdot10^{-1}$
Castanea sativa	$b_1 + b_2 \mathbf{d^2h} + b_3 \mathbf{d^2}$	$1.8104\cdot10^{-1}$	$1.0740\cdot10^{-2}$	$2.0189\cdot10^{-1}$
		1.6333	$3.4309\cdot10^{-3}$	$4.2520\cdot10^{-2}$

As expected the significant predictors are different for the various biomass compartments. For Norway spruce both the root biomass and the stem volume are strongly correlated with $\mathbf{d^2h}$, while the biomass of leaves, branches and dead branches are correlated with $\mathbf{d^2}$ and **dh**.
The determination coefficient of the different models for Norway spruce (European larch) varies between 0.67 (0.76) for the biomass of dead branches to 0.99 (0.99) for the belowground biomass. The low value of r^2 for the dead branches is due to the high variability of the samples for that compartment. Figure 8 and 9 report the comparison of observed and predicted values for the different tree compartments in Norway spruce and European larch.

Using tree diameter and height as predictors in the equations reported in Table 4 and 5 it is therefore possible to estimate:

1 – The **biomass** in the different tree compartments and the total biomass as sum;
2 – The **C content** or CO_2 equivalent of the compartments;
3 – The **stem volume**

The reported error of the regression coefficients finally allows the estimation of the uncertainties both for the single tree and for the forest stand.
The biometric models have been estimated on different datasets (model tree for South Tyrol only and for South Tyrol+Trento). The result of the comparison between models is reported in Appendix B.

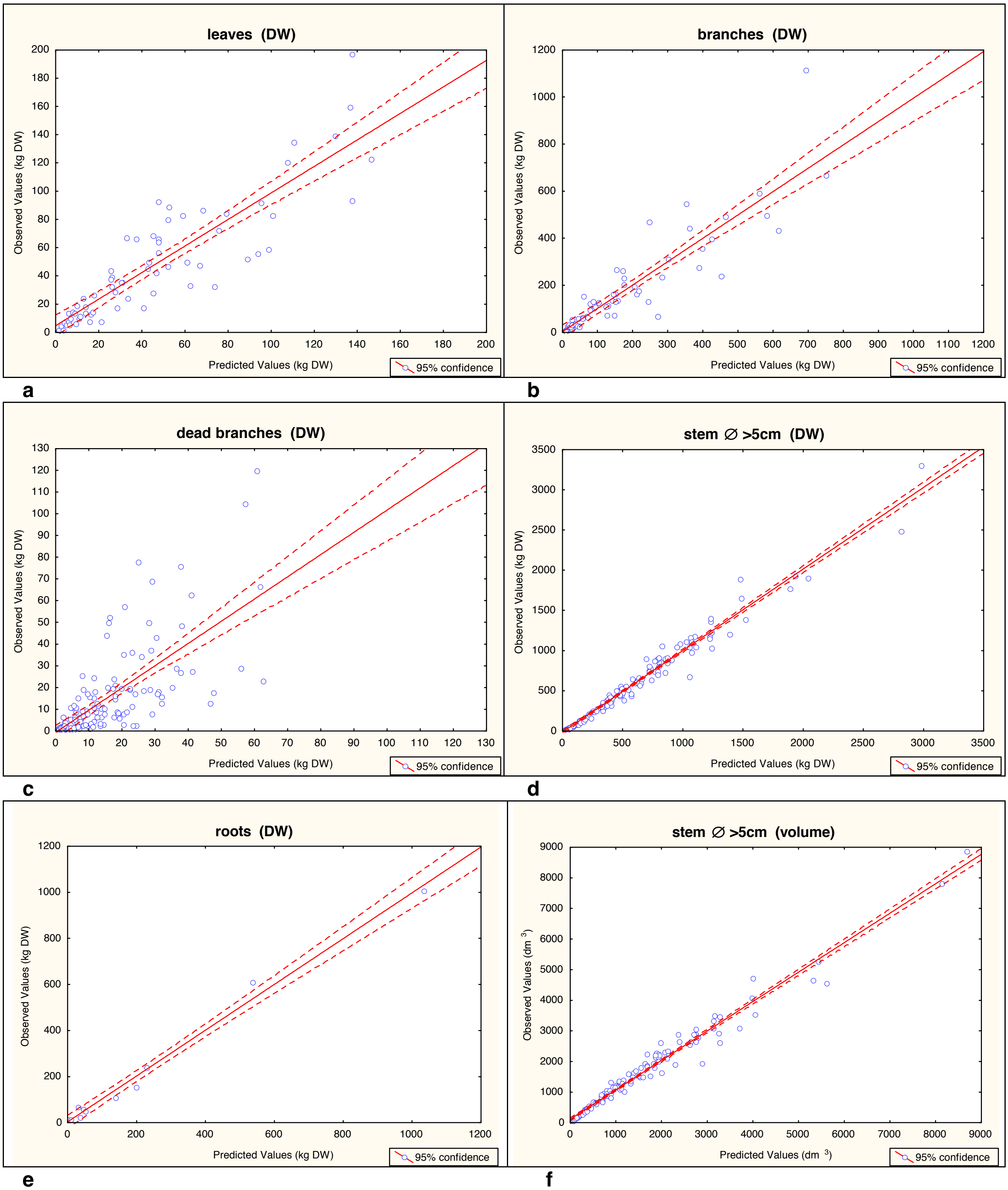

Fig. 8 - Predicted versus observed values for the different biomass compartments in Picea abies.

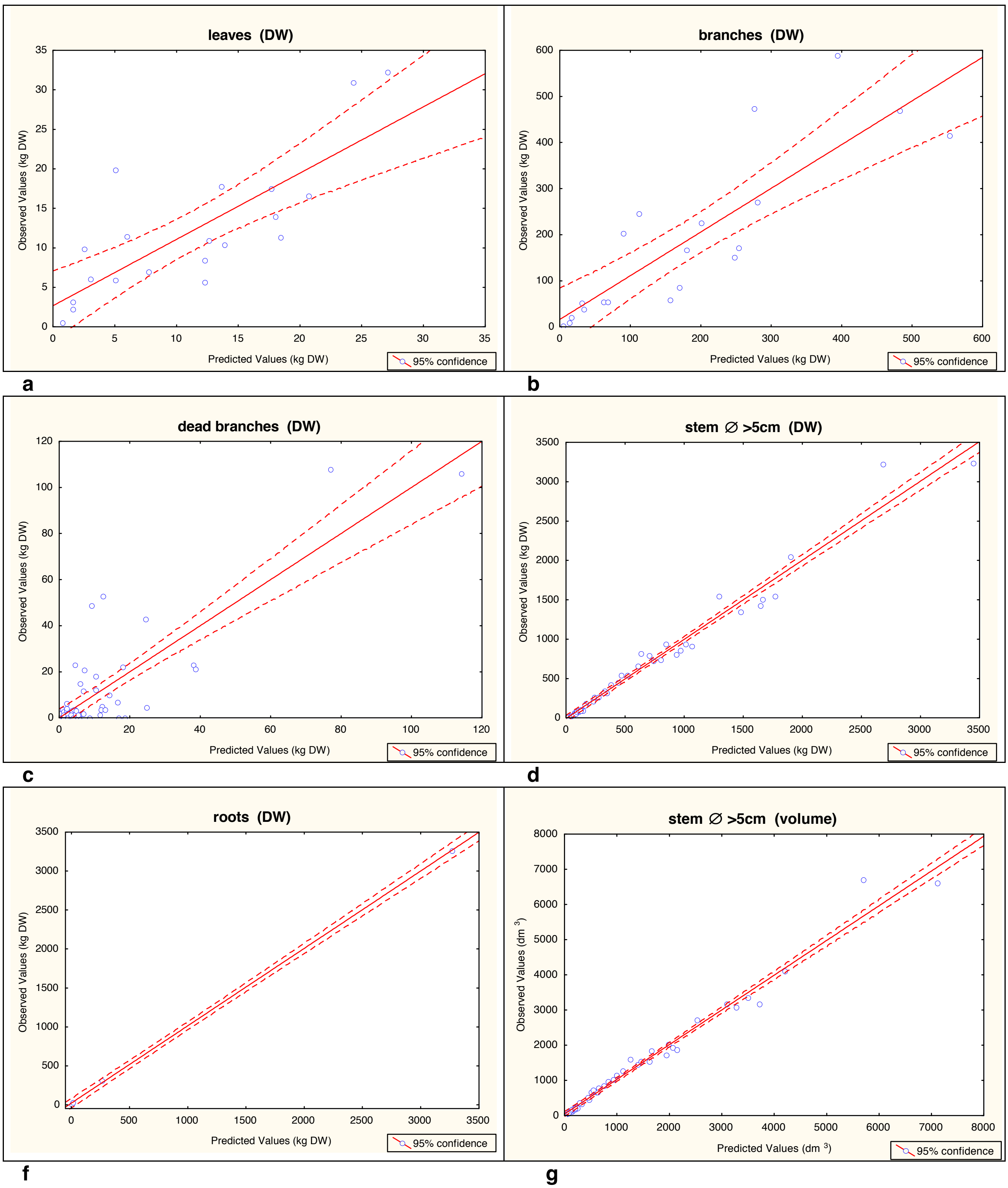

Fig. 9 - Predicted versus observed values for the different biomass compartments in Larix decidua.

On average, the aboveground biomass in Picea abies and Larix decidua is distributed in the aboveground compartments as follows:

Picea abies	%
leaves	6
branches	23
stem	71

Larix decidua	%
leaves	1
branches	16
stem	83

and when referred to the total tree biomass:

Picea abies	%
leaves	4
branches	17
stem	53
roots	26

Larix decidua	%
leaves	0,5
branches	9,5
stem	50
roots	40

In Picea abies the larger fraction of total tree biomass is allocated in the stem (53%), followed by the root system (between 7 and 30% as a function of the diameter, avg. 26%) and finally by branches. On the contrary, for Larix decidua the biomass allocated to the stem is almost equal to that allocated belowground. The European larch is characterized by low leaf biomass and a relevant fraction of mass invested in the root system (between 8 and 44% depending on the diameter, avg. 40%)).
The results of the analysis show that the experimental ratio of below- versus above-ground biomass (coarse roots, ∅ >2 mm) is on average **0.35** for Norway spruce (0.20-0.40 depending on dbh), **0.67** for European larch (0.40-0.80 depending on dbh). These values are considerably larger than those reported in the literature, typically in the range 0.20-0.26 (15,16).

The partition of the total biomass [kg DW] in the various tree compartments as a function of tree diameter is reported in Fig. 10 e 11. About 50% of the dry weight is represented by organic carbon.
The generalized models based on the complete dataset are reported in form of two-entry tables and figures in Appendix C.

Conclusions

The biometric models presented in this work are fundamental instruments to estimate the stem volume, the biomass and the carbon content of the above and belowground tree compartments of Picea abies and Larix decidua. The development of these models is finalized to the on-going assessment of the carbon stocks and sinks of the forest ecosystems in South Tyrol at various level of spatio-temporal integration (geographical sectors, administrative boundaries, individual land properties, successive inventories).
The conversion of the biomass/volume equations in simple two-entry tables offers a simple tool to quantify the relevant biometric properties of single tree and stands as required for administrative,

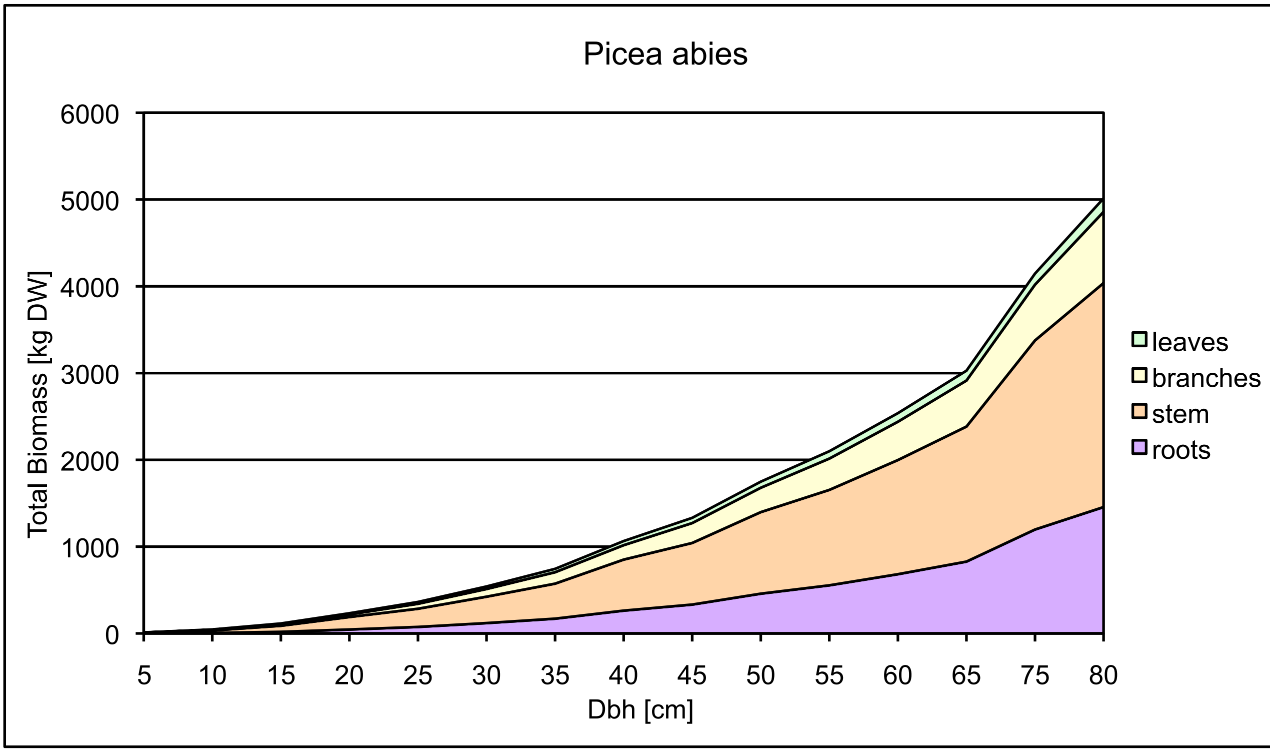

Fig. 10 – Average distribution of the biomass [kg DW] in the tree compartments for the different diameter classes in Picea abies.

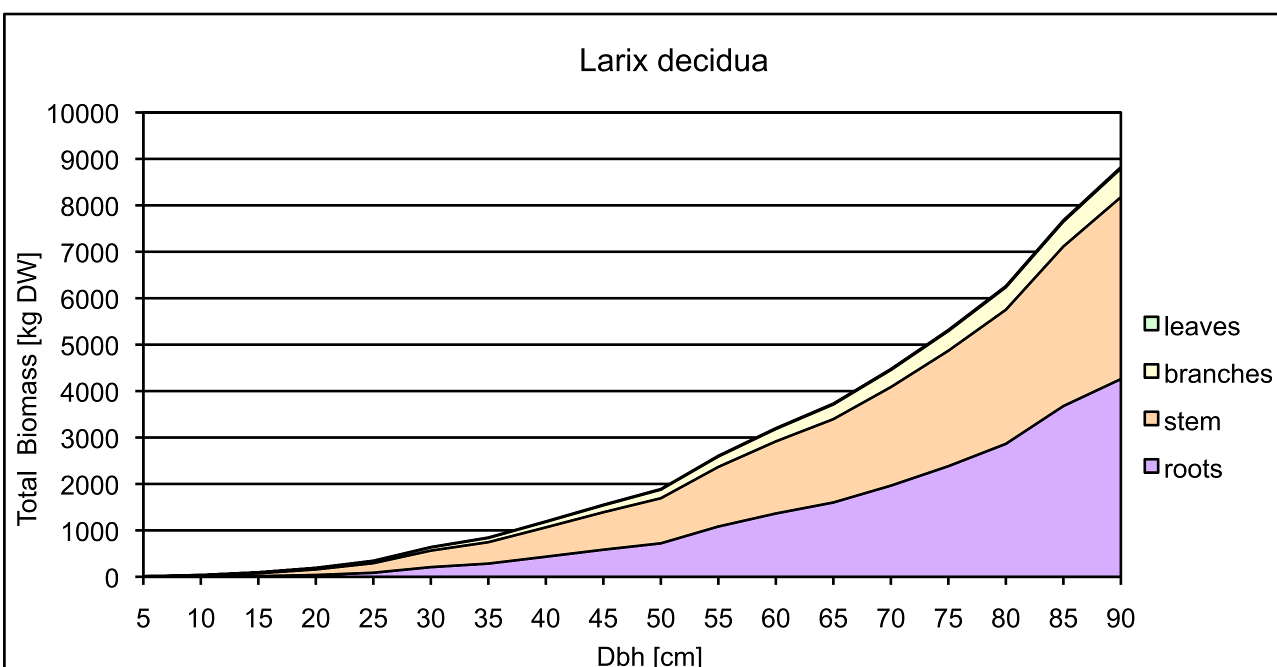

Fig. 11 – Average distribution of the biomass [kg DW] in the tree compartments for the different diameter classes in Larix decidua.

commercial or scientific needs (e.g. wood market, carbon credits, etc.).
Due to unexpected administrative constrains it was not possible to extend this statistical analysis to other forest species for which the reader is invited to explore the cited literature (1). However, the methodology defined in the present work could be further applied to datasets of model trees properly sampled and integrated with other parameters of forest ecosystems (e.g. soil properties, understory, litter, etc.) in order to assess the carbon budget of South Tyrol.

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Appendix A - Estimation of the belowground biomass

A – Sampling the root system: procedure and field work

Once the biometric sampling of the above ground tree compartments has been completed, the stem base, located between the felling and the collar sections, is weighed and summed to the aboveground biomass. Afterward, the root system below the collar section is sampled according to the following procedure.

1) The stump and the first order roots are excavated and cleaned
This task is facilitated by the use of high-pressure water jets (300 bars) supplied with 2000-9000 l of water (the water supplied with a tank truck was kindly arranged by the local fire brigades) (Fig. 12a-c).

Fig. 12a - Extraction of the root system.

12b - Tank truck, 2000-9000 lt.

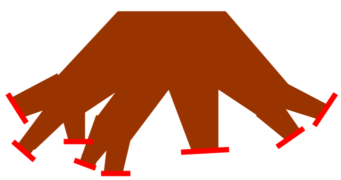
12c - Pump Falch R3B-300 bar.

2) Extraction of the stump

The 1st order roots are cut orthogonally to their main axis and at the end of the conical root section close to the stump, making sure that (Fig. 13a-b):

- the root section is approximately round;
- the root is close to cylindrical with a regular tapering (Fig. 13c).

Irregular buttress roots above the cutting sections are included in the weight of the stump.



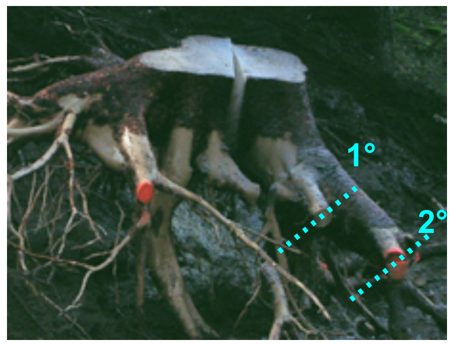


Fig. 13a-b - Cutting sections at first and second order roots.

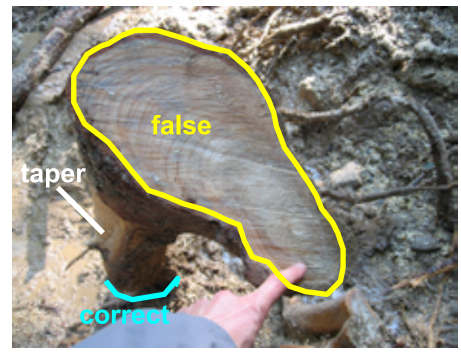


Fig. 13c

3) Weighing of the stump

The stump is weighted with high load dynamometer (max load 300 kg, precision 0.1 kg) (Fig. 14).

Fig. 14

4) Selection of three sample roots

Three 1st order roots are selected for further measurements (if possible located at 120° between them) and are extracted from the soil up to a diameter of 1cm (Fig. 15).

Fig. 15 – Schematic representation of the root system and the sampling of the three sample roots.

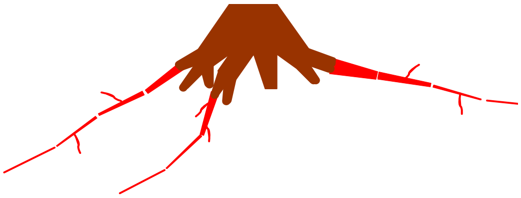


Fig. 16 – Sample root (18 m) of the sample tree Larix decidua 90_LD_010419. These images clearly show the dense net and the large development of the root system.

5) Measurement of the roots

The three sampled roots are excavated and analysed by sections at 1cm diameter steps.

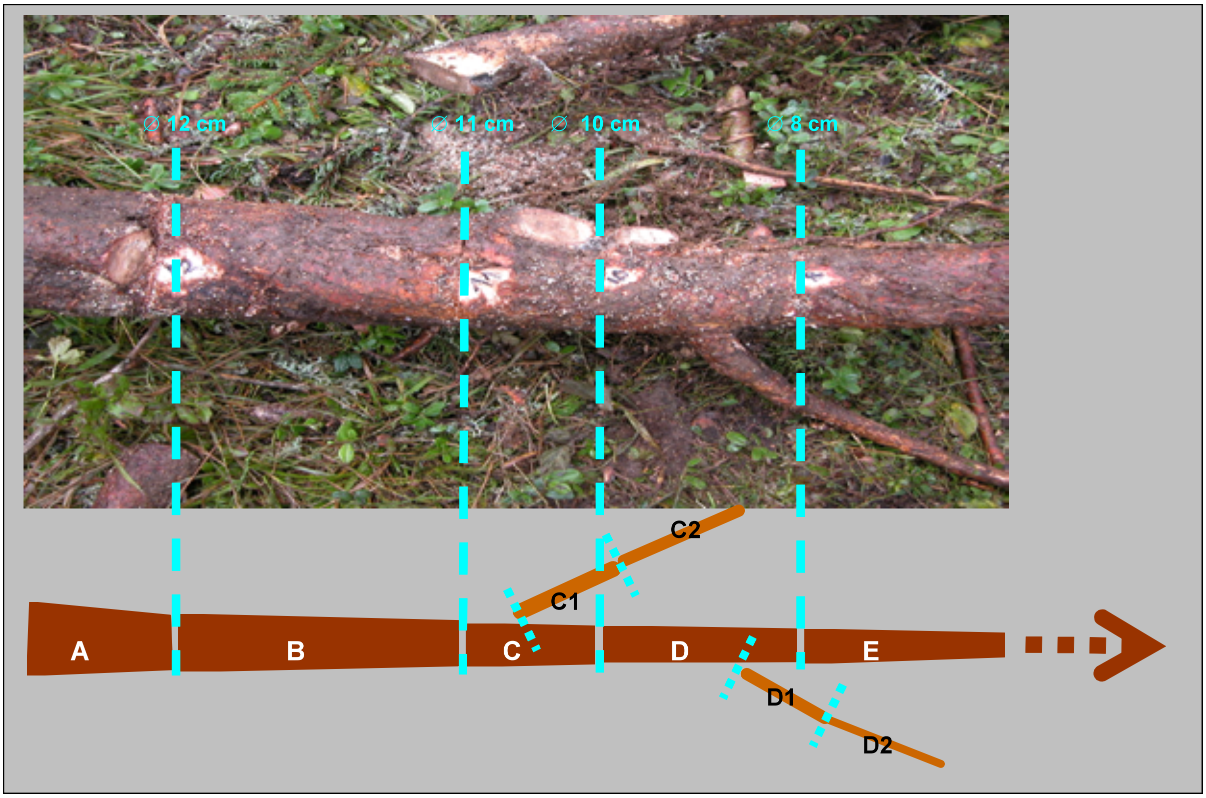


Fig. 17 - Example of the root segmentation in 1 cm diameter steps.

For each root segment the **diameter, length** and **fresh weight** are recorded up to the final section at 1 cm diameter. These variables are retrieved also for the higher order roots departing from the root segment (es. 2). For each of this roots the order and the diameter of the root section of origin are also recorded.

As an example the analysis of a roots may follow the following sequence of segments (see also Fig. 17):

A
B
C
    C1 C2
D
    D1 D2
E
etc.

Roots with ∅ < 1cm present on the sampled root are weighted separately.

This procedure is replicated for the other two sample roots.

In addition, the diameter of the root insertion in the stump is recorder for the other 1st order roots not extracted for the detailed analysis (Fig. 13a-b). Finally, a sample of each root is collected and shipped to the laboratory to estimate the water content of the wood.

N.B. Root parameters are recorder with the following precision:

Diameter: 1 mm (data recorded in two orthogonal directions with calliper or dendrometers (Permanent Tree Girth Tape- UMS GmbH · D-81379 München);

Length: 1 cm

Weights: 1 g

B - Estimation of the root biomass: methods and statistical analysis

Root growth depends on chemical (e.g. availability of nutrients and water), physical (e.g. soil texture, obstacles), biological (e.g. symbiosis with mycorrhiza) and physiological (e.g. turnover of fine roots) factors.
As a result of these multiple constrains, root developments follows preferential directions and the resulting spatial arran-gement of the root system is typically asymmetric, in contrast to the normally regular development of tree crowns.

In addition, the irregular tapering of the roots that derives from branching, anastomosis, necrosis etc. increases the difficulties in the estimation of root biomass by sectional analysis given the resulting low correlation between weight and diameter or root sections.
To overcome the difficulties generated by the uneven root shape, the series of segments that composes each sample root has been previously regularized by attributing to each segment:

Tab. 7 - Example of partition of biomass by root section (sample tree 53_PA_011296) where segments related to the diameter 9,7,6,5 cm could not be retrieved.

∅ cm	13→12	12→11	11→10	10→8	8→4	4→3	3→2	→2→1
Weight (kg)	6,794	1,515	0,644	0,615	1,486	2,343	0,667	-
Length (cm)	67,0	19,0	9,0	12,5	39,0	214,5	218,0	-

- the own weight,
- the weight of the afferent accessory roots of 2nd or higher order,
- the weight of the secondary roots having a diameter <1 cm (being randomly distributed over the entire root, the weight is allocated in proportion to the weight of the segment).

Missing or not measurable root segments (not accessible or not distinguishable segments as result of the extreme tapering or branching of the sample root, e.g. ∅ 9 cm in Fig. 17 Tab. 7) were assigned a hypothetical weight predicted by gap-filling.
Finally, the root biomass has been estimated by mean of the equation that relates the **cumulated dry weight** *(R_DW)* for all the segments below a certain diameter (d_i) used as predictor.
The parameters of the predictive equations have been estimated with the software STATISTICA 8.0, assuming zero intercept and using the least-square multiple-linear regression method in forward stepwise.
The predictive equations include only the best significant predictor between d, d^2 and d^3 (t test $p<0.05$) in order to fulfil the following conditions:

- Significant coefficient of determination (r^2);
- Predicted values in the observation range have to be positive;
- Proper description of the whole diametric series (from the root base to the 1cm ∅ tip);
- Minimum value predicted at 0 intercept;
- Maximum predicted value not larger than observations.

These conditions were set to follow a conservative approach so that the predicted values of root biomass if biased are typically underestimated.

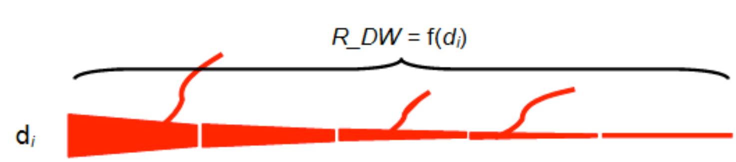


Fig. 18 – Graphical representation of the integral of the tapering root function above a section of diameter d_i.

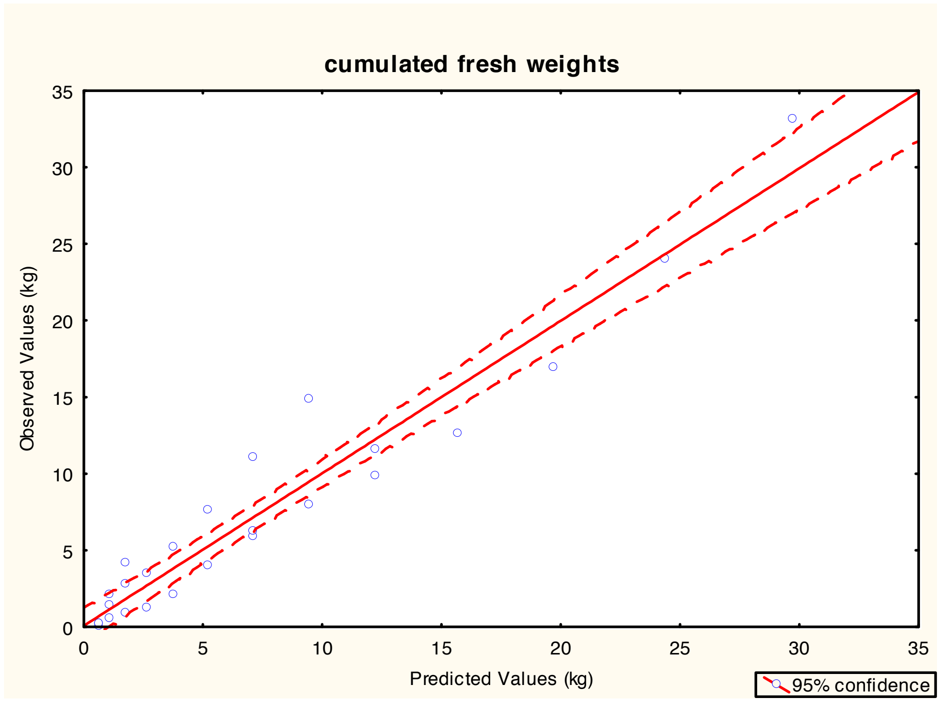


Fig. 19 – Observed vs. predicted values of fresh root weight cumulated for all the root segments below a certain threshold diameter d_i (model tree 53_PA_011296)

The general form of the equation is as follows:

Root Fresh Weight $R\_FW = b_1 d_i + b_2 d_i^2 + b_3 d_i^3$

where:

$b_{1,2,3}$ regression coefficients

d_i root diameter

In the exemplary case of the model tree 53_PA_011296 the following parameters have been estimated:

Tab. 8 – Least square regression coefficients for the root biomass model of the model tree 53_PA_011296.

R_FW = 0,293991745107125 d + 0,00935812832768314 d³				**Adj. R²**= ,96111426
	b	**Std.Err.**	**t**	**p-level**
d	0,29399174510712500	0,116219	2,529645	0,018396
d³	0,00935812832768314	0,000971	9,632714	0,000000

The predictive equation estimated on the cumulative weights as function of root diameter for the three sampled roots is applied to all other first order roots on the basis of the diameter at the insertion point previously recorded in the field. In this way the weight of the total root system is computed up to 1 cm ∅.
The fresh weight of roots is incremented of 10% until 20 cm dbh and of 15% for larger trees to account for bark losses and added to the stump weight. These values are finally converted using the coefficients estimated in the lab on root and stump samples in order to estimate the total belowground dry biomass for each model tree.

The general model for the estimation of the belowground biomass of *Picea abies* and *Larix decidua*, is build on 11 and 4 sample trees, respectively, and is resumed under the acronym R_DW_{BZ} in Tab. 4 e 5. It is worth noticing that for *Picea abies* the best predictor of root biomass is $\boldsymbol{d^2h}$, as reported also by Ogawa et al. (1965) (15), while for *Larix decidua* the best predictor is $\boldsymbol{d^2h^2}$, demonstrating the weaker dependence of root biomass on *dbh* in this latter species.

Appendix B: Comparison of alternative models for the estimate of the phytomass of Norway spruce

The biometric equations reported in Tab. 4 e 5 are the outcome of an analysis finalised to the identification of the best predictive models for South Tyrol. The accuracy in the estimate of tree biomass as a function of the selected predictors *d* and *h* is particularly important for the stem (S_DW). In fact, the stem compartment accounts for more than half of the total biomass and generates the largest economic interest.
As an example, Fig. 20 resumes the linear regression between the observed stem biomass of the 67 spruce trees sampled in South Tyrol and the values predicted by two alternative models: the first model (blue dots) is based on the combined dataset of both Provinces of Bolzano-South Tyrol (BZ) and Trento (TN), counting for 150 sample trees in total, while the second model (red dots) is referring to the sub-sample of South Tyrol only.

As it emerges from the values close to unity of the coefficient of determination (r^2) between the observed and predicted values, both biometric models describe effectively the dependence of the stem biomass from the predictors. The model based on the combined dataset BZ+TN, being based on a larger number of observations, is therefore recommended.

The model for the estimation of the aboveground biomass (AG_DW) has been developed in a similar manner, by estimating the following models on the 67 sample trees collected in South Tyrol:

SUMM sum of the biomass equations of the different compartments;
BZ+TN equation AG_DW estimated on the dataset of 150 model trees (BZ+TN);
BZ equation AG_DW estimated on the dataset of 67 model trees (BZ);
Fattorini equation AG_DW reported in Fattorini et Al. (2004)

The four models show a very similar trend up to dbh 45-50 cm, the upper threshold that includes 93-95% of the specimens of *Picea abies* sampled in the INFC (∅ max. 86 cm). The model **Fattorini** predicts higher masses for tree diameters larger than this threshold, probably due to the lack of large trees in the dataset TN used for the parameterization of the model.

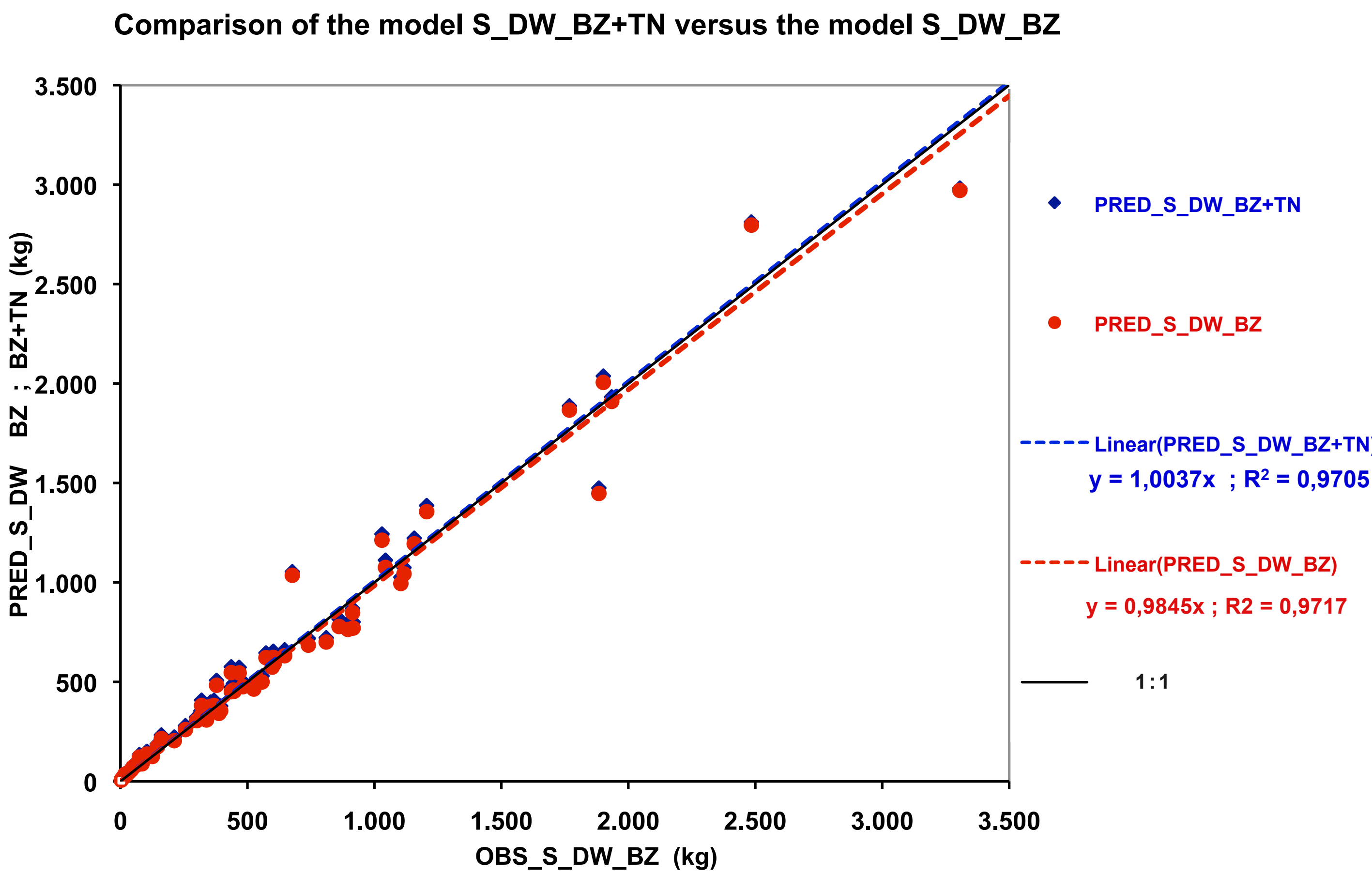


Fig. 20 - Linear regressions between the observed stem biomass of Picea abies trees sampled in South Tyrol (OBS_S_DW_BZ) and the values predicted by two alternative models (PRED_S_DW BZ+TN and BZ).

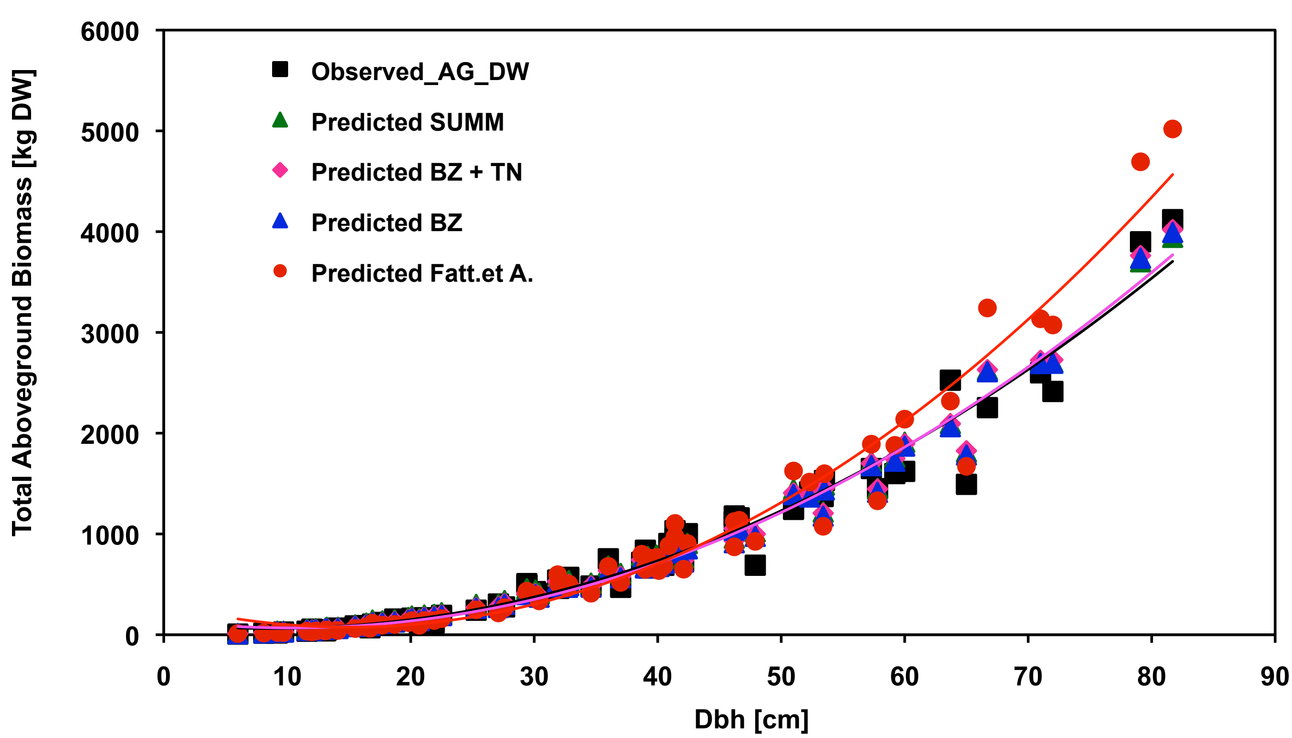


Fig. 21. Predicted values of aboveground biomass for Picea abies by four alternative equations.

The overestimation of the aboveground biomass by the **Fattorini** model for the larger trees clearly emerges from the comparison of predicted versus observed values (Fig. 22).

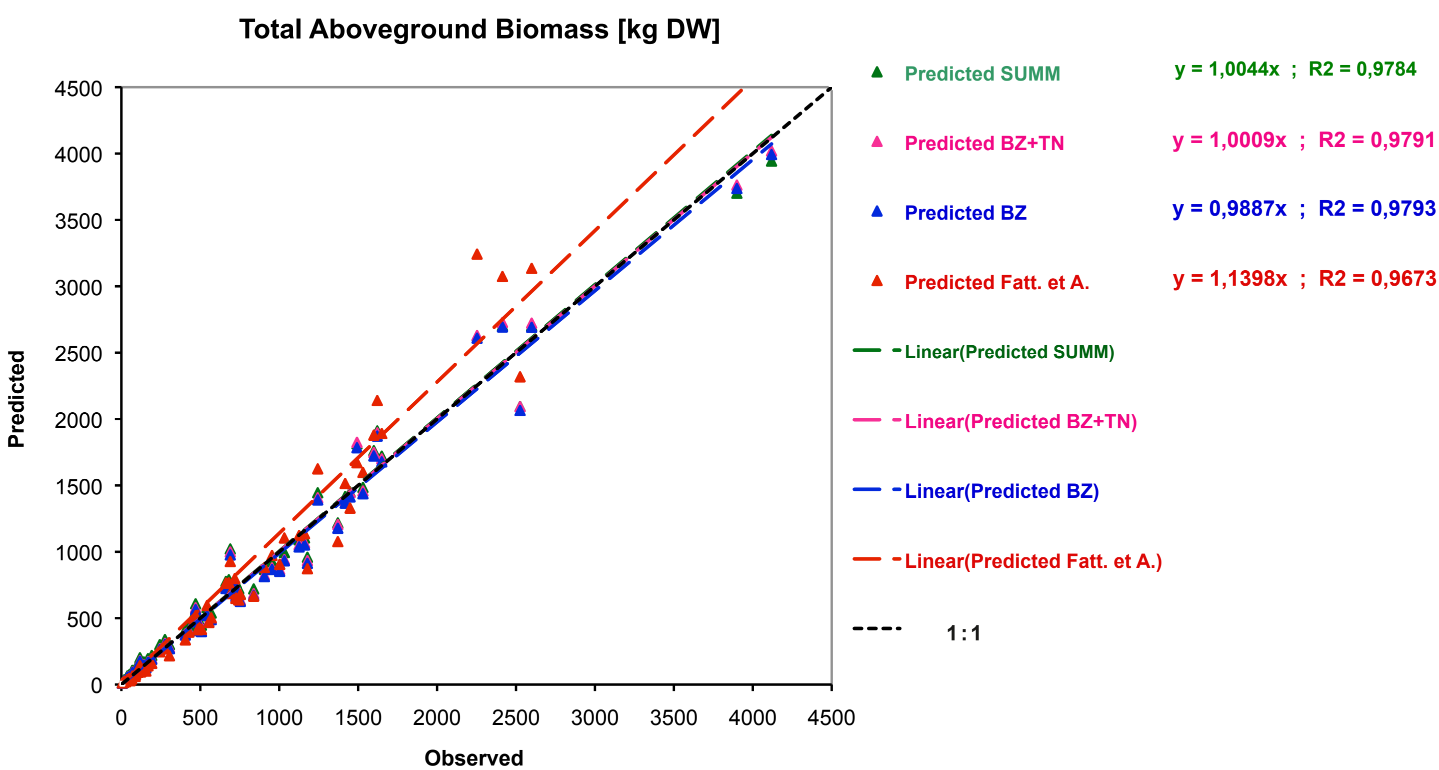


Fig. 22. Predicted versus observed aboveground biomass for Picea abies with four alternative biometric models.

These results show that the additive model (SUMM) is the more appropriate for the estimation of the aboveground biomass of *Picea abies*, given its high predictive capacity (comparable to model BZ and BZ+TN), the lack of systematic biases (slope 1,0044 in Fig. 22) and the consistency with the biometric models of the different tree compartments, of which it represents the sum (cf. paragraph 4., Tab. 4),

The linearity of the model predictions and of the observations against the predictor **d²h** is clearly shown in Fig. 23.

The predictive model for the aboveground biomass (SUMM) and the biometric equations in Tab. 4 and 5, respectively for *Picea abies* and *Larix decidua*, are finally used to derive the tables and figures reported in Appendix C.

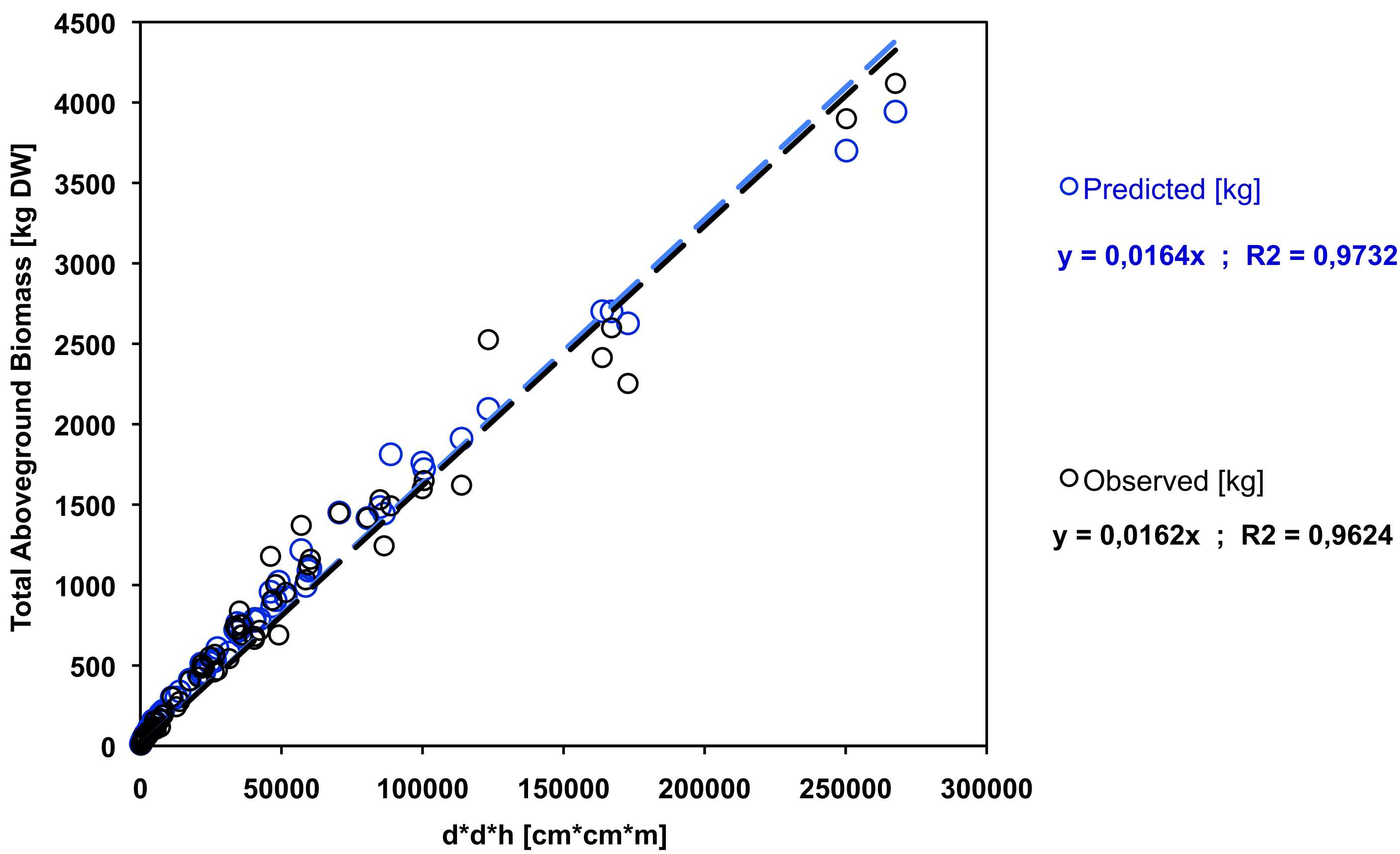


Fig. 23 – Trend of observed and predicted values of aboveground biomass as a function of the predictor d2h.

Appendix C: Two-entry tables for tree biomass and volume

The following two-entry tables (Tab. 9 and 10) and the graphs (Fig. 24 and 25) report the **aboveground dry biomass** [kg DW] for diameter (Dbh 1,30 m) and tree height classes (ranges in tree dimensions are those observed for the sample trees BZ and in the experimental plots of INFC).

Tab. 9 – Picea abies - Aboveground dry biomass [kg DW]

Height (m)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
Dbh (cm)																				
5	7	9	10	12	13															
10		31	35	38	42	46	49	53												
15			73	80	86	93	100	106	113	119										
20					146	157	167	177	187	198	208	218	228							
25					221	236	251	266	281	295	310	324	339	353						
30					312	332	352	373	393	412	432	452	472	491	511	530				
35					418	445	471	497	523	549	575	600	626	651	677	702	727			
40								639	672	705	737	770	802	834	866	898	930	962		
45								799	840	880	920	960	1000	1040	1079	1119	1158	1197		
50										1074	1123	1171	1219	1267	1315	1363	1410	1457	1505	
55										1288	1346	1403	1460	1517	1574	1631	1687	1744	1800	
60										1521	1589	1656	1723	1790	1857	1923	1989	2055	2121	2187
65											1852	1930	2007	2085	2162	2239	2316	2392	2469	2545
70																2579	2667	2755	2843	2930
75																2943	3043	3143	3243	3343
80																3331	3444	3557	3670	3782

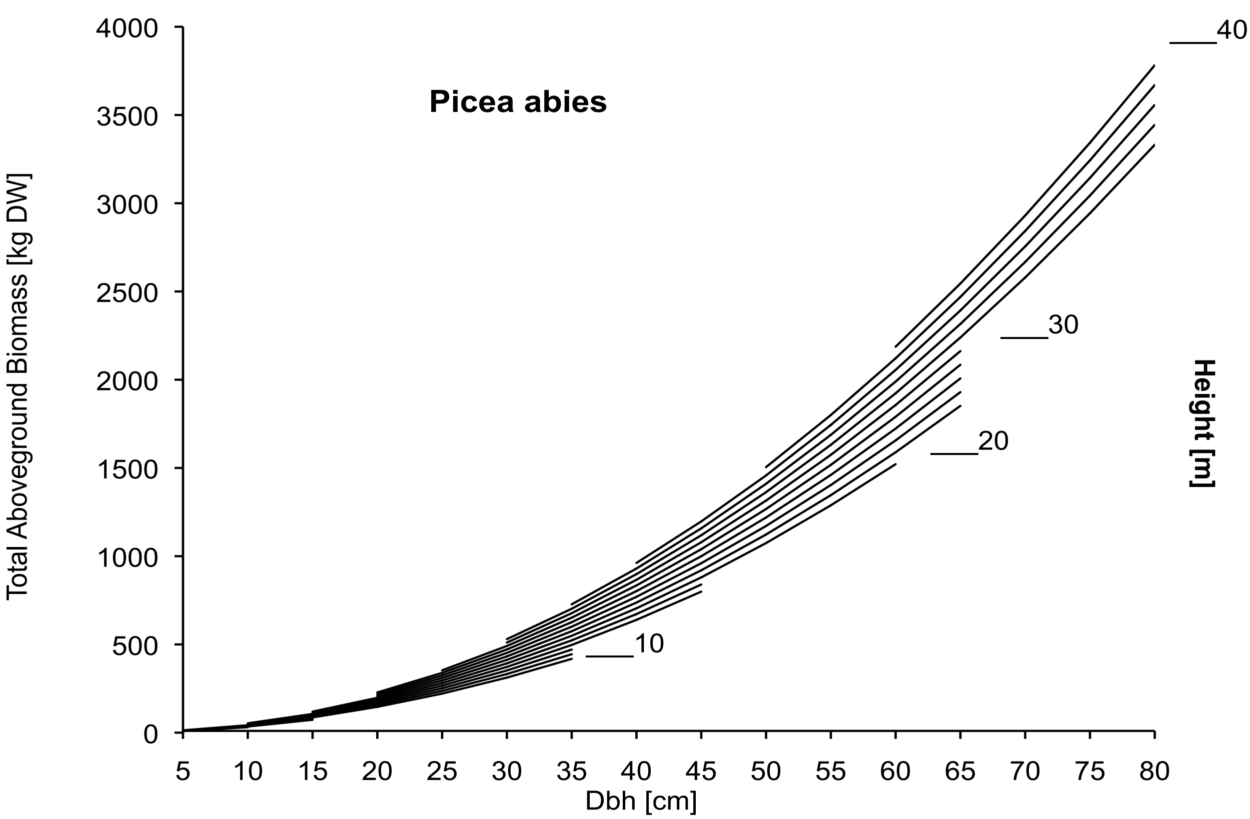


Fig. 24 – Picea abies – Aboveground dry biomass [kg DW]

Tab. 10 – Larix decidua – Aboveground dry biomass [kg DW]

Height (m) / Dbh (cm)	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
5	7	9	13	17															
10	19	25	31	38	45	52													
15	39	49	59	69	80	91	103	116	129										
20			96	111	127	144	161	178	196	215									
25				164	186	209	232	256	280	305	330	356							
30					257	287	318	349	380	412	445	478	512	546	580	615			
35					340	379	418	457	497	538	579	620	662	705	748	791			
40						483	532	581	630	681	731	782	834	886	939	992	1046		
45							660	720	780	841	903	964	1027	1090	1153	1217	1282		
50							802	874	946	1019	1093	1167	1241	1316	1391	1467	1544		
55								1044	1129	1215	1302	1389	1476	1564	1653	1742	1831	1921	2012
60									1328	1428	1529	1630	1732	1835	1937	2041	2145	2249	2354
65									1544	1660	1776	1892	2010	2127	2246	2364	2484	2603	2724
70										1908	2041	2174	2308	2442	2577	2712	2848	2985	3121
75											2325	2476	2628	2780	2932	3085	3239	3393	3547
80												2798	2968	3139	3310	3482	3655	3828	4001
85														3521	3712	3904	4097	4290	4483
90															4137	4351	4564	4779	4993

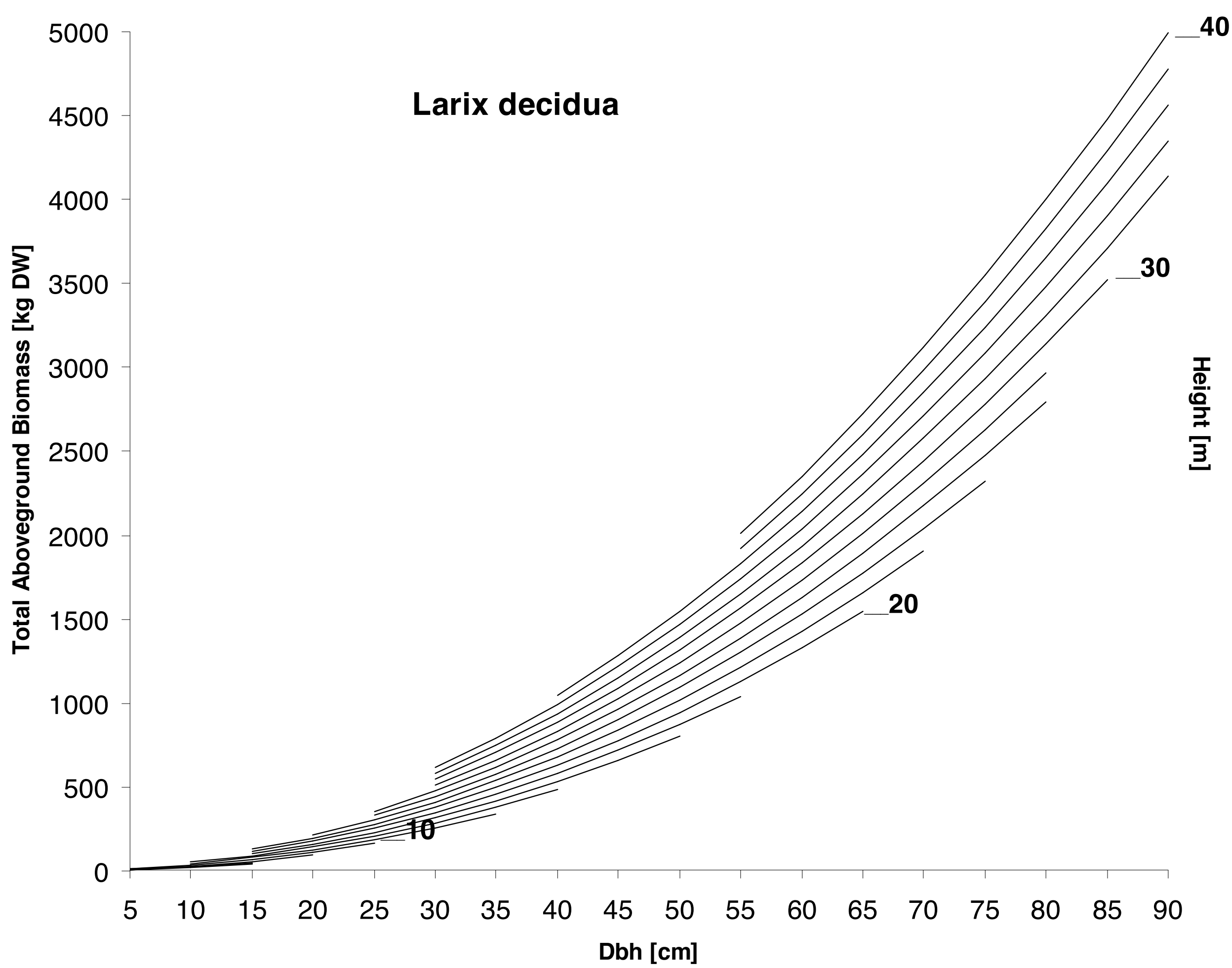


Fig. 25 – Larix decidua – Aboveground dry biomass [kg DW]

The following two-entry tables (Tab. 11 and 12) and the graphs (Fig. 26 and 27) report the **total dry biomass** [kg DW] for diameter (Dbh 1,30m) and tree height classes (ranges in tree dimensions are those observed for the sample trees BZ and in the experimental plots of INFC).

Tab. 11 – Picea abies – Total dry biomass [kg DW]

Height (m) / Dbh (cm)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
5	8	9	11	13	15															
10		33	38	43	48	53	58	63												
15			81	91	101	110	120	129	138	148										
20					171	187	202	218	233	248	263	278	293							
25					261	284	306	329	352	374	397	419	442	464						
30					369	401	432	464	495	526	557	589	620	650	681	712				
35					496	537	579	621	662	704	745	786	827	868	909	950	990			
40								801	854	907	960	1012	1065	1117	1170	1222	1274	1326		
45								1004	1070	1136	1202	1267	1333	1398	1463	1528	1593	1658		
50										1390	1470	1550	1630	1710	1789	1868	1947	2026	2105	
55										1671	1766	1862	1957	2053	2148	2243	2337	2432	2526	
60										1976	2089	2202	2315	2427	2539	2651	2763	2874	2986	3097
65											2439	2571	2702	2833	2963	3094	3224	3354	3484	3613
70																3570	3720	3870	4020	4169
75																4081	4252	4423	4594	4765
80																4626	4820	5013	5207	5400

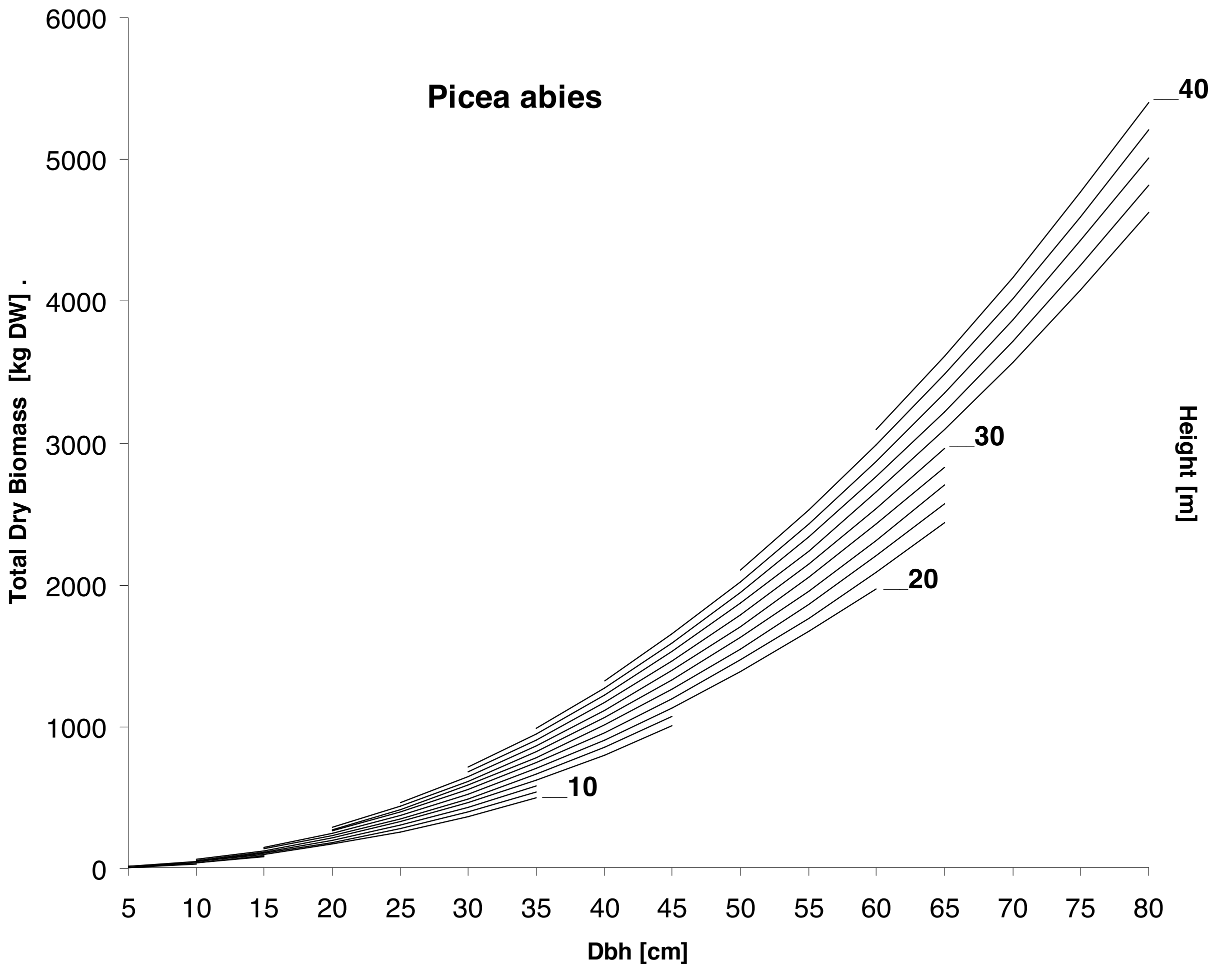


Fig. 26 – Picea abies – Total dry biomass [kg DW]

Tab. 12 – Larix decidua – Total dry biomass [kg DW]

Height (m) Dbh (cm)	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
5	7	10	13	18															
10	20	26	34	42	50	60													
15	41	52	64	78	93	109	127	145	165										
20			106	127	151	175	202	231	261	293									
25				190	223	258	297	338	381	427	475	526							
30					310	359	411	466	526	588	654	723	796	872	952	1035			
35					411	476	544	617	695	777	863	954	1050	1149	1254	1362			
40						610	697	790	888	993	1103	1218	1340	1467	1600	1738	1882		
45							869	984	1107	1236	1373	1516	1667	1825	1990	2161	2340		
50							1060	1201	1350	1507	1673	1848	2031	2223	2424	2633	2850		
55								1439	1617	1805	2004	2213	2432	2662	2902	3152	3412	3683	3964
60									1909	2131	2365	2612	2870	3141	3424	3719	4026	4345	4676
65									2225	2484	2757	3044	3345	3661	3990	4334	4692	5063	5449
70										2865	3179	3510	3857	4221	4600	4997	5409	5838	6283
75											3631	4009	4406	4821	5255	5707	6178	6668	7176
80												4542	4991	5462	5953	6466	6999	7554	8130
85														6143	6696	7272	7872	8497	9145
90															7482	8126	8797	9495	10219

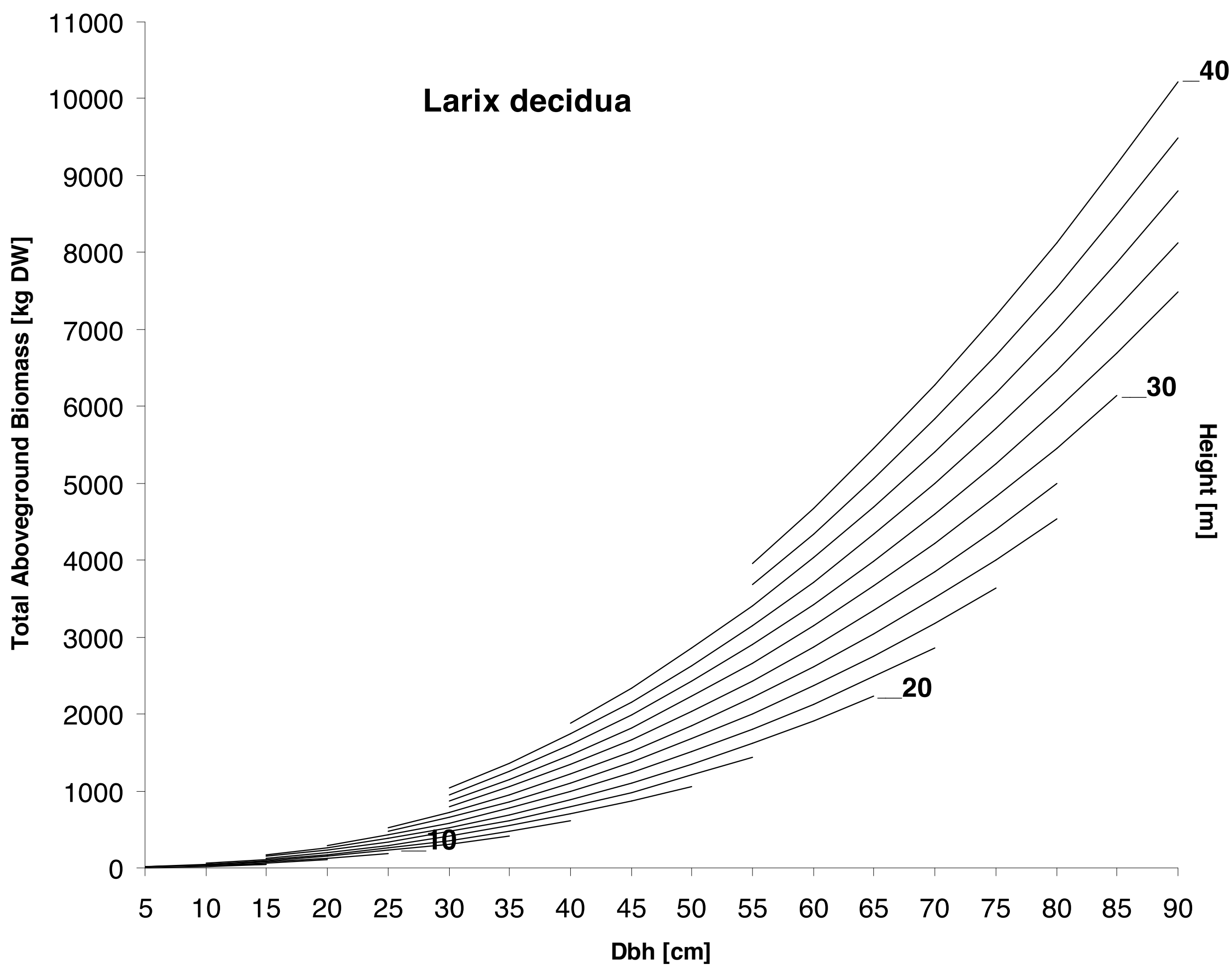


Fig. 27 – Larix decidua – Total dry biomass [kg DW]

The following two-entry tables (Tab. 13 and 14) and the graphs (Fig. 28 and 29) report the **stem volume** [dm^3] for diameter (Dbh 1,30 m) and tree height classes (ranges in tree dimensions are those observed for the sample trees BZ and in the experimental plots of INFC).

Tab. 13 – Picea abies – Stem volume [dm3]

Height (m) / Dbh (cm)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
5	2	3	5	6	8															
10		13	19	26	32	39	45	52												
15			44	58	73	88	102	117	132	146										
20					130	156	182	208	234	260	286	312	338							
25					203	244	284	325	365	406	447	487	528	568						
30					292	351	409	468	526	585	643	701	760	818	877	935				
35					398	477	557	636	716	796	875	955	1034	1114	1193	1273	1352			
40								831	935	1039	1143	1247	1351	1455	1559	1663	1767	1870		
45								1052	1184	1315	1447	1578	1710	1841	1973	2104	2236	2367		
50										1624	1786	1948	2111	2273	2435	2598	2760	2923	3085	
55										1965	2161	2358	2554	2750	2947	3143	3340	3536	3733	
60										2338	2572	2806	3039	3273	3507	3741	3975	4208	4442	4676
65											3018	3293	3567	3842	4116	4390	4665	4939	5213	5488
70																5092	5410	5728	6046	6365
75																5845	6210	6576	6941	7306
80																6650	7066	7482	7897	8313

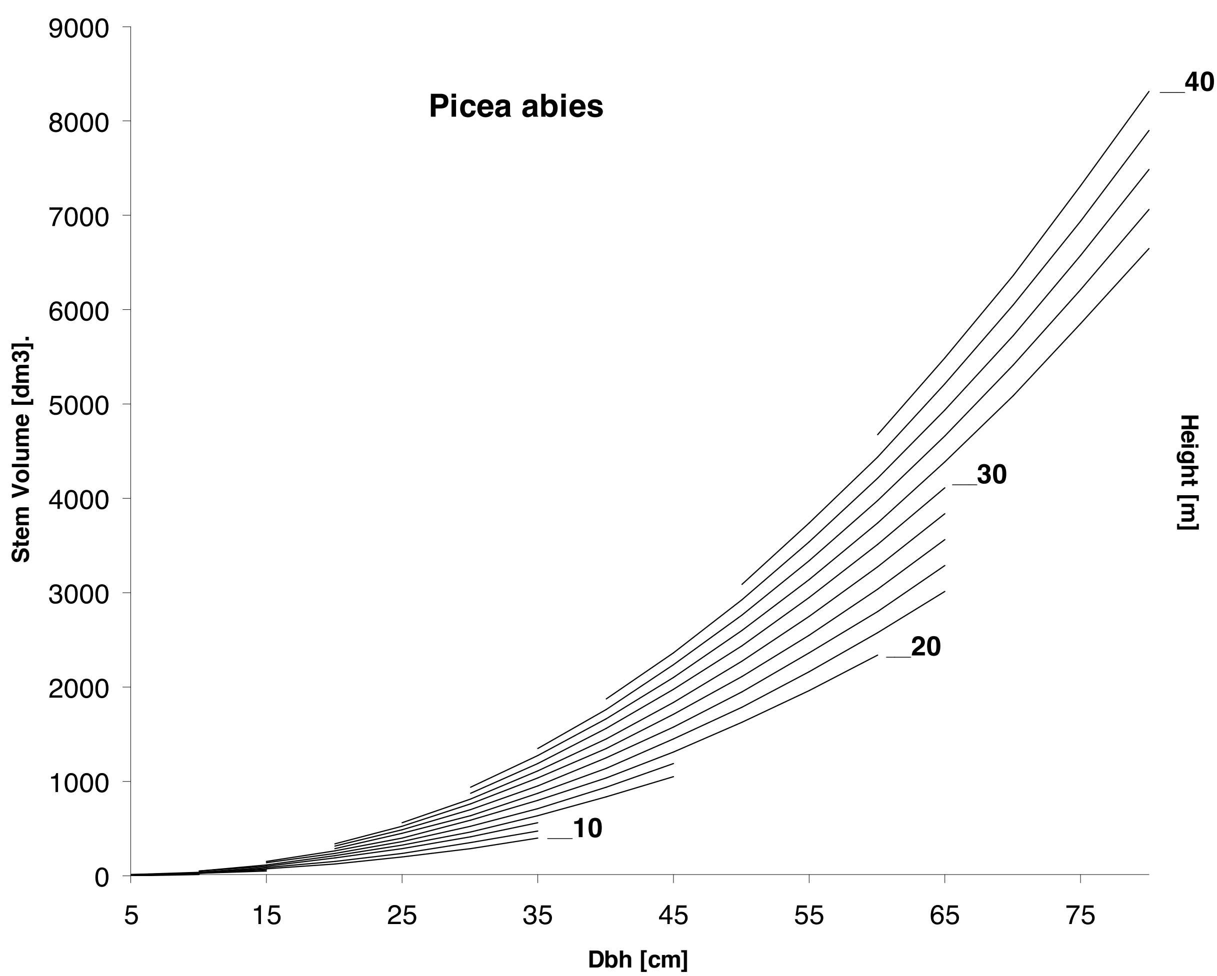


Fig. 28 – Picea abies – Stem volume [dm3]

Tab. 14 – Larix decidua – Stem volume [dm3]

Height (m) / Dbh (cm)	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
5	4	6	10	14															
10	11	19	28	39	51	64													
15	24	39	56	75	96	119	144	172	201										
20			91	121	154	189	227	268	312	358									
25				178	225	274	327	384	444	507	574	645							
30					308	374	445	519	597	680	767	858	953	1052	1156	1263			
35					405	490	579	673	773	877	985	1099	1218	1341	1469	1603			
40						620	731	847	969	1097	1230	1368	1513	1662	1818	1978	2145		
45							900	1041	1188	1341	1500	1666	1838	2016	2200	2391	2588		
50							1087	1254	1428	1609	1797	1991	2193	2402	2618	2840	3070		
55								1486	1689	1900	2119	2345	2579	2821	3070	3327	3591	3863	4143
60									1973	2216	2467	2727	2995	3271	3556	3849	4151	4461	4779
65									2277	2555	2841	3137	3441	3755	4077	4409	4749	5099	5458
70										2918	3241	3575	3918	4270	4633	5005	5387	5779	6180
75											3667	4041	4424	4819	5223	5638	6064	6499	6946
80												4535	4961	5399	5848	6308	6779	7261	7755
85														6012	6507	7014	7533	8064	8607
90															7201	7758	8327	8908	9502

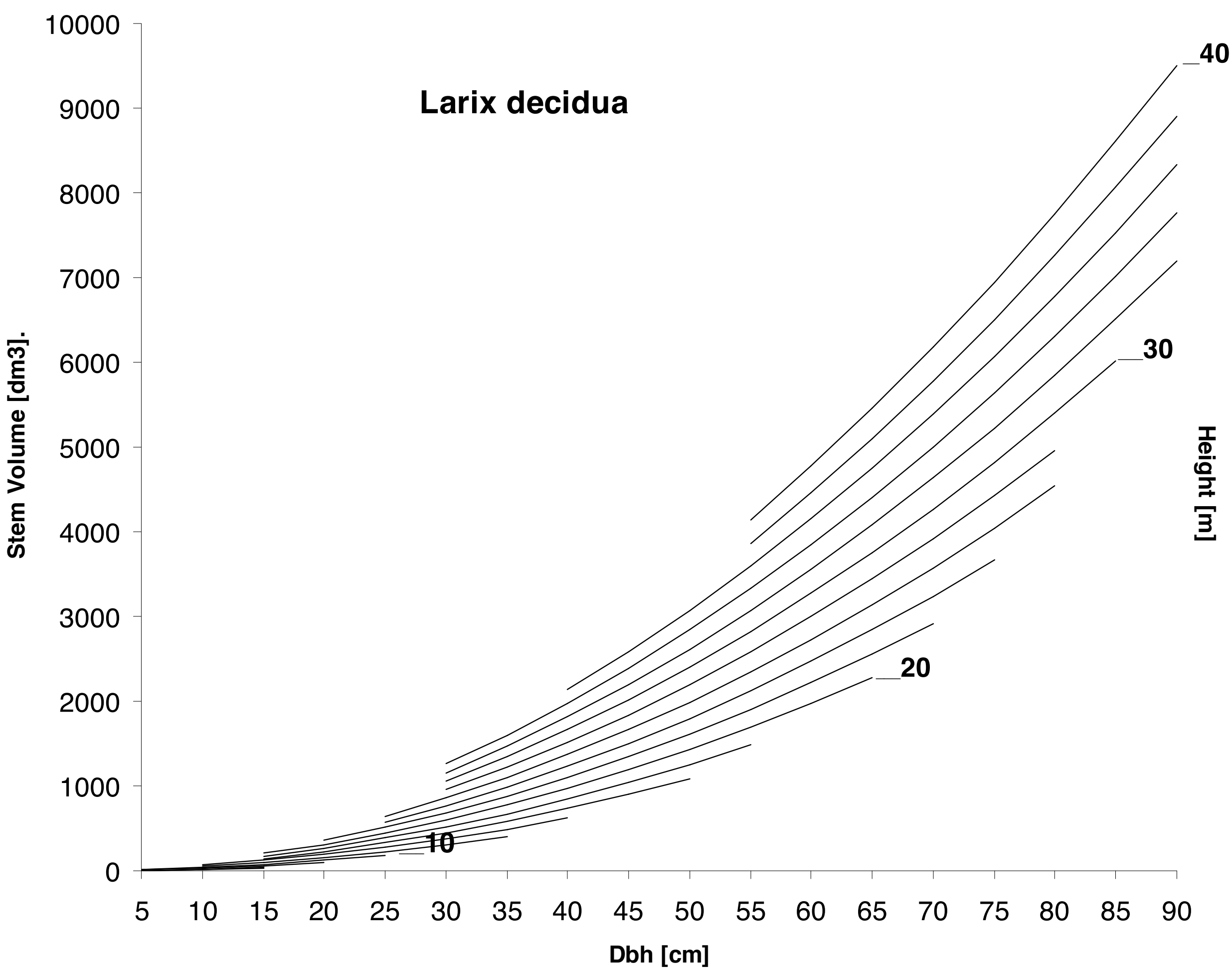


Fig. 29 – Larix decidua – Stem volume [dm3]