Norwegian University of Life Sciences
Department of Ecology and Natural Resource Management

2016
ISSN: 1891-2281

INA fagrapport 37

Models predicting stand level biomass for Norway spruce (*Picea* spp.), Scots pine (*Pinus* spp.) and broadleaf dominated forest in Norway

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Eid, T., Viken, K.O., Astrup, R. 2016. **Models predicting stand level biomass for Norway spruce (*Picea* spp.), Scots pine (*Pinus* spp.) and broadleaf dominated forest in Norway.** - INA fagrapport 37, 31 pp.

Ås, November 2016

ISSN: 1891-2281

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AVAILABILITY
Open

PUBLICATION TYPE
Digital document (pdf)

QUALITY CONTROLLED BY
The Research committee (FU), INA, NMBU

COVER PICTURE
Forest in Engerdal, Norway. Photo: Ole Martin Bollandsås

NØKKELORD
Biomasse, modeller for prediksjon, over og under bakken, bestandsnivå

KEY WORDS
Biomass, models for prediction, above- and belowground, stand level

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Preface

This report is based on Knut Ole Viken's Master Thesis "Biomass equations and biomass expansion factors (BEFs) for Scots pine (*Pinus* spp.), Norway spruce (*Picea* spp.) and broadleaf dominated stands in Norway" submitted to the Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences. The development of the report is partly funded by the Bioenergy Innovation Centre (CenBio). CenBio is a cooperation between the Norwegian University of Life Sciences, Norwegian Institute of Bioeconomy Research (NIBIO), The Foundation for Scientific and Industrial Research (SINTEF), and the Norwegian University of Science and Technology (NTNU).

Ås, 20th of October 2016

Tron Eid, Knut Ole Viken, Rasmus Astrup

Summary

Eid, T., Viken, K.O. & Astrup, R. 2016. Models predicting stand level biomass for Norway spruce (*Picea* spp.), Scots pine (*Pinus* spp.) and broadleaf dominated forest in Norway. - INA fagrapport 37, 31 pp.

This report presents models for prediction of stand level biomass in forests dominated by Norway spruce, Scots pine and broadleaves, respectively. The models cover both aboveground (stem, bark, branches, foliage) and belowground tree components. The models are based on stand level variables normally available in forest management plans and on variables that are used in relevant decision-support tools. The models can be applied for quantifying biomass for different tree components, and subsequently carbon, when data on induvial trees are not available. The models behaved reasonably well when tested over different forest conditions and regions. However, users should be aware of uncertainties related to western and northern parts of Norway, where the tests revealed underestimation of the biomass.

Sammendrag

Eid, T., Viken, K.O. & Astrup, R. 2016. Models predicting stand level biomass for Norway spruce (*Picea* spp.), Scots pine (*Pinus* spp.) and broadleaf dominated forest in Norway. [Bestandsmodeller for bestemmelse av biomasse i gran-, furu- og lauvdominert skog i Norge]. - INA fagrapport 37, 31 pp.

Denne rapporten presenter modeller for prediksjon av bestandsbiomasse for henholdsvis gran-, furu- og lauvtredominert skog. Modellene dekker biomasse både over (stamme, bark, greiner/topper og nåler/blader) og under bakken. Modellene er basert på bestandsvariabler som normalt er tilgjengelig i skogbruksplaner og variabler som brukes i ulike prognoseverktøy. Disse modellene vil kunne være nyttige dersom informasjon om enkelttrær ikke er tilgjengelig. Tester for ulike skogforhold og ulike regioner viste at modellene stort sett gav gode resultater. Brukere av modellene bør imidlertid være klar over en viss usikkerhet knyttet til estimering av biomasse i vestlige og nordlige deler av Norge der testene viste at biomassen ble undervurdert.

1. Introduction

Reliable estimates of forest biomass are important both with regard to forests as source for renewable energy and for quantification of carbon stock and carbon sequestration of forests. The biomass of individual trees is usually determined by using allometric models predicting biomass based on easily measurable tree variables such as diameter at breast height (dbh) and total tree height (ht) (e.g. Marklund 1987, 1988; Petersson & Ståhl 2006; Repola 2008, 2009; Bollandsås et al. 2009). Per unit area biomass (for a stand or sample plot) may subsequently be estimated by summation of biomass of all individual trees. If information on individual trees is available, and appropriate allometric biomass models exist, this is generally the most accurate way to quantify biomass at stand or plot level.

Quite often, however, individual tree data are not available. In all forest management plans developed in Norway for example, only stand level information such as volume ha^{-1}, number of trees ha^{-1}, basal area mean diameter (Dg) and basal area weighted mean height (H_L) is available. Furthermore, decision-support tools such as Avvirk-2000 (Eid & Hobbelstad 2000) and Gaya (Hoen & Eid 1990; Hoen & Gobakken 1997) are both dependent on-, and produce stand level information. Several studies, however, have quantified biomass or carbon (e.g. Hobbelstad 2007; Gjølsjø & Hobbelstad 2009; Raymer et al. 2009) on stand level using biomass models for individual trees with the stand level variables Dg and H_L as input. With this "average tree" approach, stand level biomass is estimated by multiplying the "average tree biomass" with the number of stems ha^{-1}. However, since the relationships between biomass and the independent variables (dbh or ht) in reality are non-linear (see e.g. Repola 2009), using average values (Dg and H_L) to predict biomass will introduce bias (e.g. Gertner 1991).

When stand level information only is available, appropriate biomass estimates can be carried out in two different ways; 1) by using stand level volume and corresponding biomass expansion factors (i.e. preferably expansion factors that are dependent on stand level variables) or 2) by predicting stand level biomass directly based on models with stand level variables. The former approach has been used for example by Rørstad et al. (2010), Bergseng et al. (2013) and Borges et al. (2015). However, they had to use expansion factors calibrated for Finland (Lehtonen et al. 2004) because expansion factors based on Norwegian conditions

were not available. The latter approach has not been applied in Norway to date since no national stand level biomass models been developed for Norway.

The main objective of this report was to present models (equations) for prediction of stand level biomass (tons dry weight) based on stand level independent variables. The report is based on a master thesis submitted by Viken (2012). Tree species-specific (Norway spruce, Scots pine, and broadleaves) models that cover both aboveground (stem, bark, branches, foliage) and belowground tree components were developed. The models are based on variables that normally are available from forest management plans and variables that are used in relevant decision-support tools. The model development was based on data from the Norwegian National Forest Inventory (NFI).

2. Materials and methods

2.1. Data collection and preparation

The data used for modeling were collected on the permanent sample plots of the Norwegian NFI, in the period between 2006 and 2010 (Landsskogtakseringen 2011). These sample plots are distributed in a 3 x 3 km grid covering the entire forested area of Norway, except Finnmark county. Only sample plots defined as productive forest (i.e. minimum production of 1 $m^3\,ha^{-1}\,yr^{-1}$ inclusive bark) within the land use classes "Forestry", "Protected areas" and "Recreation areas" in development classes III-V were included (for details on definitions, see (Landsskogtakseringen 2011). The total number of sample plots was 7004 (Table 1).

For each sample plot of 250 m^2 (radius 8.92 m), all trees with dbh over bark ≥ 5 cm was measured for dbh and recorded for species. Stand level variables such as site index (SI, defined as dominant height (m) at breast height age 40 years), stand age and elevation were also assessed for each plot. In addition, a subsample of 10 trees was selected within the sample plot proportional to stand basal area for height measurement. Total tree heights (ht), for the trees not measured for height within a certain plot, were computed based on the sample trees from the plot.

Stem volume of individual trees with dbh ≥ 5 cm was determined from tree volume models, with dbh and ht as independent variables, developed by Vestjordet (1967), Brantseg (1967), and Braastad (1966) for Norway spruce *(Picea abies)*, Scots pine *(Pinus silvestris)* and birch

(Betula pubescens and Betula pendula), respectively. For Sitka spruce *(Picea sitchensis)*, models developed by Bauger (1995) were applied. For Norway spruce and Scots pine trees growing in the western part of the country, we applied models developed by Bauger (1995).

To determine biomass for all above- and belowground tree components of individual trees, we applied Swedish models developed by Marklund (1987, 1988) and Petersson & Ståhl (2006). All these models use dbh and ht as independent variables.

Viken (2012) also tested Finish models for individual trees developed by Repola (2008, 2009) for application under Norwegian conditions. In general he found the Swedish models to perform better, probably because these models were based on larger samples, covered larger geographical areas (especially regarding the south-north dimension) and also included larger ranges in tree sizes as compared to the Finish models. Smith et al. (2014, 2016) developed individual tree biomass models for birch based on Norwegian data. These models, however, were not available when Viken (2012) developed his stand level biomass models.

For aboveground biomass of Scots pine and Norway spruce, Marklund (1987, 1988) developed models for the following components; stem, stem bark, living branches, dead branches and needles. For aboveground biomass of birch, models for stem, stem bark, living branches and dead branches were available from Marklund (1988), but not for foliage. Foliage biomass of broadleaf species was therefore determined by multiplying the stem biomass for the actual tree with a factor of 0.022 (Liski et al. 2002).

The belowground biomass models for Norway spruce and Scots pine developed by Marklund (1987, 1988) are meant for biomass determination of roots obtained in operational root extraction for bioenergy purposes. Since all root extractions, when developing these models, were based on machines, no specific minimum diameter for the roots included exists. We assume, however, that the biomass quantities predicted from these models reflect the quantities derived from practical operational root extraction procedures.

The belowground biomass models for Norway spruce and Scots pine developed by Marklund (1987, 1988) predict biomass for the following belowground components; stumps, roots ≥ 5 cm in diameter, and roots < 5 cm in diameter. According to Marklund (1988), the models for roots with diameter ≥ 5 cm should not be applied for trees with dbh < 10 cm because such

large roots have not yet been formed for trees of this size. Biomass for roots ≥ 5 cm were therefore only determined for trees with dbh ≥ 10 cm.

The belowground models for Norway spruce, Scots pine and birch developed by Petersson & Ståhl (2006) determine biomass for all roots down to 2 mm in diameter. These models are therefore suitable for quantification of belowground carbon in trees. Since the belowground models developed by Marklund (1987, 1988) and Petersson & Ståhl (2006) serve different purposes (i.e. assessment of biomass for energy and carbon, respectively), both sets of models were applied to provide two options for belowground biomass quantification.

Marklund (1987, 1988) did not develop belowground models for birch. To determine belowground biomass for energy purposes, we therefore applied the birch models developed by Petersson & Ståhl (2006) and subsequently applied a reduction factor of 0.87 (i.e. 13% reduction). This reduction factor was based on the ratio of belowground biomass determined from the Norway spruce and Scots pine models developed by Marklund (1988) and Petersson & Ståhl (2006), respectively.

Finally, volume and biomass of individual trees were summed for all plots and converted to ha^{-1} values.

2.2. Development and evaluation of models

The dataset comprising 7004 sample plots were first split randomly into a modelling dataset (approximately 80% of the plots) and a test dataset (remaining plots). Table 1 shows the distribution of the total number of sample plots distributed by dominating species (≥70% of a certain species according to volume ha^{-1}) species. Plots with volume ha^{-1} <70% of either species were classified as “mixed”.

In the variable selection phase, a Pearson correlation coefficient analysis of total biomass (tons dry weight) and candidate independent variables (Table 2) was carried out based on data from all plots in order to aid the selection of variables to be included in the models.

Table 1. Number of sample plots distributed by different datasets and dominating tree species.

Dominating species*	All	Modelling dataset	Test dataset
Norway spruce	2043	1639	404
Scots pine	1758	1405	353
Broadleaves	1927	1549	378
Mixed	1276	1021	255
Total	7004	5614	1390

* defined as plots with percentage volume ha^{-1} ≥70% of a specific species. Plots with percentage volume ha^{-1} <70% of either species are defined as "mixed"

Table 2. Pearson correlation coefficients between total biomass ha^{-1} and different stand level variables.

	Biomass	Dg	BA	SI	V	Stand age	H_L	Trees	Ele-vation
Biomass	1								
Dg	0.421	1							
BA	0.974	0.385	1						
SI	0.551	0.023	0.506	1					
V	0.977	0.452	0.945	0.554	1				
Stand age	0.014	0.585	0.005	-0.530	0.035	1			
H_L	0.700	0.697	0.623	0.473	0.753	0.254	1		
N	0,330	-0,456	0,423	0,321	0,263	-0,437	-0,096	1	
Elevation	-0.155	0.047	-0.158	-0.343	-0.159	0.246	-0.109	-0.141	1

Dg = basal area mean diameter (cm), BA = basal area (m^2 ha^{-1}), SI = site index, i.e. dominant height (m) at breast height age 40 years, V = volume (m^3 ha^{-1}), H_L = mean height by basal area (Lorey mean height) (m), N = number of trees ha^{-1}

The correlation analysis showed that biomass was strongly correlated with BA (r = 0.973) and V (r = 0.977). Other variables with relatively high correlation coefficients were H_L (r = 0.700) and SI (r = 0.551). Basal area ha^{-1} and V were highly inter-correlated (r = 0.945) suggesting that simultaneous use of them as independent variables in a model will lead to multi-collinearity. Since V always is available in Norwegian forest management plans, while BA sometimes is missing, the selection of V as independent variable in the models therefor was obvious. The variable selection phase also revealed that inclusion of SI as an independent variable, in addition to volume, was important for explaining variation biomass.

The variable selection phase also highlighted two additional important issues; (1) the regression residuals clearly displayed heteroscedasticity (i.e. increasing variance in residuals over increasing predicted biomass ha^{-1}, see e.g. Parresol (1999)) and (2) the relationships between volume ha^{-1} and biomass ha^{-1} were nonlinear. To account for this we decided to fit nonlinear models. The selected model form was therefore:

$$Y = \beta_0 + \beta_1 \times V^{\beta_2} + \beta_3 \times SI + \varepsilon$$

where Y is the biomass (tons), V is volume ha^{-1}, SI is site index (m), while $\beta_0, \beta_1, \beta_2, \beta_3$ are the estimated regression parameters and ε is the error term assumed to be normally distributed with mean 0 and variance σ^2.

To account for the heteroscedasticity we followed the example of Lilles & Astrup (2012) who fitted models assuming the error distribution to be normal with a variance that increased proportionally to the predicted value. Hence, the error (ε_i) for the *i*th observation was modelled as:

$$\varepsilon_i = \alpha_1 \times X_i$$

where X_i is the predicted value and α_i is a parameter estimated with maximum likelihood simultaneously with all the parameters in the selected model form. The models were fitted with the NLMIXED procedure in SAS. To ensure that global optima were reached, several search algorithms and initial start values were tested for each model.

Biomass models were fitted for the following tree components; stem, bark, living branches, dead branches, needles/foliage, total aboveground, stump and large roots (biomass for energy purposes), total belowground (biomass for carbon assessment) and total tree. Separate models were developed for Norway spruce, Scots pine and broadleaf dominated forest and for mixed species forest (see Table 1 for definitions).

The models were evaluated by comparison of model predicted and observed biomass ha^{-1} on the test dataset. Here we tested whether the differences between predicted and observed values were significantly different from zero by means of paired *t*-tests for different groups of the material such as dominating tree species, site index classes, volume classes and geographical regions.

3. Results

Tables 3, 4, 5 and 6 show the stand level models for predicting biomass of different tree components for Norway spruce dominated, Scots pine dominated, broadleaf dominated and mixed species, respectively.

Generally, the models predicted increasing biomass with increasing volume and decreasing site index. For some of the tree component models, however, predicted biomass increased also when the site index increased (e.g. model for dead branches in Norway spruce dominated forest, Table 3). A few models had non-significant parameter estimates for site index (e.g. model for stem biomass in Norway spruce dominated forest, Table 3). However, as long as the sign of the parameter estimates conform with the other tree component models, this is not considered as a serious problem.

The coefficients of determination (R^2) ranged from 0.9749 to 0.9913 for the total tree models, from 0.9229 to 0.9494 for the total belowground models and from 0.9845 to 0.9932 for the total aboveground models. Generally, R^2 for branches and foliage models were lower ranging from 0.5745 to 0.9412. Tables displaying stand level biomass (tons ha^{-1}) over volume ha^{-1} and site index based on some selected tree component models are presented in the Appendix Tables A1-A9.

Tables 7, 8, 9 and 10 display the results from the comparisons of predicted biomass ha^{-1} with observed biomass ha^{-1}. A few cases of differences significantly different from zero appear over the site index and volume classes, but any particulars patterns can hardly be seen. Over the regions, however, there are some cases of significant over- and underestimations made by the stand level models that might be more severe. Generally, this relates to western and northern Norway where the models seem to underestimate biomass.

Table 3. Stand level biomass models for Norway spruce dominated forest (forest with at least 70% volume of Norway spruce).

Tree component	Model	R^2
Stem	$B = 0.2541 + 0.3098 \times V^{1.0277} - 0.0077 \times SI^{NS}$	0.9983
Bark	$B = 0.0338 + 0.1058 \times V^{0.8225} - 0.0076 \times SI$	0.9596
Living branches	$B = 0.3139 + 1.1503 \times V^{0.6069} - 0.0926 \times SI$	0.7522
Dead branches	$B = -0.0717 + 0.0087 \times V^{1.0097} + 0.0108 \times SI$	0.9618
Foliage	$B = -0.0570 + 0.5830 \times V^{0.6164} - 0.0262 \times SI$	0.7799
Total aboveground	$B = 2.1234 + 1.2073 \times V^{0.8764} - 0.1533 \times SI$	0.9845
Stumps and large roots*	$B = 0.4470 + 0.6145 \times V^{0.7832} - 0.0702 \times SI$	0.9239
Total belowground**	$B = 0.5267 + 0.7422 \times V^{0.7771} - 0.0823 \times SI$	0.9229
Total tree	$B = 3.0419 + 1.8851 \times V^{0.8507} - 0.2550 \times SI$	0.9749

B = biomass ha^{-1} (tons), V = stem volume ha^{-1}, SI = site index defined as dominant height in meter at breast height age of 40 years for Norway spruce

* Stump and large roots as potential for bioenergy use based on Marklund (1988), ** Total belowground based on Petersson & Ståhl (2006), NS non-significant parameter estimate ($p > 0.05$)

Table 4. Stand level biomass models for Scots pine dominated forest (forest with at least 70% volume of Scots pine).

Tree component	Model	R^2
Stem	$B = -2.0138 + 0.2409 \times V^{1.0666} + 0.3276 \times SI$	0.9928
Bark	$B = 0.0386 + 0.0647 \times V^{0.8614} - 0.0063 \times SI^{NS}$	0.9401
Living branches	$B = 5.3423 + 0.4992 \times V^{0.6884} - 0.4954 \times SI$	0.6277
Dead branches	$B = -0.0143 + 0.0273 \times V^{0.8328} + 0.0011 \times SI^{NS}$	0.9031
Foliage	$B = 0.7274 + 0.2514 \times V^{0.6108} - 0.1007 \times SI$	0.6117
Total aboveground	$B = 3.6217 + 0.8303 \times V^{0.9150} - 0.4651 \times SI$	0.9866
Stumps and large roots*	$B = 2.0571 + 0.4228 \times V^{0.8344} - 0.2684 \times SI$	0.9191
Total belowground**	$B = 2.3114 + 0.4868 \times V^{0.8256} - 0.3019 \times SI$	0.9230
Total tree	$B = 6.2616 + 1.2918 \times V^{0.8905} - 0.8079 \times SI$	0.9791

B = biomass ha^{-1} (tons), V = stem volume ha^{-1}, SI = site index defined as dominant height in meter at breast height age of 40 years for Scots pine

* Stump and large roots as potential for bioenergy use based on Marklund (1988), ** Total belowground based on Petersson & Ståhl (2006), NS non-significant parameter estimate ($p > 0.05$)

Table 5. Stand level biomass models for broadleaf dominated forest (forest with at least 70% volume of broadleaves).

Tree component	Model	R^2
Stem	$B = -1.0821 + 0.2998 \times V^{1.0670} + 0.1512 \times SI$	0.9918
Bark	$B = -0.0895 + 0.0743 \times V^{1.0024} + 0.0078 \times SI$	0.9916
Living branches	$B = 0.1738 + 0.3615 \times V^{0.8445} - 0.0596 \times SI$	0.9412
Dead branches	$B = -0.0190 + 0.0452 \times V^{0.7227} - 0.0036 \times SI$	0.6584
Foliage	$B = -0.0003 + 0.0041 \times V^{1.2403} - 0.0006 \times SI$	0.5745
Total aboveground	$B = -0.7097 + 0.7187 \times V^{0.9915} + 0.0375 \times SI$	0.9932
Stumps and large roots*	$B = 0.4838 + 0.5379 \times V^{0.8628} - 0.1035 \times SI$	0.9489
Total belowground**	$B = 0.5444 + 0.6189 \times V^{0.8628} - 0.1180 \times SI$	0.9494
Total tree	$B = -0.0430 + 1.3110 \times V^{0.9463} - 0.1150 \times SI$	0.9913

B = biomass ha^{-1} (tons), V = stem volume ha^{-1}, SI = site index defined as dominant height in meter at breast height age of 40 years for birch

* Stump and large roots as potential for bioenergy use based on Petersson & Ståhl (2006) with correction factor, ** Total belowground based on Petersson & Ståhl (2006), NS non-significant parameter estimate ($p > 0.05$)

Table 6. Stand level biomass models for mixed species forest (forest with less than 70% of volume for Scots pine, Norway spruce or broadleaves).

Tree component	Model	R^2
Stem	$B = -0.8754 + 0.3269 \times Vs^{1.0175} + 0.2905 \times Vp^{1.0467} + 0.3354 \times Vb^{1.0633} + 0.1062 \times SI$	0.9961
Bark	$B = 0.1219 + 0.0756 \times Vs^{0.8685} + 0.0325 \times Vp^{0.9021} + 0.0707 \times Vb^{1.0305} - 0.0055 \times SI$	0.9861
Living branches	$B = 3.6458 + 0.4708 \times Vs^{0.7474} + 0.1591 \times Vp^{0.7935} + 0.1363 \times Vb^{1.0139} - 0.1783 \times SI$	0.7961
Dead branches	$B = -0.2932 + 0.0034 \times Vs^{1.1458} + 0.0199 \times Vp^{0.3648} + 0.0102 \times Vb^{0.8181} + 0.0320 \times SI$	0.8399
Foliage	$B = -1.3949 + 0.3126 \times Vs^{0.7235} + 0.0665 \times Vp^{0.6198} + 0.1169 \times Vb^{0.0519} + 0.0729 \times SI$	0.8855
Total aboveground	$B = 2.5836 + 1.0721 \times Vs^{0.8947} + 0.6374 \times Vp^{0.9470} + 0.6067 \times Vb^{1.0241} - 0.1664 \times SI$	0.9883
Stumps and large roots*	$B = 2.7840 + 0.3339 \times Vs^{0.8772} + 0.1775 \times Vp^{0.9573} + 0.3157 \times Vb^{0.9430} - 0.1389 \times SI$	0.9305
Total belowground**	$B = 3.2949 + 0.4105 \times Vs^{0.8685} + 0.1954 \times Vp^{0.9534} + 0.3631 \times Vb^{0.9448} - 0.1643 \times SI$	0.9332
Total tree	$B = 5.8227 + 1.4894 \times Vs^{0.8872} + 0.8659 \times Vp^{0.9469} + 0.9854 \times Vb^{0.9964} - 0.3433 \times SI$	0.9811

B = biomass ha^{-1} (tons), Vs, Vp, Vb = stem volume ha^{-1} for Norway spruce, Scots pine and broadleaves, SI = site index defined as dominant height in meter at breast height age of 40 years for the species with the largest volume proportion

* Stump and large roots as potential for bioenergy use based on Marklund (1988) for Norway spruce and Scots pine and Petersson & Ståhl (2006) with correction factor for broadleaves, ** Total belowground based on Petersson & Ståhl (2006), NS non-significant parameter estimate ($p > 0.05$)

Table 7. Differences between predicted total biomass based on the stand level models and observed total biomass from individual trees for Norway spruce dominated sample plots.

Site index class (m)	n	Observed biomass (tons ha^{-1})	Difference between predicted and observed biomass		
			(tons ha^{-1})	(%)	SE (tons ha^{-1})
6	38	91.14	-6.83*	-7.50	2.15
8	83	120.55	-2.28	-1.89	1.39
11	83	137.76	1.52	1.11	1.28
14	62	165.13	3.48	2.11	1.94
17	65	197.55	4.95*	2.51	1.91
20	50	246.50	-0.05	-0.02	3.15
23	21	317.47	2.39	0.75	3.57
26 -	2	234.92	-5.73	-2.44	6.37
Volume class [1)]					
25	32	33.79	3.36*	9.95	0.48
75	87	75.48	0.59	0.78	0.85
125	64	114.81	-1.17	-1.02	1.64
175	61	149.52	0.59	0.40	1.96
225	37	190.45	-2.68	-1.40	2.74
275	33	221.22	1.67	0.76	3.25
325	31	248.85	7.11*	2.86	2.65
375	16	286.30	3.93	1.37	6.91
425	15	322.09	-2.62	-0.81	5.90
475	6	348.20	0.29	0.08	8.13
625	20	430.58	-1.45	-0.34	4.84
≥750	2	603.47	-51.00	-8.45	23.03
Region					
Southern Norway	274	166.06	3.78*	2.28	0.84
Elevation (m):					
0 – 249	58	204.73	13.46*	6.57	1.46
250 – 499	75	187.54	7.00*	3.73	1.54
500 – 749	102	143.08	0.76	0.53	1.03
750 -	39	129.80	-8.38*	-6.46	2.41
Middle Norway	77	133.50	-2.58	-1.93	1.48
Western Norway	29	296.79	-18.00*	-6.06	4.01
Northern Norway	24	134.03	-5.59*	-4.17	2.36
All plots	404	166.53	0.56	0.34	0.76

* significantly different from zero ($p < 0.05$), [1)] mean values (m^3 ha^{-1}) for classes

Table 8. Differences between predicted total biomass based on the stand level models and observed total biomass from individual trees for Scots pine dominated sample plots.

Site index class (m)	N	Observed biomass (tons ha^{-1})	Difference between predicted and observed biomass		
			(tons ha^{-1})	(%)	SE (tons ha^{-1})
6	64	64.85	-3.49*	-5.37	1.00
8	148	86.44	-0.08	-0.09	0.83
11	83	106.83	0.64	0.60	0.98
14	37	147.86	1.79	1.21	1.97
17	20	155.27	0.25	0.16	2.85
20	1	159.59	2.05	1.29	---
Volume class [1)]					
25	57	28.19	0.57	2.01	0.47
75	89	60.07	-0.89	-1.48	0.82
125	90	93.62	-0.86	-0.92	0.94
175	46	121.48	3.12*	2.57	1.34
225	27	155.12	0.42	0.27	2.29
275	22	188.63	0.24	0.13	3.02
325	9	224.45	-3.61	-1.61	3.27
375	5	257.55	-4.48	-1.74	10.41
425	4	308.56	-24.00	-7.78	16.54
475	1	317.09	-1.93	-0.61	---
≥ 625	3	359.31	-6.65	-1.85	20.56
Region					
Southern Norway	248	99.52	2.16*	2.17	0.57
Elevation (m):					
0 – 249	71	122.78	2.69*	2.19	1.20
250 – 499	86	114.52	3.07*	2.68	1.12
500 – 749	69	71.99	1.58*	2.19	0.75
750 -	22	65.45	-0.68	-1.04	1.39
Middle Norway	24	70.31	-1.77	-2.52	1.25
Western Norway	67	106.92	-8.84*	-8.27	1.29
Northern Norway	14	68.67	-1.46	-2.12	1.25
All plots	353	97.72	-0.32	-0.33	0.53

* significantly different from zero ($p < 0.05$), [1)] mean values (m^3 ha^{-1}) for classes

Table 9. Differences between predicted total biomass based on the stand level models and observed total biomass from individual trees for broadleaf dominated sample plots.

Site index class (m)	n	Observed biomass (tons ha^{-1})	Difference between predicted and observed biomass		
			(tons ha^{-1})	(%)	SE (tons ha^{-1})
6	62	35.09	0.24	0.68	0.16
8	149	60.13	-0.84*	-1.39	0.30
11	96	100.13	-1.37*	-1.37	0.63
14	46	133.03	-1.21	-0.91	1.19
17	20	134.74	0.80	0.60	2.48
20	3	196.37	8.64	4.40	2.25
23 -	2	193.96	14.35*	7.40	1.09
Volume class [1)]					
25	140	28.96	0.37*	1.29	0.09
75	141	74.12	-0.58*	-0.79	0.26
125	45	124.24	-1.62	-1.31	0.90
175	29	170.14	-3.09	-1.81	2.01
225	12	218.70	-1.44	-0.66	3.06
275	5	248.86	5.29	2.12	5.30
325	2	334.36	-23.66*	-7.07	0.46
375	2	373.52	-35.59	-9.53	8.23
≥ 425-	2	406.65	-7.05	-1.73	22.80
Region					
Southern Norway	113	89.42	0.67	0.74	0.54
Elevation (m):					
0 – 249	35	171.49	0.97	0.57	1.63
250 – 499	21	102.45	1.50	1.47	1.46
500 – 749	20	83.19	0.04	0.05	0.92
750 -	37	42.38	0.45	1.07	0.23
Middle Norway	30	87.17	-3.34	-3.84	1.63
Western Norway	88	84.32	-1.70*	-2.01	0.55
Northern Norway	147	56.75	-0.39	-0.70	0.27
All plots	378	75.18	-0.59*	-0.78	0.27

* significantly different from zero ($p < 0.05$), [1)] mean values (m^3 ha^{-1}) for classes

Table 10. Differences between predicted total biomass based on the stand level models and observed total biomass from individual trees for mixed species sample plots.

Site index class (m)	n	Observed biomass (tons ha^{-1})	Difference between predicted and observed biomass		
			(tons ha^{-1})	(%)	SE (tons ha^{-1})
6	25	64.54	-5.71*	-8.85	1.78
8	69	85.93	-5.25*	-6.11	1.22
11	68	115.78	-3.06*	-2.64	1.35
14	67	132.15	0.52	0.39	1.60
17	16	186.48	3.33	1.78	5.29
20	7	182.49	9.24	5.06	7.37
23 -	3	254.77	-5.00	-1.96	13.20
Volume class [1)]					
25	37	34.12	-1.16	-3.41	0.78
75	67	69.64	-2.65*	-3.80	0.98
125	54	105.96	-5.22*	-4.93	1.56
175	41	140.77	-2.47	-1.75	2.25
225	20	175.93	1.30	0.74	3.83
275	21	205.56	-0.35	-0.17	4.48
325	6	251.98	-2.89	-1.15	10.28
375	6	271.45	5.43	2.00	8.11
425	2	325.62	-17.27*	-5.30	1.76
≥ 475	1	347.61	21.96	6.32	-
Region					
Southern Norway	187	120.65	-0.57	-0.48	0.92
Elevation (m):					
0 – 249	63	156.74	-0.98	-0.62	1.86
250 – 499	60	123.30	1.86	1.51	1.73
500 – 749	45	86.51	-1.69	-1.95	1.33
750 -	19	77.17	-3.97	-5.14	2.14
Middle Norway	37	105.94	-5.54*	-5.23	1.89
Western Norway	19	86.73	-7.99*	-9.21	2.99
Northern Norway	12	87.62	-9.21*	-10.52	3.54
All plots	255	114.25	-2.29*	-2.00	0.80

* significantly different from zero ($p < 0.05$), [1)] mean values (m^3 ha^{-1}) for classes

4. Concluding remarks

We have presented models for prediction of stand level biomass for Norway spruce, Scots pine and broadleaf dominated forests, respectively. The models are based on stand level independent variables normally available in forest management plans and on variables used in decision-support tools. The models may be useful for quantifying biomass for different tree components, and subsequently carbon, when data on induvial trees are not available. The models behaved reasonably well when tested over different forest conditions and regions. However, users should be aware of uncertainties related to western and northern parts of Norway, where the tests revealed underestimation of the biomass.

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Appendix. Tables displaying stand level biomass

Table A1. Total tree biomass (tons ha^{-1}) for Norway spruce dominated forest (forest with at least 70% volume of Norway spruce) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	30.66	30.15	29.38	28.62	27.85	27.09	26.32
50	54.07	53.56	52.80	52.03	51.27	50.5	49.74
75	75.72	75.21	74.44	73.68	72.91	72.15	71.38
100	96.30	95.79	95.02	94.26	93.49	92.73	91.96
125	116.11	115.6	114.83	114.07	113.3	112.54	111.77
150	135.34	134.83	134.06	133.30	132.53	131.77	131.00
175	154.09	153.58	152.81	152.05	151.28	150.52	149.75
200	172.44	171.93	171.17	170.40	169.64	168.87	168.11
225	190.46	189.95	189.18	188.42	187.65	186.89	186.12
250	208.17	207.66	206.90	206.13	205.37	204.60	203.84
275	225.63	225.12	224.35	223.59	222.82	222.06	221.29
300	242.85	242.34	241.57	240.81	240.04	239.28	238.51
325	259.85	259.34	258.58	257.81	257.05	256.28	255.52
350	276.66	276.15	275.39	274.62	273.86	273.09	272.33
375	293.30	292.79	292.02	291.26	290.49	289.73	288.96
400	309.76	309.25	308.49	307.72	306.96	306.19	305.43
425	326.08	325.57	324.80	324.04	323.27	322.51	321.74
450	342.25	341.74	340.98	340.21	339.45	338.68	337.92
475	358.29	357.78	357.01	356.25	355.48	354.72	353.95
500	374.20	373.69	372.93	372.16	371.40	370.63	369.87
525	390.00	389.49	388.72	387.96	387.19	386.43	385.66
550	405.68	405.17	404.40	403.64	402.87	402.11	401.34
575	421.26	420.75	419.98	419.22	418.45	417.69	416.92
600	436.73	436.22	435.46	434.69	433.93	433.16	432.40

Grey: outside data range

Table A2. Total aboveground biomass (tons ha^{-1}) for Norway spruce dominated forest (forest with at least 70% volume of Norway spruce) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	21.48	21.17	20.71	20.25	19.79	19.33	18.87
50	38.42	38.12	37.66	37.20	36.74	36.28	35.82
75	54.31	54.00	53.54	53.08	52.62	52.16	51.70
100	69.53	69.23	68.77	68.31	67.85	67.39	66.93
125	84.29	83.99	83.53	83.07	82.61	82.15	81.69
150	98.69	98.38	97.92	97.46	97.00	96.54	96.08
175	112.79	112.48	112.02	111.56	111.10	110.64	110.18
200	126.64	126.34	125.88	125.42	124.96	124.50	124.04
225	140.28	139.98	139.52	139.06	138.60	138.14	137.68
250	153.74	153.43	152.97	152.51	152.05	151.59	151.13
275	167.03	166.72	166.26	165.80	165.34	164.88	164.42
300	180.17	179.86	179.40	178.94	178.48	178.02	177.56
325	193.17	192.87	192.41	191.95	191.49	191.03	190.57
350	206.05	205.75	205.29	204.83	204.37	203.91	203.45
375	218.82	218.52	218.06	217.60	217.14	216.68	216.22
400	231.49	231.18	230.72	230.26	229.80	229.34	228.88
425	244.05	243.75	243.29	242.83	242.37	241.91	241.45
450	256.53	256.22	255.76	255.30	254.84	254.38	253.92
475	268.92	268.61	268.15	267.69	267.23	266.77	266.31
500	281.23	280.92	280.46	280.00	279.54	279.08	278.62
525	293.46	293.15	292.69	292.23	291.77	291.31	290.85
550	305.62	305.31	304.85	304.39	303.93	303.47	303.01
575	317.71	317.41	316.95	316.49	316.03	315.57	315.11
600	329.74	329.44	328.98	328.52	328.06	327.60	327.14

Grey: outside data range

Table A3. Total belowground biomass (tons ha^{-1}) for Norway spruce dominated forest (forest with at least 70% volume of Norway spruce) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	9.09	8.92	8.68	8.43	8.18	7.94	7.69
50	15.55	15.38	15.14	14.89	14.64	14.4	14.15
75	21.30	21.13	20.88	20.64	20.39	20.14	19.90
100	26.62	26.46	26.21	25.96	25.72	25.47	25.22
125	31.66	31.49	31.25	31.00	30.75	30.51	30.26
150	36.47	36.31	36.06	35.81	35.57	35.32	35.07
175	41.11	40.94	40.70	40.45	40.20	39.96	39.71
200	45.60	45.44	45.19	44.94	44.69	44.45	44.20
225	49.97	49.80	49.56	49.31	49.06	48.82	48.57
250	54.23	54.06	53.82	53.57	53.32	53.08	52.83
275	58.39	58.23	57.98	57.74	57.49	57.24	57.00
300	62.48	62.31	62.07	61.82	61.57	61.32	61.08
325	66.48	66.32	66.07	65.83	65.58	65.33	65.09
350	70.42	70.26	70.01	69.77	69.52	69.27	69.02
375	74.30	74.14	73.89	73.64	73.40	73.15	72.90
400	78.12	77.96	77.71	77.46	77.22	76.97	76.72
425	81.89	81.72	81.48	81.23	80.98	80.74	80.49
450	85.61	85.44	85.19	84.95	84.70	84.45	84.21
475	89.28	89.11	88.87	88.62	88.37	88.12	87.88
500	92.91	92.74	92.49	92.25	92.00	91.75	91.51
525	96.50	96.33	96.08	95.84	95.59	95.34	95.10
550	100.05	99.88	99.63	99.39	99.14	98.89	98.65
575	103.56	103.40	103.15	102.90	102.66	102.41	102.16
600	107.04	106.88	106.63	106.38	106.14	105.89	105.64

Grey: outside data range

Table A4. Total tree biomass (tons ha^{-1}) for Scots pine dominated forest (forest with at least 70% volume of Scots pine) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	24.12	22.50	20.08	17.65	15.23	12.81	10.38
50	43.50	41.88	39.46	37.04	34.61	32.19	29.76
75	61.80	60.18	57.76	55.34	52.91	50.49	48.07
100	79.43	77.82	75.39	72.97	70.55	68.12	65.70
125	96.58	94.97	92.54	90.12	87.70	85.27	82.85
150	113.36	111.74	109.32	106.9	104.47	102.05	99.62
175	129.83	128.21	125.79	123.37	120.94	118.52	116.10
200	146.05	144.43	142.01	139.58	137.16	134.73	132.31
225	162.04	160.42	158.00	155.58	153.15	150.73	148.31
250	177.84	176.22	173.80	171.38	168.95	166.53	164.11
275	193.47	191.85	189.43	187.00	184.58	182.16	179.73
300	208.94	207.32	204.90	202.48	200.05	197.63	195.21
325	224.27	222.66	220.23	217.81	215.38	212.96	210.54
350	239.47	237.86	235.44	233.01	230.59	228.16	225.74
375	254.56	252.94	250.52	248.10	245.67	243.25	240.83
400	269.53	267.92	265.50	263.07	260.65	258.22	255.80
425	284.41	282.79	280.37	277.94	275.52	273.10	270.67
450	299.18	297.57	295.14	292.72	290.30	287.87	285.45
475	313.87	312.26	309.83	307.41	304.98	302.56	300.14
500	328.47	326.86	324.44	322.01	319.59	317.16	314.74
525	343.00	341.38	338.96	336.53	334.11	331.69	329.26
550	357.45	355.83	353.41	350.98	348.56	346.13	343.71
575	371.82	370.21	367.78	365.36	362.93	360.51	358.09
600	386.13	384.51	382.09	379.67	377.24	374.82	372.39

Grey: outside data range

Table A5. Total aboveground biomass (tons ha^{-1}) for Scots pine dominated forest (forest with at least 70% volume of Scots pine) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	16.62	15.69	14.29	12.90	11.50	10.11	8.71
50	30.60	29.67	28.28	26.88	25.49	24.09	22.70
75	43.97	43.04	41.65	40.25	38.86	37.46	36.07
100	56.97	56.04	54.64	53.25	51.85	50.45	49.06
125	69.68	68.75	67.36	65.96	64.57	63.17	61.77
150	82.18	81.25	79.86	78.46	77.07	75.67	74.27
175	94.50	93.57	92.18	90.78	89.39	87.99	86.60
200	106.68	105.75	104.35	102.96	101.56	100.17	98.77
225	118.72	117.79	116.40	115.00	113.61	112.21	110.82
250	130.65	129.72	128.33	126.93	125.54	124.14	122.75
275	142.48	141.55	140.16	138.76	137.37	135.97	134.58
300	154.22	153.29	151.9	150.50	149.11	147.71	146.32
325	165.88	164.95	163.55	162.16	160.76	159.37	157.97
350	177.46	176.53	175.13	173.74	172.34	170.95	169.55
375	188.97	188.04	186.64	185.25	183.85	182.46	181.06
400	200.41	199.48	198.09	196.69	195.30	193.90	192.51
425	211.80	210.87	209.47	208.08	206.68	205.28	203.89
450	223.12	222.19	220.80	219.40	218.01	216.61	215.22
475	234.40	233.47	232.07	230.68	229.28	227.89	226.49
500	245.62	244.69	243.29	241.90	240.50	239.11	237.71
525	256.80	255.87	254.47	253.08	251.68	250.28	248.89
550	267.93	267.00	265.60	264.21	262.81	261.42	260.02
575	279.01	278.08	276.69	275.29	273.90	272.50	271.11
600	290.06	289.13	287.74	286.34	284.95	283.55	282.15

Grey: outside data range

Table A6. Total belowground biomass (tons ha^{-1}) for Scots pine dominated forest (forest with at least 70% volume of Scots pine) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	7.44	6.84	5.93	5.03	4.12	3.22	2.31
50	12.80	12.20	11.29	10.39	9.48	8.58	7.67
75	17.69	17.09	16.19	15.28	14.37	13.47	12.56
100	22.30	21.70	20.8	19.89	18.98	18.08	17.17
125	26.72	26.11	25.21	24.30	23.39	22.49	21.58
150	30.97	30.37	29.46	28.56	27.65	26.75	25.84
175	35.11	34.51	33.60	32.69	31.79	30.88	29.98
200	39.14	38.54	37.63	36.73	35.82	34.92	34.01
225	43.09	42.49	41.58	40.68	39.77	38.86	37.96
250	46.96	46.36	45.45	44.55	43.64	42.73	41.83
275	50.76	50.16	49.26	48.35	47.44	46.54	45.63
300	54.51	53.90	53.00	52.09	51.19	50.28	49.38
325	58.20	57.59	56.69	55.78	54.88	53.97	53.07
350	61.84	61.23	60.33	59.42	58.52	57.61	56.71
375	65.43	64.83	63.92	63.02	62.11	61.21	60.30
400	68.99	68.38	67.48	66.57	65.67	64.76	63.86
425	72.50	71.90	70.99	70.09	69.18	68.28	67.37
450	75.98	75.38	74.47	73.57	72.66	71.76	70.85
475	79.43	78.82	77.92	77.01	76.11	75.20	74.30
500	82.84	82.24	81.33	80.43	79.52	78.62	77.71
525	86.23	85.62	84.72	83.81	82.91	82.00	81.09
550	89.58	88.98	88.07	87.17	86.26	85.36	84.45
575	92.91	92.31	91.40	90.50	89.59	88.69	87.78
600	96.22	95.61	94.71	93.80	92.90	91.99	91.09

Grey: outside data range

Table A7. Total tree biomass (tons ha^{-1}) for broadleaf dominated forest (forest with at least 70% volume of broadleaves) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	26.84	26.61	26.26	25.92	25.57	25.23	24.88
50	52.40	52.17	51.82	51.48	51.13	50.79	50.44
75	77.25	77.02	76.67	76.33	75.98	75.64	75.29
100	101.64	101.41	101.07	100.72	100.38	100.03	99.69
125	125.71	125.48	125.14	124.79	124.45	124.10	123.76
150	149.53	149.30	148.95	148.61	148.26	147.92	147.57
175	173.12	172.89	172.55	172.20	171.86	171.51	171.17
200	196.54	196.31	195.96	195.62	195.27	194.93	194.58
225	219.80	219.57	219.22	218.88	218.53	218.19	217.84
250	242.92	242.69	242.35	242.00	241.66	241.31	240.97
275	265.92	265.69	265.34	265.00	264.65	264.31	263.96
300	288.80	288.57	288.23	287.88	287.54	287.19	286.85
325	311.59	311.36	311.01	310.67	310.32	309.98	309.63
350	334.27	334.04	333.70	333.35	333.01	332.66	332.32
375	356.88	356.65	356.3	355.96	355.61	355.27	354.92
400	379.40	379.17	378.82	378.48	378.13	377.79	377.44
425	401.84	401.61	401.27	400.92	400.58	400.23	399.89
450	424.22	423.99	423.64	423.30	422.95	422.61	422.26
475	446.52	446.29	445.95	445.60	445.26	444.91	444.57
500	468.77	468.54	468.19	467.85	467.50	467.16	466.81
525	490.95	490.72	490.38	490.03	489.69	489.34	489.00
550	513.08	512.85	512.51	512.16	511.82	511.47	511.13
575	535.16	534.93	534.58	534.24	533.89	533.55	533.2
600	557.18	556.95	556.61	556.26	555.92	555.57	555.23

Grey: outside data range

Table A8. Total aboveground biomass (tons ha^{-1}) for broadleaf dominated forest (forest with at least 70% volume of broadleaves) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	17.00	17.07	17.19	17.30	17.41	17.52	17.64
50	34.28	34.35	34.46	34.58	34.69	34.8	34.91
75	51.48	51.55	51.66	51.78	51.89	52.00	52.11
100	68.63	68.7	68.81	68.93	69.04	69.15	69.26
125	85.74	85.82	85.93	86.04	86.15	86.27	86.38
150	102.83	102.9	103.01	103.13	103.24	103.35	103.46
175	119.89	119.96	120.07	120.19	120.30	120.41	120.52
200	136.93	137.00	137.11	137.23	137.34	137.45	137.56
225	153.95	154.02	154.13	154.25	154.36	154.47	154.58
250	170.95	171.03	171.14	171.25	171.37	171.48	171.59
275	187.94	188.02	188.13	188.24	188.36	188.47	188.58
300	204.92	205.00	205.11	205.22	205.33	205.45	205.56
325	221.89	221.96	222.07	222.19	222.30	222.41	222.52
350	238.84	238.92	239.03	239.14	239.25	239.37	239.48
375	255.79	255.86	255.97	256.09	256.20	256.31	256.42
400	272.72	272.80	272.91	273.02	273.13	273.25	273.36
425	289.65	289.72	289.83	289.95	290.06	290.17	290.28
450	306.56	306.64	306.75	306.86	306.98	307.09	307.20
475	323.47	323.55	323.66	323.77	323.89	324.00	324.11
500	340.38	340.45	340.56	340.68	340.79	340.90	341.01
525	357.27	357.35	357.46	357.57	357.68	357.80	357.91
550	374.16	374.23	374.35	374.46	374.57	374.68	374.80
575	391.04	391.11	391.23	391.34	391.45	391.56	391.68
600	407.91	407.99	408.10	408.21	408.33	408.44	408.55

Grey: outside data range

Table A9. Total belowground biomass (tons ha^{-1}) for broadleaf dominated forest (forest with at least 70% volume of broadleaves) distributed on volume and site index classes.

Volume	Site index (m)						
(m^3 ha^{-1})	6	8	11	14	17	20	23
25	9.79	9.55	9.20	8.84	8.49	8.13	7.78
50	17.93	17.69	17.34	16.98	16.63	16.28	15.92
75	25.51	25.27	24.92	24.56	24.21	23.85	23.50
100	32.74	32.50	32.15	31.79	31.44	31.09	30.73
125	39.72	39.49	39.13	38.78	38.43	38.07	37.72
150	46.52	46.28	45.93	45.57	45.22	44.87	44.51
175	53.16	52.92	52.57	52.22	51.86	51.51	51.15
200	59.67	59.43	59.08	58.73	58.37	58.02	57.66
225	66.07	65.83	65.48	65.13	64.77	64.42	64.06
250	72.37	72.14	71.78	71.43	71.08	70.72	70.37
275	78.59	78.36	78.00	77.65	77.29	76.94	76.59
300	84.73	84.50	84.14	83.79	83.43	83.08	82.73
325	90.80	90.57	90.21	89.86	89.50	89.15	88.80
350	96.81	96.57	96.22	95.86	95.51	95.16	94.80
375	102.76	102.52	102.17	101.81	101.46	101.10	100.75
400	108.65	108.41	108.06	107.70	107.35	107.00	106.64
425	114.49	114.26	113.90	113.55	113.19	112.84	112.49
450	120.29	120.05	119.70	119.34	118.99	118.64	118.28
475	126.04	125.80	125.45	125.10	124.74	124.39	124.03
500	131.75	131.51	131.16	130.81	130.45	130.10	129.74
525	137.42	137.19	136.83	136.48	136.12	135.77	135.42
550	143.06	142.82	142.47	142.11	141.76	141.40	141.05
575	148.66	148.42	148.07	147.71	147.36	147.00	146.65
600	154.22	153.99	153.63	153.28	152.92	152.57	152.22

Grey: outside data range