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USING STEM ANALYSIS DATA FOR MODELLING THE VOLUME OF KINUYANAGI WILLOW /.../ M. M. A. SALAM ET AL.

Using Stem Analysis Data for Modelling the Volume of Kinuyanagi Willow (*Salix schwerinii* E. L. Wolf)

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Abstract

Biomass can be estimated by different apparoaches. Volume and taper are important factors to assess the opportunties to utilize biomass from multipurpose short rotation forestry. The properties of biomass may vary from clone to clone and site to site. Therefore, accurate estimates of volumes, for instance, are needed based on clone and site specific. Several non-linear and liner functions were fitted to the data set processed from the cloned willow (*Salix schwerinii* E. L. Wolf) plantation in Siikasalmi, Finland, to estimate volumes and to compare the best fitted taper and volume approach based on the strategy of the number of radius measurements observation per stem (i.e. 3-15 radius measurements including *RBH* and *H* measurements) for cost-efficient estimates of volume. The functions were evaluated based on the fit statistics so as to select the best-fitted models. The nonlinear function of Demaerschak (taper function) with 2- parameters and Schumacher and Hall (direct volume function) were fitted to the data set more accurately to predict the volume than other taper and volume functions, since these had goodness-fit-statistics. Two best-fitted functions were also compared with compromising accuracy, using this strategy to select the suited to the cost-efficient estimation of volumes. The overall results suggested that the taper model was much more robust than the direct volume model when extrapolations were needed because a lower RMSE was found in the taper model approach. Without extrapolating the taper approach was better than the volume model only in the case of lower numbers of radius measurements (i.e. 3-5), which would therefore permit a cost-efficient estimate of volumes. The RMSE and B% were lower in these measurements.

Key words: Willow, Volume, Radius, Taper function, Volume function

Introduction

Nowadays there is a strong emphasis in the bioenergy sector on using biomass as an energy source in the world because it is renewable, to a great extent carbon neutral, abundant, and can be produced virtually everywhere. Global climate change, fossil fuel issues, national energy security, and a host of other factors all increase the interest in using biomass as an energy source (Grebner et al. 2009). As countries strive to find sustainable sources of renewable energy, the importance of biomass, especially woody biomass, increases because of its vast availability (IEA 2006). In addition to energy use, biomass of SRF can be harnessed to many alternative bioeconomic purposes such as phytoremedation, furniture industries and handcrafted items, for instance.

Fast-growing willows can be bred and selected for high biomass production. Willows have numerous inherent characteristics that make them a good choice as a biomass crop. They have rapid juvenile growth rates, a vigorous coppicing ability that is maintained even after multiple harvests, an ease of establishment from unrooted cuttings, a tolerance of high planting densities, a high degree of genetic diversity, and a potential for rapid genetic improvement. The biomass production concept that is being developed and formalized is based on these characteristics (Abrahamson et al. 2002). In addition, willow's perennial nature, long vegetative season, extensive and diffuse root systems, high transpiration rates, and tolerance of waterlogged conditions make them potentially beneficial for a wide range of other applications (Kuzovkina and Volk 2009). According to Āboliņa et al. (2014), cultivation of willow crops is a great opportunity for the utilization of agricultural lands in Latvia, especially, in the areas not well suited for food production.

Short-rotation willows (SRSW) provide multifunctional environmental services, such as: bioenergy for climate change mitigation, phytoremediation, nutrient management, living snow fences, stream bank stabilization, rehabilitation of fragile ecosystems, forest landscape restoration, and bioengineering in various geographical regions of the world (Salam and Pelkonen

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2012). For example, in Sweden shrub willows are being used to remediate and contain sites contaminated with various industrial wastes through a process referred to as phytoremediation (Hasselgren 1994, Aronsson and Perttu 2001, Mirck et al. 2005, Licht and Isebrands 2005).

Very recently, Holm and Heinsoo (2014) have analysed the possibilities to use the digestion from pig slurry anaerobic digestion as a nutrient supply for Short Rotation Coppice (SRC) *Salix* species. Their results suggested that, digestate can be an alternative fertilizer in SRC and the nutrients from digestate are more available for Salix plants than those from mineral fertilizer. Heinsoo and Dimitriou (2014) have also studied the growth performances of different willow clones in SRC after the application of sewage sludge. They reported that, sludge application did not have any significant impact on growth performances of willow clones.

The willow biomass crop production system sequestrates carbon while producing biomass, and, in addition, the production system produces low sulphur emissions compared to fossil fuels (Verwijst and Selenium 1999). Willow biomass crops can consider as an alternative crop for the production of heat, power, fuels, and/or bioproducts for environmental reasons (Verwijst and Selenium 1999).

Willow may be valuable cultivated forest genus in Northern Europe due to fast growth and high productivity. Modelling volume of willow may have been a challenge for foresters in recent years due to the strong site and genetic variations. Because of the lack of wide interest in other northern countries except Sweden, volume modelling of *Salix* has been negligible so far. However, due to the fast growth and high production capacity, interest has arisen to assess the potential of *Salix* plantations to produce biomass, which kinds of clones are most suitable for biomass production. Therefore, development of models required in assessments has become topical.

Estimates of volume are needed to evaluate biomass and terrestrial carbon stocks (Hall 1997, Henry et al. 2011). The volume of wood contained in the stem of a tree is one of the most important measurements made in forestry, because the stem contains a very large proportion of the biomass of a tree. Biomass of a tree stem is usually determined by measuring stem volume by sectional measurement. Stem biomass is often derived from stem volume by multiplying its volume by wood density (West 2003). These indirect methods are attempts to estimate tree biomass by measuring variables that are more accessible and less time-consuming to assess (e.g., wood volume and gravity (Peltier et al. 2007)).

Biomass can be also estimated using the allometric relationships. Different authors reviewed the methods of estimation of *Salix* biomass based on power and polynominal functions (i.e. Nilsson 1982, Hytönen et al. 1987, Tahvanainen 1996, Verwijst and Selenium 1999, Nordh and Verwijst 2004 and Arevalo et al. 2007). Weighting trees in the field is undoubtedly the most accurate method of estimating aboveground tree biomass, but it is time-consuming (Henry et al. 2011).

Volume prediction is an important issue in short rotation forest management and planning (West 2003). Therefore, accurate methods are needed to estimate the volumes for various short rotation tree species. Among the different ways to estimate tree volume, modelling methods may represent the most accurate and versatile approach (de-Miguel et al. 2012).

There are two approaches for estimating standing tree volume using predictive models: to use a volume equation or to compute the volume of the whole stem or part of it by integrating a predicted taper curve. Direct stem volume equations are used to predict the volume of stems of standing trees as a function of easily measured tree attributes, for example the diameter at breast height (*DBH*) and total tree height (*H*). In the various methods of direct modelling of tree volume, different regression equations can be fitted to estimate total stem (stump to tip) volume (Burkhart and Tome 2012). Laar and Akça (2007) and Burkhart and Tome (2012) list various recommended functions for fitting total volume models, and those tested in this study were developed by Schumacher and Hall (1933), Spurr (1952) and Burkhart (1977), Newnham (1967) and Romancier (1961).

Generally speaking, stem taper is defined as the rate of change of diameter with height along the stem, where stem profile reflects the shape of the entire stem (West 2003). Unlike volume equations, taper equations provide estimates for the diameter at any height or the height at any diameter, and provide flexibility for total stem volume estimates (Kozak 1988).

Accurate volumes are needed to estimate biomass to utlize the usable biomass cost-efficiently and effectively. Volumes are also needed in growth and yield study and research purposes to select the best clone for the high profitibality of willow cultivation in practice. The main aim of the study was to compare the taper and volume functions for estimating volumes of *Salix schwerinii* accurately and cost-efficiently. The specific objectives of this study were: to evaluate the different taper and volume functions to find which of them best fit the willow data; to evaluate the effect of reduced sample size (no. of radius measurements at a stem) and extrapolation of tree sizes on the accuracy of the two alternative methods and to evaluate the

resulting predictions using a cross-validation approach. The reduced datasets were constructed by removing measurements from the modelling data so that the number of measurements per tree varied from 15 to 3 in different measurement strategies. The hypothesis of this study were: 1) there are large differences in the existing models for predicting the volume growth of *Salix schwerinii;* 2) the taper based method is more robust in tree volume prediction if the number of measurements per stem is low; 3) taper prediction is also more robust if extrapolated for tree sizes that have not been included in the modelling data.

Materials and Methods

Area Characterization

Data used in this study proceed from a plantation of willow clone (*Salix schwerinii)* located in the east of Finland, in the municipality of Liperi, Finland (62° 30' N, 29° 30' E). At this site study was focused on the growth dynamic of variety clones of willow. The plantation site was in an open-drained fallow field and the soil type was silty and sandy where the pH ranges from 5.3 to 6.6 (Kuusela et al. 2004). The distance between each of the rows of planted stem cuttings was 0.7 m and between each cutting 0.5 m, thus making the planting density approximately 15,000 cuttings ha^{-1}. Each plant provided multiple stems. The regional climate was a moist mid-latitude climate with cold winters (characteristics of both a maritime and a continental climates). In this boreal climate, the mean temperature was below -3 °C in the coldest month, while the warmest was at above +10 °C, with sufficient year-round precipitation (Tahvanainen 1996).

Data collection

Random sampling was undertaken for the establishment of a total of 4 sample plots. The stems were sampled separately at 15- and 4-year-old plantations in the winter time. Within each plot, the sample tree stumps were sampled systematically by utilizing the regular pattern of planting locations. In the case of multiple stems in a stump, the three thickest stems (dominant diameter at 130 cm height measured using a tree caliper) were selected based on selective sampling. In most cases we found two stems in a stump. Altogether 26 stems (10 stems at the 15-year-old plantation and 16 stems at the 4-year-old plantation) were sampled by random selection and systematic sampling for stem analysis data. The data used in this study was based on a stem analysis data set of 714 pieces of stem section and 216 measurements of taper. The stem analysis was used to determine the stem taper and to estimate volume for all of the past years. The total tree height was recorded and determined from the annual current increment of the height of stem in past years.

The sampled stems were felled and cut into different sections at stump height (10 cm) and the desired lengths of a stem sections were 5 cm (i.e. (5-6) pieces),10 cm (i.e. (5-6) pieces, 20 (i.e. (5-6) pieces) cm, 50 (i.e. (5-6) pieces) cm, and 100 (i.e. (3-4) pieces) cm. All of the stem sections from the sampled stems were placed in a large breathable bag, moved, and stored at –10 °C until 24 hours prior to their preparation for analysis, which involved sanding the surface of the stem sections. The sanded sections were scanned and the resulting images were saved at a resolution of 720 DPI or higher. These images were then analyzed for radius growth and ring number along the marked radii from the pith using WINDENDRO™ software. The radii were calculated in the inner bark as the mean of four measurements made in four directions (90°), where the direction was the same at each measuring height (i.e. $r = (r_1 + r_2 + r_3 + r_4)/4$). The volume of each section in a stem was estimated using the equation concerned with the volume of truncated cone. The total stem volumes of the different growing seasons were estimated by summing up the volume of each section in a stem:

$$V = \Sigma^n_{i=1} \pi * (h_i - h_{i-1}) * (r_{i_1}^2 + r_{i_2}^2 + r_{i_1} * r_{i_2}) * 1/3 * C \qquad (1)$$

where, $i = 1, 2.........n$

In equation 1, V = volume of a stem (dm³); h_i = height for each section in a stem (cm); r_{i_1} = top radius for each section in a stem (mm); r_{i_2} = bottom radius for each section in a stem (mm); i = no. of stem sections in a stem; n = total no. of stem sections in a stem; C = constant value (100,000) for unit conversion of dm³. The summary of statistics for the sampled stems and other variables are presented in Table 1.

Table 1. Summary statistics of some of the variables in the dataset

Variables	Min	Max	Mean	Std. dev.	N
Big-sized plantation					
H (cm)	139	1088	797.31	64	10
RBH (mm)	1.02	26.7	17.01	6.61	10
Age (years)	1	15	8.52	4.18	10
Small-sized plantation					
H (cm)	137	700	411.1	48	16
RBH (mm)	1.01	16.28	8.11	4.28	16
Age (years)	1	4	2.66	1.08	16

N = Sample size; Minimum & minimum; Maximum & maximum; Std. dev. = standard deviation; *RBH* = radius at breast height (130 cm) and *H* = total stem height.

Taper model fitting method

There are currently no update and efficient taper/volume equations for managed stands of the many willow species studied, one of which is *Salix schwer-*

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inii. For the sprout-based trees of this species, Salam and Pelkonen (2012) have developed the first preliminary model, which is based on the 3-parameter Gompertz sigmoid curve to predict radius and volume on the basis of stem analysis data. The results from the preliminary model have encouraged them also to extend their modelling work on *Salix schwerinii*. Taper/ volume functions become the primary tool for estimating the volume of a whole stem or at any part of a stem by means of mathematical integration of the section area along the tree axle (Silva et al. 2006 and de-Miguel et al. 2012).

Several equation forms were screened for modelling the stem shape and for estimating the stem volume, based on a review of the literature (Newton and Sharma 2008, Fonweban et al. 2011, Subedi et al. 2011, de-Miguel et al. 2012, Li et al. 2012 and Menéndez-Miguélez et al. 2014). Very recently, Padari et al. (2014) have used taper function to estimate volumes of assortments. In this study, for our taper modeling we evaluated the equivalents developed by Kozak et al. (1969), Demaerschalk (1972), Demaerschalk (1973), Ormerod (1973), Max and Burkhart (1976), Laasasenaho (1982), Kozak (1997), Zakrzewski (1999), Bi (2000), Sharma and Oderwald (2001) and Lee et al. (2003); for the fitting volume functions we focused on the models published by Schumacher and Hall (1933), Burkhart (1977), Romancier (1961) and Newnham (1967).

In a preliminary analysis, all of the cited taper functions were fitted to the whole data set and explored graphically. In this study, all of the statistical evaluation and other graphical renderings of the data were obtained by using the R-software tool (R Development Core Team 2011). The graphically best fitted taper functions were selected in order to estimate the volumes. The models were fitted for r^2 since tree volume is the integral of the cross-sectional stem area over the tree height. A model that provides unbiased predictions for the cross-sectional area is needed for an unbiased prediction of volume. This condition is satisfied with the model for r^2 but not with the model for r (Bruce et al. 1968 and Gregoire et al. 2000 and de-Miguel et al. 2012). Models for the whole data can be represented by

$$y_{ijt}^2 = [f(z_{ijt}, x_{jt}, \boldsymbol{\beta})]^2 + \varepsilon_{ijt}, \quad (2)$$

where: y_{ijt} is the ith measurement of the response variable (radius in mm) on the jth subject (tree) at age (t); z_{ijt} is the ith measurement of the corresponding predictor (sectional height; cm) on the jth subject (tree) at age (t), x_{jt} also represents the corresponding predictors (i.e., *RBH* (radius at 130 cm height) and total tree height (*H*)), $\boldsymbol{\beta}$ is a $p+1$-length vector of parameters; e.g., $\boldsymbol{\beta} = (\beta_0, \beta_1, \ldots\ldots, \beta_p)$, f is a non-linear function; and ε_{ijt} is the residual (Pinheiro and Bates 2004, Sharma and Parton 2007).

The resultant selected functions are referred to as: Model (*M1*) – (*M6*) and these taper functions can be replaced in Equation (2). The mathematical expressions and details are presented in Table 2.

If we assume that the sectional area (*A*) of a tree with radius r_{ijt} (mm; at height h_{ijt}) is equal to (πr^2_{ijt}), and that the integration of this area from h_1 to h_2 along height h_{ijt}, we can obtain a compatible volume estimate for the section between h_1 and h_2, where the setting $h_2 = 0$ (base of the tree), $h_1 = H$ (top of the tree). The volume equation for the whole stem can be represented mathematically as follows:

$$\hat{V}_{jt} = \frac{1}{c} * \int_0^H \pi r_{ijt}^2 (h_{ijt}) \, dh \quad (9)$$

In Equation 9, $\hat{V}_{jt}$ can be seen the predicted volume (dm³) of stem *j* at age *t*, while all other notations have been previously defined (West 2003; Silva et al. 2006 and de-Miguel et al. 2012). By substituting the right-hand sides of the taper functions Equations (3) - (8) for r_{ijt}^2 in Equation 9, the volumes can be estimated and the mathematical expression of the functions can be also represented as follows, where the notations have been previously defined in Table 2:

$$\hat{V}_{jt} = \frac{1}{c} * \int_0^H \pi \, \hat{r}_{ijt}^2 (h_{ijt} | H_{jt}, RBH_{jt}, \beta_0, \beta_1, \beta_2, \beta_3) \, dh \quad (10)$$

Direct modelling of tree volume

A general expression of the volume models for the whole data can be written as:

$$y_{jt} = f(x_{jt}, \boldsymbol{\beta}) + \varepsilon_{jt} \quad (11)$$

where: y_{jt} is the response variable (volume; dm³) on the jth subject (tree) at age (t), x_{jt} represents the corresponding predictors (i.e., *RBH* (radius; mm at 130 cm height) and total tree height (*H*)), $\boldsymbol{\beta}$ is a $p+1$-length vector of the parameters; e.g., $\boldsymbol{\beta} = (\beta_0, \beta_1\ldots \beta_p)$, f is a function; and ε_{jt} is the residual (Pinheiro and Bates 2004, Sharma and Parton 2007).

The cited volume functions are referred to as: Model (*M7*) – (*M10*). The models referred to can be replaced respectively in Equation (11). The mathematical expressions and details are presented in Table 3.

Model Evaluation criteria

The regression evaluation criteria for model development and selection, and also for cross validation involving root mean square error (RMSE), the coefficient of determination (R^2) can be represented using the equations:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (v_i - \hat{v}_i)^2}{n}}, \quad (16)$$

$$R^2 = 1 - \left[\frac{\sum_{i=1}^n (v_i - \hat{v}_i)^2}{\sum_{i=1}^n (v_i - \bar{v})^2}\right], \quad (17)$$

Table 2. Selected fitted taper model

CNM	Expression	EN	Source
M1	$r_{ijt}^2 = \left[RBH_{jt} * \left(\dfrac{H_{jt} - h_{ijt}}{H_{jt} - 130} \right)^{\beta_0} \right]^2 + \varepsilon_{ijt}$	3	Omerod (1973)
M2	$r_{ijt}^2 = \left[RBH_{jt} * \sqrt{ \left(\dfrac{h_{ijt}}{130} \right)^{2-\beta_0} * \left(\dfrac{H_{jt}-h_{ijt}}{H_{jt}-130} \right) } \right]^2 + \varepsilon_{ijt}$	4	Sharma and Oderwald (2001)
M3	$r_{ijt}^2 = \left(RBH_{jt} * \sqrt{ \beta_0 * \left(\dfrac{H_{jt}-h_{ijt}}{H_{jt}} \right)^{\beta_1} } \right)^2 + \varepsilon_{ijt}$	5	Demaerschalk (1972)
M4	$r_{ijt}^2 = \left[RBH_{jt} * \sqrt{ \beta_0 * \left(\dfrac{h_{ijt}}{H_{jt}} - 1 \right) + \beta_1 * \left(\left(\dfrac{h_{ijt}}{H_{jt}} \right)^2 - 1 \right) } \right]^2 + \varepsilon_{ijt}$	6	Kozak et al. (1969)
M5	$r_{ijt}^2 = \left[RBH_{jt} * \sqrt{ \beta_0 * \dfrac{(H_{jt}-h_{ijt})^{\beta_1}}{RBH_{jt}^{2} * H_{jt}^{\beta_1+1}} + \beta_2 * \left(\dfrac{H_{jt}-h_{ijt}}{H_{jt}} \right)^{\beta_3} } \right]^2 + \varepsilon_{ijt}$	7	Demaerschalk (1973)
M6	$r_{ijt}^2 = \left[RBH_{jt} * \left(\beta_0 * \left(\dfrac{h_{ijt}}{H_{jt}} \right) + \beta_1 * \left(\dfrac{h_{ijt}}{H_{jt}} \right)^2 + \beta_2 * \left(\dfrac{h_{ijt}}{H_{jt}} \right)^8 + \beta_3 * \left(\dfrac{h_{ijt}}{H_{jt}} \right)^{32} \right) \right]^2 + \varepsilon_{ijt}$	8	Laasasenaho (1982)

where, r_{ijt} is the ith predicted radius (mm) of stem j at age t; h_{ijt} is the ith sectional height (cm) of j at age t; RBH_{jt} is radius (mm) at 130 cm height of j at age t; β_0, β_1, β_2 and β_3 are parameters and other notations have been previously defined; CNM – Code Name of Model; EN – Equation Number

Table 3. Selected fitted volume model

CNM	Expression	EN	Source
M7	$V_{jt} = \frac{1}{c}(\beta_0 * RBH_{jt}^{\beta_1} H_{jt}^{\beta_2}) + \varepsilon_{jt}$	3	Schumacher and Hall (1933)
M8	$V_{jt} = \frac{1}{c} * (\beta_0 + \beta_1 RBH_{jt}^{2} H_{jt}) + \varepsilon_{jt}$	4	Spurr (1952); Burkhart (1977)
M9	$V_{jt} = \frac{1}{c} * (\beta_0 + \beta_1 RBH_{jt}^{\beta_2} H_{jt}^{\beta_3}) + \varepsilon_{jt}$	5	Newnham (1967)
M10	$V_{jt} = \frac{1}{c} * (\beta_0 + \beta_1 RBH_{jt}^{2} + \beta_2 H_{jt} + \beta_3 RBH_{jt}^{2} H_{jt}) + \varepsilon_{jt}$	6	Romancier (1961)

where, V_{jt} is predicted volume (dm³) and other notations have been previously defined; CNM – Code Name of Model; EN – Equation Number

where: V_i is the observed volume and $\hat{V}_i$ is the predicted volume for the ith sample, n is the number of observations, and $\overline{V}$ is the mean of the true values.

To evaluate the accuracy of the predictive capacity of the regression models further, Bias (B) and the Bias percentage (B%) were calculated using:

$$\text{Bias (B)} = \frac{\sum_{i=1}^n (V_i - \hat{V}_i)}{n}, \qquad (18)$$

$$(B\%) = \left[\sum_{i=1}^n \frac{V_i - \hat{V}_i}{V_i} \right] \times \frac{100}{n}, \qquad (19)$$

where all of the notifications have been previously defined. An RMSE that is relatively small and an R^2 value that is large indicate a better goodness-of-fit for the respective data set. A positive bias indicated underestimation, while negative bias indicated overestimates of volumes.

Comparison between taper and volume function

To explore how a reduction in the number of sample tree measurements affects the accuracy of volume prediction using the two methods (taper or direct volume prediction), we made 15 individual sub-data sets based on the number of radius measurement observations. The individual sub-data sets consisted of between three and fifteen systematically selected observations of radius measurement per sample stem. We mainly concentrated on the radius measurement observations between the base and middle part of each sample stem as tapers were very frequent, and the maximum volume can be found in that part of a stem.In addition, radius measurements at the height of 130 cm (*RBH*), and the total tree height (*H*) were added to each individual data set. The selected best-fitted taper and volume functions were re-fitted to each of the individual sub-data sets and the fit statistics were calculated (RMSE and (% Bias) of volume) in order to facilitate further evaluation of the predictive capacities. The approaches were compared. We did not, however, report on the estimated parameter values of the individual sub-data sets, since the objective of the present study was primarily focused on obtaining a suitable function with the lowest possible prediction error in estimating volumes cost-efficiently vis-a-vis a limited number of radius observations per tree.

Cross-validation method

The data in this study were used to analyze large and small trees from two different plantations. To evaluate the prediction accuracy of the fitted models, we divided the whole data set into two parts, forming a modelling and an evaluation data set based on the plantations. This approach facilitated cross-validation. The whole procedure was completed in two stages. In the first stage, the best selected taper and volume functions were fitted to the plantation of small-sized trees (modelling data set: plots 1-3, a total of 64 observed stem profiles from 16 trees). The fitted models were then used to predict the plantation of large trees (evaluation dataset: plot 4, 160 stem profiles from 10 trees). In the second stage, the best selected models were fitted to the modelling data set (plantation of large trees), and the fitted models were used to predict the evaluation data set (plantation of small-sized trees)

We also conducted an analysis of the complete data, where all of the trees (with a reduced strategy-specific number of measurements per stem) were used in model fitting. The evaluation in this case was conducted in relation to the true volumes (based on all measurements per tree).

Results

Tables 4 and 5 display the estimated parameter values and goodness-of-fit statistics (R^2, Root Mean Square Error (RMSE), Bias (B), Bias Percentage (B%)) for the taper models ($M1$) – ($M6$) derived from the Nonlinear Least Square (NLS) procedure in an R statistical package. Model ($M3$) had the best (RMSE = 0.107, B = 0.0112 and B % = -0.06) and ($M1$)

the poorest fits (RMSE = 1.159, B = -0.828 and B % = -7.11), respectively, amongst these six nonlinear taper models. The coefficient of determination (R^2) for $M3$ (0.98) and $M1$ (0.91) had the highest and lowest values, respectively.

The estimated parameters values (β_0) in Equation (5) were highly significant, with a 95% level of confidence ($P < 0.0001$). The standardized residuals of the best fitted model ($M3$) were plotted according to fitted values (radius) (Figure 1) and predictor (radius at 130 cm height) (Figure 2). In the residual plots, the model seems to have a slight bias towards the smallest radius. No other clear evidence of a nonlinearity trend or heteroscedasticity was found in the residual plot, which indicated that the applied taper model ($M3$) fitted the data set appropriately (Figures 1 and 2). The predicted taper curves developed from the model ($M3$) fitted the measured taper of sample stems in different growing seasons appropriately. Figure 3, for example, shows the fitted and measured curves of sample stem No. 25 in the course of the early part of four growing seasons.

In the case of direct volume modelling, the estimated parameter values and goodness-of-fit statistics are presented in Tables (6) and (7). Of the four volume models, models ($M7$) and ($M8$) had the best (RMSE=0.039, B = -0.002 and B% = -0.98) and poorest fits (RMSE= 0.199, B = 1.101 and B% = 14), respectively. The coefficient of determination (R^2) for $M7$ (0.99) and $M8$ (0.92) had the highest and lowest values, respectively. The estimated parameter values (β_0) in Eq. (12) were highly significant, with a level of confidence of 95% ($P = 0000$). The plots of the standardized residuals suggested that the applied model ($M7$) fitted the data set well (Figure 4).

Table 4. Estimated parameters values (standard errors in parentheses) for the candidate functions of the taper model. Bold print indicates the best model

| Model | Estimated parameter values | | | | RSE | DF |
	β_0	β_1	β_2	β_3		
M1 (Taper)	1.9653 (0.1029)				8.892	4524
M2 (Taper)	0.32 (0.018)				11.523	4524
M3 (Taper)	**4.50 (0.621)**	**2.06 (0.109)**			**4.245**	**4523**
M4 (Taper)	− 2.25531 (0.02188)	0.83353 (0.01967)			11.234	4523
M5 (Taper)	16650 (4426)	39.27 (0. 8641)	1.289 (.0030)	1.257 (0.098)	33.39	4521
M6 (Taper)	2.225 (0.01942)	− 1.390 (0.029)	0.3884(0.01751)	0.0742 (0.0105)	36.86	4521

RSE: Residual of standard error and DF – degree of freedom

Table 5. Fit statistics (R^2, Root Mean Square Error (RMSE), Bias (B), Bias percentage (B%)) for Model (M1-M6). Bold print indicates the best model

Model	R^2	RMSE	Bias (B)	Bias percentage (B%)
M1	0.91	1.159	− 0.828	− 7.11
M2	0.92	0.288	+ 0.041	+ 3.169
M3	**0.98**	**0.107**	**+ 0.0112**	**− 0.06**
M4	0.97	0.108	+ 0.029	+ 0.358
M5	0.93	0.238	+ 0.0114	+ 3.142
M6	0.94	0.188	+ 0.0907	− 2.76

Figures 5-7 show the RMSE and B% of the two best fitted taper and volume models as a function of the number of radius measurements per tree. The best selected taper and volume models were fitted to the complete data set and the RMSEs of the two models were shown (Figure 5). The RMSEs and B % of the two best fitted taper and volume models based on the evaluation data set (plantation of large trees) were also presented (Figures 6a and 6b). In addition, the RMSEs
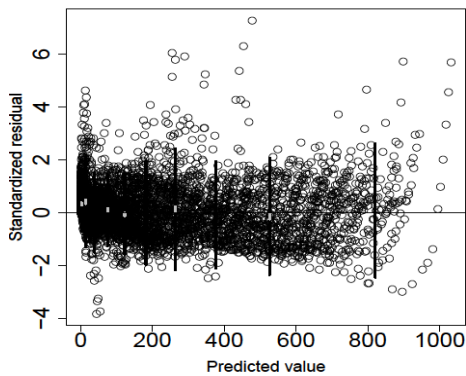
Figure 1. Standardized residuals of the best selected taper model (*M3*) on the radius (response variable (radius in mm)). The small vertical thick lines show the 95 % confidence intervals for the class means (class mean ± 1.96 × SE), and the large, thin, vertical lines indicate the 95% confidence interval for a single observation (class mean ± 1.96 × *SD*)
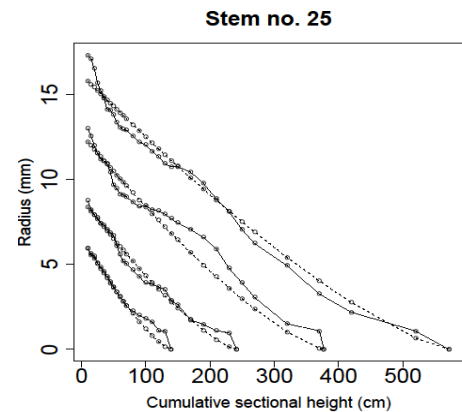

Figure 3. Taper curve (model *M3*) fitting of sample stem no. 25. Solid line (——) and broken line (…) indicate the observed and predicted taper curves for the four early growing seasons, respectively
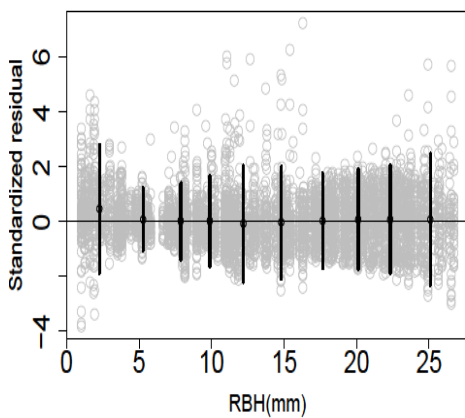
Figure 2. Standardized residuals of the best selected taper model (*M3*) on RBH (predictor)
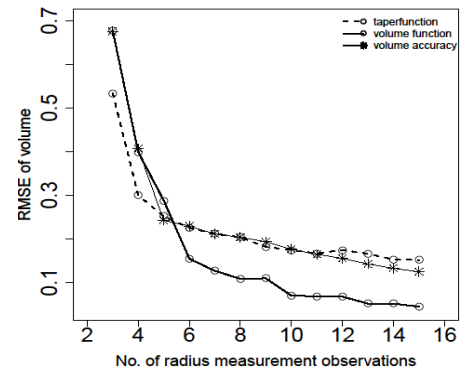
Figure 4. Standardized residuals of the best selected volume model (*M7*) of fitted value (volume; dm^3).

Table 6. Estimated parameters values (standard errors in parentheses) for the candidate functions of the volume model. Bold print indicates the best model

Model	Estimated parameters values				RSE	DF
	β_0	β_1	β_2	β_3		
M7 (Volume)	**0.0007(0.00027)**	**2.161(0.068)**	**0.372 (0.079)**		**0.0125**	**211**
M8 (Volume)	0.0916 (0.0188)	0.00017 (0.00006)			0.0957	212
M9 (Volume)	0.0401 (0.0259)	0.000029 (.00001)	1.976 (0.042)	0.933 (0.0692)	0.1928	210
M10 (Volume)	0.0701 (0.0403)	0.00247 (0.00088)	0.00018 (0.00014)	0.000015 (0.00000071)	0.1923	210

RSE: Residual of standard error and DF – degree of freedom

Table 7. Fit statistics (R^2, RMSE, Bias, and Bias Percentage) for Model (M7-M10). Bold print indicates the best model

Model	R^2	RMSE	Bias (B)	Bias percentage (B%)
M7	**0.99**	**0.039**	**– 0.002**	**– 0.98**
M8	0.92	0.199	+ 1.101	+ 14
M9	0.93	0.190	– 0.089	+ 1.370
M10	0.93	0.191	+ 1.056	+ 4.370

and B% of the two best fitted taper and volume models based on the evaluation data set (plantation of small-sized trees) have been indicated (Figures 7a and 7b).

The ranges of RMSE were 0.151-0.533 (taper model) and 0.044-0.677 (volume model) (Figure 5). The ranges of RMSE varied from 0.146-0.332 (taper model) and from 0.41- 1.04 (volume model), when the models were extrapolated for the plantation of large sample trees (Figure
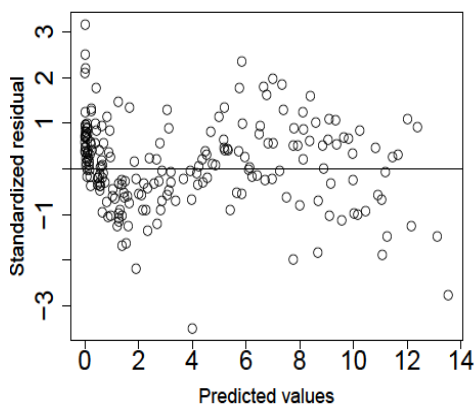
Figure 5. Comparisons of the best fitted taper model (*M3*) and volume model (*M7*) based on fit statistics (RMSE of volume; dm^3) and the strategy of the number of radius measurement observations. The legend of the volume accuracy indicates the true volume accuracy.
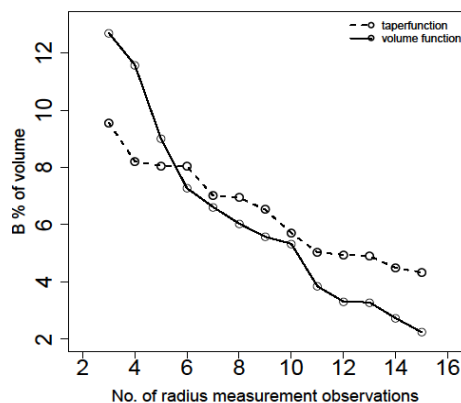
cluding *RBH* and *H* in a stem, while the taper model had a lower RMSE for these measurement strategies (Figure 5). However, the volume function was better than the taper function for the higher number of radius measurements per stem since a lower rate of RMSEs were found. It should, however, be noted that these particular values of RMSE were based on the complete data (Figure 5).

In the first stage of cross-validation, the results and graphics of the evaluation data set suggested that the taper function re-fitted the data quite accurately and was much more reliable, with lower prediction errors, than in the case of the volume function, since a lower rate of RMSE were found (Figure 6a). The taper model was, however, better in the sense that it demonstrated a lower B % for the limited number of radius measurements (i.e. 3-5 measurements) than did the volume model. A lower B % was found in the volume
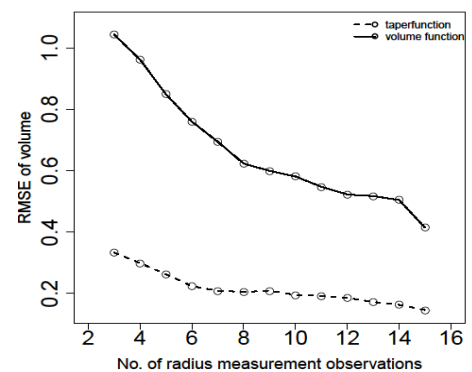

Figure 6a. Comparisons of best fitted taper model (*M3*) and volume model (*M7*) based on the fit statistics (RMSE of volume; dm^3) and strategy of the number of radius measurement observations for the evaluation data processed from the plantation containing large sample stems in the context of a cross-validation approach

Figure 6 b. Comparisons of best fitted taper model (*M3*) and volume model (*M7*) based on fit statistics (B% of volume; dm^3) and a strategy of the number of radius measurement observations for evaluation data processed from the plantation of large sample stems in the context of a cross-validation approach

6a). The ranges of RMSE also varied from 0.122-0.157 (taper model) and from 0.106-0.203 (volume model) when the models were evaluated with regard to the plantation of small-sized sample trees (Figure 7a).

The RMSE of the fitted two models including their true volumes decreased with the increased number of radius measurements. The highest true volume accuracy was found in the case of 15 radius measurements (Figure 5). In the context of the cross-validation approach, the RMSE and B% of the best fitted two models also decreased with the increase in the number of radius measurement observations (Figures 6a, 6b, 7a, and 7b)

The results suggest that the taper model was better than the direct volume model when the number of radius measurements per tree amounted to 3-5 in-

model along with increases in the number of radius measurements (i.e. 6-15 measurements). The details have been presented in Figure 6b.

In the second stage of cross-validation, the taper function re-fitted the data quite accurately and also better than did the volume function for a limited number of radius measurements since the lowest RMSE (Figure 7a) and lowest B % (Figure 7b) in relation to the volumes were found. The results suggest that a limited number of measurements are needed to develop a taper function so that volumes can be estimated cost-efficiently. In the sub-data set there was, however, also a noticeable reduction in the RMSE and B % with increases in the radius measurements for both models.
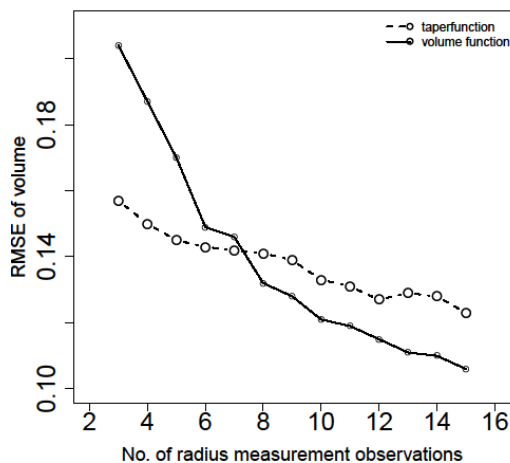
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Figure 7 a. Comparisons of best fitted taper model (*M3*) and volume model (*M7*) based on fit statistics (RMSE of volume; dm³) and a strategy of the number of radius measurements observations for the evaluation data processed from the plantation of small-sized sample stems in the context of a cross-validation approach
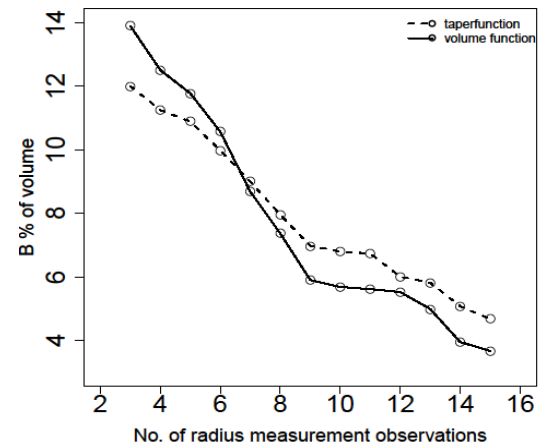
Figure 7 b. Comparisons of best fitted taper model (*M3*) and volume model (*M7*) based on fit statistics (B% of volume; dm³) and a strategy of the number of radius measurements observations for the evaluation data processed from the plantation of small-sized sample stems in the context of a cross-validation approach

Discussion

Several nonlinear functions were tested and evaluated, based on the fitted statistics, in order to estimate volumes cost-efficiently. The results suggested that the taper model (*M3*) and the volume model (*M7*) were best fitted to the data set in predicting the volume. The results showed that the simple taper and volume models presented better fittings than did more complicated models with a great number of parameters.

It was also observed that there was a slight lack of taper curve fitting to the same portion of each of the whole stems (Figure 3), while heteroscedasticity were detected in the residual plot, and especially in the volume residual plot (Figures 1, 2 and 4). We applied different variance and autocorrelation functions to model the heteroscedasticity and stem variabilty but all functions generally failed to achieve model convergence for the strategy of limited number of radius measurement per stem (i.e. 3-12 measurements). Therefore, we discarded variance and autocorrelation function for the error modelling in this study for that particular strategy. Nevertheless, we considered these deviations small enough to be ignored. The form of a tree is usually less ideal than models can predict. In consequence, it is realistic to consider that an applied model would not fully fit any measured data. Another reason for this may also be that an applied model based on the NLS procedure might not fit the stem analysis data with complete accuracy (consisting of age and tree and plot variation, this is usually referred to as the longitudinal data set).

Mixed models may also be much more efficient and effective in predicting the volume in this parsimony and nested data set, especially if they can be calibrated by using subject-specific measurements (Calama and Montero 2005, Pinheiro and Bates 2004). However, in this particular situation, the calibration using subject-specific measurements would not be an alternative. The nonlinear mixed effect modeling approach using 2 random parameters at different levels of grouping (tree level and age level, and only at tree level or age level) was also used to fit a data set based on the basis of the number of radius measurements. This was used to overcome the lack of curve fitting and to produce a good predictive capacity without compromising accuracy. But the applied selected functions generally failed to achieve model convergence for the limited number of radius measurement per stem (i.e. 3-12 measurements). In consequence, nonlinear mixed effects modelling methods were also discarded and the nonlinear least square method (model with fixed part) was selected for further analysis. Another alternative would have been to restrict the choice to linearized models, but this would have led to problems of bias.

Based on these results and graphics, it was concluded that when we extrapolated (i.e. when the best-fitted selected taper and volume models were applied to the plantation of small-sized trees and evaluated in relation to the plantation of large-sized trees), the taper approach was much more robust than the direct volume modelling, since a lower rate of RMSE was observable (Figure 6a). When not extrapolated (i.e. fitted to the selected taper and volume models for the

plantation of large-sized trees and evaluated in the plantation of small-sized trees), the taper model was better than the volume model, and displayed a lower RMSE only in the presence of a limited number of measurements i.e. 3-5 measurements including RBH and H measurements (Figure 7a)

In this study, however, we use taper method as an alternative to a direct volume equation in order to estimate the total volume and volume increment of short-rotation willows. The taper based method may be more robust in tree volume prediction if the number of measurements per stem is low or if prediction is extrapolated for tree sizes that have not been included in the modelling data. Hence, this kind of volume prediction could be used as an alternative in situations where a local (e.g. plantation-specific) volume model needs to be developed using a small number of taper measurements from very few sample trees in practice. There may be a great number of species grown and also different clones, with a consequence that large-scale models will not be suitable for all situations. In such a situation, the local taper models can be adjusted using a minimal number of sample tree measurements to estimate the volume.

Newton and Sharma (2008) studied the optimal number and locations of pair-wise height and diameter measurements (i.e. the disk selection protocol) required to fit a taper equation. They reported 13 samples per tree in stem analysis data as the optimal number to fit taper equations for plantation-grown jack pine (*Pinus banksiana* Lamb.). The locations of these 13 samples (diameter and height pairs) were at approximately 0.15, 0.5, 0.9, and 1.3 m (breast height) above-ground and at every 10% interval of the height above breast height. Subedi et al. (2011) fitted different taper function in their data set based on stem analysis data. They were also recommended 13 samples per tree needed to fit taper function to estimate volume. Furthermore, they reported that, the function developed by Sharma and Zhang (2004) was best fit. de-Miguel et al. (2012) tested 33 published taper functions based on stem analysis data to estimate volume of *Pinus brutia* in Syria. Stem diameter was measured at relative heights of 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% of the total tree height, DBH and H. The authors reported that, the function developed by Kozak (1997) fitted best. We found, if the number of measurements per tree is below a certain limit, then the taper curve approach performs better than the volume model. We suggested using 3-5 measurements including RBH and H measurements (altogether 7 samples) to fit taper function to estimate volumes with lowest prediction error in that situation. We were mainly concentrated most on the lowest part of the stem to take diameter and height measurement pairs because tapers were very frequent in that part of the stem. The taper function developed by Demaerschalk (1972) was the best fit in this study.

Menéndez-Miguélez et al. (2014) tested different published taper functions to data set derived from chestnut (*Castanea. sativa* Mill.) coppice stands in northwest Spain to estimate total volumes and merchantable volumes. They reported that, the model developed by Fang et al. (2000) was superior to other equations in predicting volumes for chestnut coppice stands. Li et al. (2012) evaluated different taper models to predict upper stem diameters, as well as total tree volume for 11 major conifer species in the Acadian Forest Region of North America. The authors reported that, the taper function developed by Kozak et al. (2004) and the volume function developed by Honer (1965) were best fit. Fonweban et al. (2011) examined different taper functions for Scots pine (*Pinus sylvestris* L.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) to estimate volumes in Northern Britain. The authors also reported that, the taper function developed by Kozak et al. (2004) provided the best volume predictions. In this study, we found the taper function developed by Demaerschalk (1972) was the best fit to estimate volumes in past growing seasons. Every species need specific studies and measurements for finding a cost-efficient method of volume and biomass estimation.

Burkhart and Tomé (2012) have reported that numerous tree-stem volume models have been proposed, but one of the most effective is the "combined variable" equation, which combines dbh and height in a single predictor. Although Honer (1965), found simple linear regression to provide accurate estimates of total stem volume, other comparisons with alternative estimating equations, e.g. Burkhart (*1977*) have shown that the combined-variable form is preferable. Louis (2005) tested and evaluated several volume functions to estimate the volumes for *Tectona grandis* in Tanzania, and he reported that logarithmic volume functions predicted volume quite accurately. In this study, logarithmic volume function was better fitted to the data set than other volume functions in order to predict volumes with a minimum of prediction errors.

Data processing ranging from stem analysis to radius measurement and top height in the field is relatively expensive. It is very important to know the optimal or sufficient number of radius measurements, with the radius at a height of 130 cm and at top height so as to develop effective taper and volume functions for estimating the volumes cost-efficiently in the different growing seasons. One of the aims of the present study is that it may help to point towards further research. For specific research purposes, past taper

measurements are essential for estimating the volumes achieved in different growing seasons.

The limitations of our results (i.e. the lack of taper curve fitting, the nonlinearity trend in the volume residual plot, a bias in the smallest radius in the taper residual plot, inclusion of ranges of density in the data set) suggested that developing new equations of higher predictive accuracy on the basis of more parsimonious models may well require further research. Nevertheless, applied best fitted functions are still acceptable for predicting the volumes at a low rate of prediction error, owing to the usefulness of the goodness-of-fit statistics.

We have presented the poposed methodology as an example of specific willow clone (*Salix schwerinii*) to estimate volume. This kind of study may help to estimate volume for other willow clones and short rotation species not only in the Nordic and Baltic countries but everywhere where fast growth is studied for widening biomass base of bioeconomy.

We can also estimate the biomass by volume multiplying with density of wood in practice though the main focus of the study was concentrated for SRF related research purposes. The poroposed methodology consisted of different taper functions and volume functions. Predicting total tree height based on observed diameter at breat height outside bark is routinely required in practical management and silvicultural research work. Many growth and yield models also require height and diameter as two basic input variables, with all or part of the tree heights predictied from measured diameters (Huang and Titus 1992). Measurement of heights in the field is also time consuming and expensive. In the cases where the actual measurements of height growth are not avaible, this kind of proposed functions can also be used to indirectly predict height growth. Padari et al. (2009) developed a classical approach to obtain stand mean height H_{Dq} at young naturally regenerated stands in Estonia and recommended to use regression height prediction at the quadratic mean diameter Dq if considerable number of young trees does not reach breast height. The approach developed by Padari et al. (2009) can be a option to model mean height in willow juvenile stand in that particular situation.

West (2003) described different approaches of biomass estimation methods based on the review of several authros in his book. He concluded based on others authors study that, height is important predictor to estimate biomass in the power and polynominal function. The developed function can be used to predict height and height can be use as a predictor, if actual measurement of height is not avaible, in the different approach of biomass estimation methods

(power and ploynominal function) studied by several authors.

In the power and polynomial function, many authors have used dry mass and diameter as response and predictor varaibles respectively for the biomass estimation of salix clone (i.e. Nilsson 1982, Hytönen et al. 1987, Tahvanainen 1996, Verwijst and Selenium 1999, Nordh and Verwijst 2004 and Arevalo et al. 2007). They estimated the biomass based on their developed functions only upto 4 to 5 years. However, they did not use height as a predictor in their function. Inclusion of height may improve the model fit and predictive performances. In our approach, we used several past growing seasons upto 15 years. Using the volume and density of wood, we can estimate the biomass from first year to 15 years. We used radius at 130 cm above the shoot base (RBH or DBH) because several authors used RBH or DBH in the developed taper and volume function. Our motivation for this study was to estimate volume to study growth and development of fast growing trees . Further research could also be an option to use diameter at 55 cm to 130 cm above shoot base and inclusion of ranges of densities in this kind of study. We did not include the ranges of densities due to the lack of data.

Conclusion

Accurate and cost-efficient volume estimates are needed for multipurposes such as, estimate biomass, research purposes, forest inventory and planning, growth and yield study in various silviculture and forestry practices. Biomass can be estimated by volume multiplying with wood density in practices. Our proposed methodology in this study may help to facilitate growth and yield study. This kind of study is also needed in the research purposes. Moreover, number of radius measurements are needed to estimate the volume cost efficiently. After developing and cross-validating regression estimators using mainly non-linear least squares and linear regression for *Salix* cloning in Siikasalmi, North Karelia, Finland, it was concluded that a limited number of radius measurements (i.e. 3-5 measurements including RBH and H measurements) were sufficient for predicting volume cost-efficiently with compromising accuracy based on the taper function. The volume function was superior to taper the function as a result of the large number of radius measurements (i.e. 6-15 measurements including RBH and H measurements) and in the situation where there was no extrapolation to predict volume efficiently with compromising accuracy. Use should be made of between 4 and 5 radius measurements per tree on the basis of annual rings, including DBH and H, if the aim

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is to gain a sufficiently good volume prediction locally for a willow plantation. The overall results suggested that the Demaerschalk taper function with 2-parameters and volume function, developed by Schumacher and Hall (1933), best fitted to the data set since this involved better goodness-of-fit statistics (R^2, RMSE and B).

Acknowledgements

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