Empirical Models for Estimating Volume and Biomass of Poplars on Farmland in Sweden

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Abstract

There is growing interest in establishing short-rotation poplar plantations in Sweden, primarily as a future feedstock for bioenergy. Cost-efficient planning and effective management of these plantations would be greatly facilitated by robust equations for estimating the taper, volume and height of poplar trees, and the biomass of poplar stumps and roots. Thus, the aim of the studies this thesis is based upon were to construct and evaluate such equations. Six equations were constructed: a stem taper equation, a stem volume equation, three stem height equations, and a stump and root biomass equation. The constructed taper and volume equations were compared with five and six published equations, respectively. The taper and volume equations are based on measurements of 69 and 72 trees, respectively, at 37 sites, the height equations on measurements of 117 trees at 40 sites, and the stump and root biomass equations on measurements of 72 stumps at six sites. All sites were located in central and southern Sweden (lat. 55-60° N). The mean age of the stands was 21 years (range 6-43 years) for the taper, volume and height analyses and 20 years for the stump/root biomass analysis.

The results confirm many previous findings that exponential equations provide the best descriptions and predictions of taper. A complex exponential equation presented by Kozak provided the best fit to the collected data. However, the constructed (polynomial) equation is recommended when a simpler model is required and larger bias is acceptable. Equations developed by Eriksson and Scott, and the constructed equation for estimating volume, provided the best fits to the volume data, but a constructed new equation is recommended for simplicity, as it only includes three parameters.

The diameter-height models were developed using a mixed model approach. The models included the stand variables mean diameter and age, and were improved by including a random site effect (to address variations among sites and provide locally calibrated estimates) which increased the R^2 value from 0.87 to 0.96.

The stump and root biomass equations were based on a power equation with DBH as an independent variable. The R^2 values were 0.93 and 0.80 for dry weight estimates of stumps and roots, respectively. The mean dry stump weight represented 21% of the mean stem weight. The total dry weight per hectare for stumps and for roots amounted to 34.9 and 12.0 tons, respectively.

*Keywords: B*io-energy, diameter-height equations, mixed effect models, poplar, short rotation forestry, stump biomass equations, taper equations, volume equations

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Dedication

To my sons, Joel and Jonathan

Men hälsa allt som andas i tysta dalars ro och säg mig alla under som där sker!

Dan Andersson

Contents

List of Publications

This thesis is based on studies described in the following papers, which are referred to by the corresponding Roman numerals in the text. For convenience the studies described in Papers I-IV are sometimes referred to as Studies I-IV.

I Hjelm, B. (2013). Stem taper equations for poplars growing on farmland in Sweden. *Journal of Forestry Research* 24: 15-22

II Hjelm, B., Johansson, T. (2012). Volume equations for poplars growing on farmland in Sweden. *Scandinavian Journal of Forest Research* 27: 561-566

III Hjelm, B., Mola-Yudego, B., Dimitriou, I., Johansson, T. (2014). Diameter-height models for rapidly growing poplar plantations on agricultural land in Sweden. Manuscript.

IV Johansson, T., Hjelm, B. (2012). Stump and root biomass of poplar stands. *Forests* 3: 166–178

Papers I-II and IV are reproduced with the permission of the publishers.

The contribution of Birger Hjelm to these papers was as follows:

I 80% input to the data collection, analysis and evaluation, and writing.

II 80% input to the data collection, analysis and evaluation, and writing.

III 45% input to the data collection, data compilation and analysis, and writing.

IV 40% input to the data collection, analysis and evaluation, and writing.

1 Introduction

1.1 Poplar characteristics and distribution

Poplars belong to the genus *Populus* of the Salicaceae family, which also includes the genus *Salix*. European aspen (*Populus tremula* L.) is the only domestic *Populus* species in Sweden. Thus, all poplar species and clones in Sweden are introduced. The natural distribution of *Populus* extends from the tropics to the latitudinal and altitudinal limits of tree growth in the Northern hemisphere (Dickman & Kuzovkina, 2008). Species of the genus *Populus* are deciduous or (rarely) semi-evergreen and divided into six sections: *Abaso* (Mexican poplar), *Aigeiros* (cottonwoods and black poplar), *Leucoides* (swamp poplars), *Populus* (white poplars and aspens), *Tacamahaca* (balsam poplars), and *Turanga* (arid and tropical poplars). Poplars usually grow rapidly, particularly some North American cottonwood species (*P. deltoides* and *P. trichocarpa*) and some Asian balsam poplars (*P. maximowicii* and *P. suaveolens*). Old poplar trees can be huge, with diameters at breast height (DBH) up to 3 m and total heights exceeding 40 m. *Populus* species are dioecious (i.e. individual trees are either male or female), and can be regenerated by coppicing and from cuttings. Various species of the genus have been widely planted around the globe, both within and outside their natural distributions (including various sites in the southern hemisphere). Useful products of poplar plantations include both raw materials (e.g. fuelwood) and various extracts or processed materials (e.g. pulp and veneers). Poplar trees or plantations can also be used for environmental and ecological purposes (Isebrands & Richardson, 2014).

1.1.1 Wood, timber and other products from poplars

In continental Europe, US and Canada, among other countries, large trees in mature poplar stands are commercially used as saw timber. The wood is soft, with a low basic density and light colour. It is used to manufacture furniture frames and various building elements, including framework and roof trusses. Logs from high quality poplar trees have been also used to manufacture veneers and reconstituted wood products, ranging from plywood to matches, and oriented strand board (which has opened new markets for poplar wood, especially in North America). Beside these timber products, the wood from poplar plantations has also been used in the pulp industry in many countries. Furthermore, there is increasing interest among diverse stakeholders (estate owners, forest and energy companies, and various authorities and organizations concerned with energy and environmental issues) in expanding poplar plantations grown under short rotation forestry (SRF) regimes in Sweden, due to the large amounts of renewable bioenergy they could provide (Isebrands & Richardson, 2014).

1.1.2 Environmental improvement and biodiversity in poplar stands

Poplars, and willows, are among the most commonly used species in SRF plantations, because they grow rapidly and can make important contributions to reducing CO_2 emissions through fossil substitution and carbon storage in vegetation and soil (Canell, 2003). In Sweden, they have also been shown to provide better groundwater than traditional agricultural crops (Dimitriou *et al.*, 2012). Hybrid poplar is recommended for reclamation of top soils severely damaged by extraction of shallow oil sands, following studies of their growth on tailings in Alberta, Canada (Khasa *et al.*, 2005). In New Zealand, poplars and willows are widely planted on hillsides for erosion management in pastoral hill country, as they strongly enhance the mass stability of the slopes, grow rapidly and tolerate wet soil conditions for long periods (Gray, 1996). Permanent retirement of the land from grazing is usually only necessary in the most extreme situations, which is highly significant due to the importance of sheep and cattle farming in New Zealand (McIvor *et al*., 2011). Furthermore, planting poplars on pastoral hills provides shade and shelter for the herds, and if they are pollarded they can be kept in suitable shape to produce quality fodder for grazing during drought periods (McIvor *et al.*, 2011).

Establishing SRF plantations in homogenous arable landscapes also increases the floristic biodiversity. The biodiversity in poplar plantations is often higher than in arable fields and conifer forests, but lower than in old mixed deciduous forests and small plantations with higher edge length to area ratios (Baum *et al*., 2009, 2012). Weih *et al*. (2003) found that the cumulative species number was identical (20 on average) in 6 to 14-year-old poplar stands covering 0.1 to 13 ha and adjacent arable fields in south and central Sweden. However, only eight species on average were present in both habitat types. Thus, the cited authors concluded that small-scale poplar plantations increase floristic diversity in agricultural landscapes.

1.1.3 Yield of poplar plantations

Sweden

As already mentioned, most poplar plantations in Sweden were established in the 1980s and 1990's on set-aside agricultural land for demonstration purposes to assess their productivity, but the area they covered was small, and the total area of mature plantations is still less than 1 000 ha (Nordh *et al*., 2014). Furthermore, they largely consist of the clone OP 42 (*P. maximowiczii x P. trichocarpa*) (Fig. 1.). However, the increasing demand for biofuel has increased interest in growing poplar (among other species) in Sweden, and poplars have been planted on 120 ha of former forest land where previous stands were damaged by storm Gudrun in 2005 (Rytter *et al*., 2011). Growing poplar as an exotic species in SRF regimes has clear advantages from a production perspective (Christersson, 2010; Jonsson, 2008). For instance, Persson (1973) recorded high growth rates (ca. 12 m^3 ha^{-1} $year^{-1}$) for a 42-year-old stand of the "Robusta" (*P. deltoides x P. nigra*) poplar hybrid, and Johansson & Karacic (2011) showed in a study a total above ground biomass yield of 140 tDM ha^{-1} (tonnes dry matter) after 20 year with an annual increment of 7 tDM ha^{-1} $year^{-1}$. Another study by Johansson (2010) showed that growth rates of hybrid poplars growing on former farmland are ca. 19 m^3 ha^{-1} $year^{-1}$ (excluding branches and leaves). This is higher than the productivity of hybrid aspen plantations (ca. 13 m^3 ha^{-1} $year^{-1}$), and plantations of various domestic species, e.g. birch (*Betula spp.*), alder (*Alnus spp.*), Norway spruce (*Picea abies L.* Karst.), wild cherry (*Prunus avium L.*) and hybrid larch (*Larix decidua Mill. x Larix kaempferi Lamb.* Carr.), with reported mean annual increments (MAI) ranging from 3 to 7 m^3 ha^{-1} $year^{-1}$ (Johansson, 2010).

Figure 1. Stand of poplar clone OP42 outside Uppsala, Sweden (photo T. Johansson)

Two related and relevant studies, in this context, include the book "Papperspopplar och energipilar" (in Swedish) by Christersson (2013), providing a historical review of research on willow and poplars in Sweden and one in which site index curves for poplars were developed (Johansson, 2011).

Other pertinent recent studies have addressed the production of coppicing in 2nd generation poplar plantations in Sweden where McCarthy *et al*. (2014) discovered clonal differences in survival and straightness of sprouts. Johansson & Hjelm (2012) found the annual coppice growth to be in average 4.8 tDM ha^{-1} $year^{-1}$ in poplar stands (1-7 year after harvest). The fertilization study of poplar stumps and the impact on the coppice production by Johansson & Hjelm (2014) presented small but significant effect of the fertilization.

Other regions

Some of the world's most important poplar producers, including China, France, India, Italy and Turkey, each produce more than 1 million m^3 of poplar wood annually (Spinneli *et al*., 2011). Numerous studies have examined the productivity of poplar plantations consisting of various clones, under diverse management regimes, in various parts of the world. Variations in reported yields and growth rates are illustrated by the following examples.

In a study on the growth dynamics of stands of three poplar clones (NL-80351, I-69 and I-72) with four stem densities (500, 625, 833 and 1 111 stems ha^{-1}) at Hanyuan Forestry Farm, Baoying County, P.R.C., 10 years after planting the aboveground biomass was found to be maximal (146 tDM) at the highest stem density (Fang *et al.*, 2007). The cited authors concluded that the best regimes for production (and carbon storage) included planting densities of 1111 or 833 stems ha^{-1} with 5- or 6-year cutting cycles, respectively, and if 3- or 4-year cutting cycles were used the planting density should be higher (e.g., 1667 or 2500 stems ha^{-1}).

Similar results were obtained in a four-year study of the growth and incidence of disease in stands of 10 willow and two poplar clones, established with 18 000 trees per hectare, in Southern Quebec, Canada (Labrecque & Teodorescu, 2005). The aboveground biomass yield after four growing seasons was 66.5 to 72.2 tDM ha^{-1} for the two poplar clones NM5 (*Populus* *maximowiczii* x *P. nigra*) and NM6 (*P. maximowiczii* x *P. nigra*), with annual yields of 16.6 and 18.1 tDM ha^{-1}, respectively.

Serbia annually produces ca. 350,000 m^3 of poplar wood from plantations covering ca. 48,000 ha, largely dominated by the clone *Populus x euramercana* (Dode) Guinier, and generally established to produce high-value veneer logs. The rotation length of these plantations is long (25-30 years), compared to the other cited examples, and their productivity ranges between 350-550 m^3, with annual increments between 15 and 25 m^3 ha^{-1} $year^{-1}$, under 20-year rotations (Keca *et al*., 2011).

Various poplar and willow hybrids were established in a growth and yield study, at a density of 680 trees per acre (275 ha^{-1}), in the Central Upper Peninsula of Michigan in 1998 and fertilized in 2000, 2001 and 2002. After 10 growing seasons the growth rate of the fastest-growing clone, NM6 (*Populus nigra X P. maximowiczii*), was found to be 3.75 tDM per acre and year, 2.2 times higher than the maximum recorded rates for native aspens (Miller & Bender, 2008).

Biomass growth rate and tree spacing in hybrid poplar plantations have been studied during 16 years in northern Wisconsin (Strong & Hanssen, 1993). The maximum mean annual biomass increment was 12.8 tDM ha^1 yr^1 for poplar clone NE-41 (*Populus maximowiczii x P. trichocarpa* 'Androscoggin') planted at 1x1 m spacing. Yield differences related to spacing were found to be minor, conflicting with findings of Fang *et al*. (2007), possibly because the spacings were lower and not close to the critical threshold for significant productivity losses. Instead, the growth rate was influenced mainly by clone, irrigation and diseases.

In a study by DeBell, *et al*. (1996) in Washington state (USA) two poplar hybrids, 11-11 (*Populus trichocarpa x P. deltoides*) and D-01 (taxonomic identity unknown, but suspected to be either *Populus. trichocarpa x P. nigra* or *Populus. trichocarpa x P. angustifolia*), were planted in blocks at three spacings (0.5, 1.0, and 2.0 m), then both the growth rates of individual trees and above-ground stand yields were evaluated during the following seven years. Differences in yield were substantial between clones, and tended to increase with spacing. Furthermore, in contrast to findings by Strong & Hanssen (1993), effects of variations in spacing substantially affected both individual tree characteristics (height and diameter growth) and stand yield. At 1.0 m spacing the biomass production for clones 11-11 and D-01 averaged 18.2 and 10.1 tDM ha^{-1} yr^{-1}, respectively.

The production potential of 36 poplar clones grown in 5–13 year rotations has been studied in Denmark. The estimated mean annual increment of above ground biomass ranged from 1 to 9 tDM ha^{-1} yr^{-1} at 13 years. The clone O.P. 42 (*Populus maximowiczii* × *trichocarpa*) performed best, but clones of the species *Populus trichocarpa* also had high biomass production. Generally, hybrids generated using *P. maximowiczii* as a parent performed well, while production rates of *Populus nigra* and *Populus deltoides*, as well as their hybrids, were lowest (Nielsen *et al*., 2014).

The yield and annual growth rates are, as shown, in general higher and rotation periods are shorter in those studies compare to Sweden

1.2 Models for estimating taper, biomass and volume

1.2.1 Taper equations

The terms ‘form’ and ‘taper’ are often used synonymously, but as noted by Gray (1956) ‘form’ strictly describes the shape or structure of a stem, e.g. a cone or paraboloid, whereas ‘taper’ is defined as ‘the rate of narrowing in diameter in relation to increases in height of a given shape or form’. The major advantage of taper equations is their ability to predict the diameter of a stem at a given height or, following re-arrangement, the height of a stem with a given diameter. Numerous taper equations have been developed, and evaluated, for various tree species. They generally include DBH, total height (H) and the height (h) above ground where the diameter (d) will be predicted as independent variables (Figure 2).

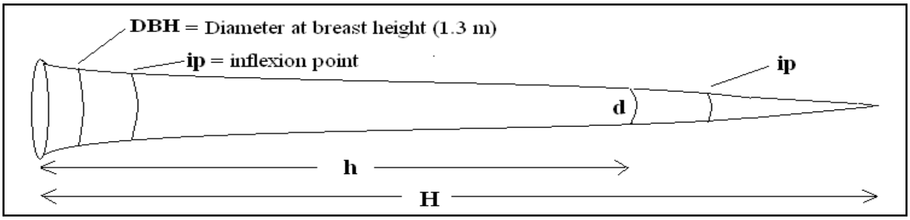

Figure 2. Illustration of variables usually included in taper equations

Analysis of relationships between these variables is important for two reasons (Newnham, 1988). Firstly, no single theory has been able to explain satisfactorily all the variability in tree stem shape. Secondly, taper equations provide flexible tools for estimating total and merchantable tree volumes, which can be used to adjust management objectives as market demands and product specifications change. From a practical perspective, the latter reason is the most important (Muhairwe, 1999). Stem taper is a complex trait (Assmann, 1970), which is influenced by variations in genetic factors (within and among species), environmental factors (soil type, hydrology, altitude and climate), forest management practices and interactions between all of these factors (Steven, 1988; Karlsson, 2005). The range of factors involved (natural and anthropogenic) complicates the development of a universal model for tree stem taper.

Many models have been constructed to describe the taper of species in various regions based on equations of the following three types (Dieguez-Aranda *et al*., 2006; Sakici *et al*., 2008):

1. Simple taper equations (Demaerschalk, 1972; Demaerschalk, 1973; Ormerod, 1973; Sharma & Odervald, 2001);
2. Segmented taper equations (Max & Burkhart, 1976; Clark *et al*., 1991);
3. Variable-form taper equations (Kozak, 1988; Newnham, 1992).

The term “Simple taper equations” refers to equations that apply the same parameter coefficients along the stem. Until the mid-1970s all published equations were of this type (Figueiredo-Filho et al., 1996), and did not account for variations in the form of different tree sections (e.g. root/base, main stem & top) and did not adequately describe the taper of the stem either close to the base or at the top. Alternative procedures were examined to solve these problems. Max & Burkhart (1976) developed the first segmented equation, for which the tree stem was divided into three sections (neiloid, paraboloid and cone-shaped), represented by separate sub-functions. Variable exponent equations utilise an exponent that changes along the stem, reflecting differences between the neiloid, paraboloid and cone-shaped sections (Kozak, 1988; Newnham, 1992). Assumptions for these approaches are that the form of a stem varies continuously along its height (Lee *et al*., 2003). Variable-form equations have been found to be superior to segmented and simple models for estimating stem diameters and volumes (Kozak, 1988; Newnham, 1992; Muhairwe, 1999). However, variable-form equations cannot be integrated analytically to calculate total stem or log volumes (Diéguez-Arunda *et al*., 2006), which must be estimated from calculated diameters and lengths by numerical integration (Kozak, 1988). Despite the advantages of these two model types they have major drawbacks: statistical complexity and difficulties in estimating parameters and re-arrangement to calculate heights for given diameters (Sakici, 2008). They also require additional inflexion point/s (Fig.2) demarking the form sections. The variable-form equations provide the lowest degree of local bias and the most precise predictions (Kozak, 1988; Muirhairwe, 1999), but there is a need for simple equations in practical forest management. A simple polynomial taper equation developed by Kozak *et al*. (1969) has been frequently used. In forest inventories in southern Brazil, the simple equation has been assessed (Figueiredo-Filho & Schaaf, 1996). However, Figueiredo-Filho & Schaaf (1999) found that taper equations generally underestimated true volumes (as determined by xylometry) of trees surveyed in Southern Brazil.

1.2.2 Volume equations

Several volume equations have been developed for various species. The volume of an individual tree depends on its height, diameter and stem form. The height and diameter are easy to measure and estimate, but not the stem form, which (as mentioned) is a complex trait (Assmann, 1970). Equations for the stem volume and commercial volume for logs of specified commercial diameters are the most commonly used in Scandinavian forest management. Compared to the compatible taper and volume equations they are stiff equations with only one possible value for each predicted variable per tree and usually these equations are based on two independent variables: height (H) and DBH. There are also equations based on the single independent variable DBH (Case & Hall, 2008; Gautam & Thapa, 2009) and equations with additional independent variables, such as a diameter at a specified upper height (Brandel, 1990; Burk *et al*., 1989), height at crown base, bark thickness, and/or site indicator variables such as, altitude, latitude, soil type and vegetation type.

Some of the most important and well-known volume equations and stem volume models applied in Sweden are briefly described below. Jonson (1928) presented a model dealing with stem curves and form classes, and introduced a new method was introduced in which the stem is divided into two sections, the lower (2 m long) section is directly measured and the taper for the upper section is estimated from an upper diameter and form class assigned to the section. Two major contributions were made by Näslund (1940; 1947), in which he presented two kinds of total volume equations for Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea* abies L. Karst.) and birch (*Betula* spp) trees in northern, southern and all of Sweden: equations using the independent variables DBH and H; and equations using DBH, H and the additional variables crown height and bark thickness at breast height. The equations were constructed using data from >4000 sampled trees, and have been frequently used. Carbonnier (1954) presented volume equations for three larch species. Volume equations for ash (*Fraxinus excelsior L.*), aspen (*Populus tremula L.*), common alder (*Alnus glutinosa L. Gaertn.*) and lodgepole pine (*Pinus contorta*, Douglas) have been developed by Eriksson (1973). While Näslund's equations were additive polynomials Eriksson also developed multiplicative equations. Beside the variables DBH and H, Eriksson used crown height and crown length (as a percentage of tree height) in some of his equations. Hagberg and Matern (1975) developed volume equations for oak (*Quercus robur L.*) and beech (*Fagus sylvatica L.*), using the approach applied by Näslund (1940; 1947). A major study of volume equations for Scots pine, Norway spruce and birch in Sweden was published by Brandel (1990), in which a multiplicative base equation with DBH and H as independent variables was presented. Further variables (upper height diameter, crown height above ground and bark thickness at breast height) were then added to the base equation, either solely or in combination. Brandel also tested the potential for improving the volume estimations by using the indicator variables altitude, latitude and forest type. Volume equations of multiplicative, additive and logarithmic variable exponent types for common alder and grey alder (*Alnus incana L. Moench*) in Sweden have also been developed and assessed recently (Johansson, 2005).

1.2.3 Diameter-height models for biomass and volume estimations

In Sweden recent research has reported taper, volume and biomass models for individual poplar trees (Hjelm, 2011; Johansson & Karacic, 2011). The taper and volume equations require several measurements of tree heights (H) and DBH to be applicable on plantation level. The presented biomass model is based solely on DBH. They do not take into account the potential effects of site parameters or age. Generally, there are two main types of models for estimating stand volume and biomass:

1) Single-tree models, which require data on the diameter distribution, e.g. diameters of individual trees in the stand or (more commonly) in sample plots and the total height of the trees;

2) Whole-stand models, which use stand-level parameters such as stand density and stand basal area to predict standing volume, biomass, growth or yield.

Stand models require few details to simulate growth and yield, but provide rather general information about the stand, while single-tree models provide detailed tree-level information (Rodrigues *et al.*, 2010). Tree diameter measurements and stand basal area estimates can be acquired rapidly, easily, and accurately, but individual tree height and stand dominant height measurements are time-consuming and often have low accuracy. In forest surveys and inventories, DBH measurements are usually acquired for all trees, but height measurements for only a sub-sample of trees across the range of observed diameters (Sharma & Parton, 2007). Diameter-height models are then used to estimate the heights of all studied trees. The development of simple and accurate diameter-height models, based on easily obtainable tree and stand characteristics, is a common precursor to using inventory and sample plot data to calculate volume and other stand characteristics. Several diameter-height equations for various species have been developed, using DBH as the only independent variable, of including five by Curtis (1967), Larsen & Hann (1987), Huang et al. (1992), Peng (1999) and Fang & Bailey (1998).

The relationship between a tree's diameter and its height is not static; it can vary among stands and depends on the growing environment and site conditions (Sharma & Parton, 2007; Calama & Montero, 2004). Furthermore, it changes over time. Thus, additional predictor variables are required to develop generalized diameter-height models in order to avoid the need to establish specific diameter-height relationships for every stand (Sharma & Parton, 2007; Temesgen & Gadow, 2004). In the development of generalized diameter-height relationships, several approaches have been applied. Larsen &

Hann (1987), Parresol (1992) and Sharma & Parton (2007) used stand characteristics such as density, basal area, dominant height, age, and dominant diameter as additional explanatory parameters.

Even after including additional stand variables in the models there are always random variations in diameter-height relationships among stands and plots. One approach to account for this random variability is to fit the predictions with a Mixed Effect Model. Diameter-height equations based on a Mixed Effect Model have been developed by Sharma & Parton, (2007) for eight species in Ontario and by Crecente-Campo *et al*. (2010) for *Eucalyptus globulus* L. in northern Spain. It is appropriate to fit a Mixed Effect Model when data in yield studies are based on several measurements of the same tree (taper equations and cumulative volume equations) or trees from the same stocks/stands. The method is complex, but statistically more robust than previous methods since it can calculate and correct for different forms of autocorrelation. A mixed effect modelling improves the estimates of the parameters and their standard errors. Furthermore, separate models for describing the individual factors impact on the volume and biomass production do not need to be constructed, thus site-specific predictions of future biomass and volume can be acquired more rapidly and cheaply. In addition, the estimates for other stocks can be easily calibrated using a limited number of new measurements.

1.2.4 Biomass equations for stumps and roots

Models for estimating stump and root biomass have been developed in studies on several species in various regions, including analyses of hybrid poplars' root biomass distributions by Heilman *et al*. (1994) and Fortier *et al*. (2013) in Washington state and Quebec, respectively, and two models developed for *Populus deltoides* in India (Das *et al*., 2011; Puri *et al*., 1994). However, relatively few stump and root biomass models have been developed, partly because it is time-consuming and laborious to collect the empirical data required. The stumps and roots must be excavated (by hand or by excavators), cleaned of stones, soil and mud, then finally cut into pieces, dried and weighed. Furthermore, there has been little demand for these models until recently, as stump and root biomass was rarely harvested. However, due to recent policies to decrease the use of fossil energy, the demand for new and alternative sources of biomass from tree plantations has prompted increasing efforts to develop new techniques to harvest it. Thus, there is increasing need for models to estimate the biomass of stumps and roots. A beneficial side effect of removing poplar stumps is that it reduces risks of pathogen attacks on seedlings in the new plantation (Verani *et al*., 2008).

2 Objectives

The main aims of the studies this thesis is based upon were to:

- Develop and evaluate new equations, and to evaluate the suitability of previously published equations, for estimating the taper and volume of poplar trees.
- Develop diameter-height models for individual trees enabling accurate volume estimates of poplar plantations based on data from an extensive pool of plantations under different management regimes and site conditions in Sweden.
- Construct an equation for estimating stump and root biomass of poplar trees.
- Recommend stem taper, volume and diameter-height equations, and stump biomass equations, which can be applied to standing trees in the field, based on results of the evaluations.

These models should provide a complete set of tools for estimating yields, volumes and stump biomasses of the first generations of poplar plantations established on farmland, thus improving their management, and facilitate efficient planning of future energy feedstocks.

The main specific objectives for the studies reported in Papers I-IV were:

- Paper I: To develop and evaluate a polynomial equation for stem taper estimates of poplars and evaluate the performance of five published taper equations.
- Paper II. To construct and evaluate a volume equation with the independent variables DBH and H for poplars, and evaluate the performance of six published volume equations.
- Paper III. To develop height-diameter model~~s~~ of existing or newly established poplar plantations, and to determine if including a site-specific random-effect improves their prediction power.
- Paper IV. To measure the biomass of poplar stumps and parts of their root system, and construct biomass equations based on data collected from clear-cut or thinned poplar plantations.

3 Material and Methods

As already mentioned, this thesis is based on studies presented in four appended papers that are referred to in the text by the Roman numerals presented in the List of Publications. When a table or figure in one of the papers is cited, its number in the paper follows after the Roman numeral.

3.1 Site data

All study sites were located on former farmland, and most were planted between 1988 and 1992. For equations presented in Paper III additional fitting data were collected from younger poplar stands (6-15 years). Data were collected from 37, 40 and six stands for constructing the taper and volume equations, the diameter-height models and the stump biomass equation, respectively. All these stands were located in central and southern Sweden between latitudes 55-60° N (Fig. 3). The ages of the stands ranged between 6 and 43 years. The management of the stands varied; some had not been thinned at all and thinning regimes ranging from moderate to heavy had been applied in the others. The number of stems varied from 287 to 3493 per hectare, covering most existing stand densities. In some stands the initial spacing and densities of planted trees were known, but not for most of the stands. The stands were established as research-sites, for commercial production, or as demonstration sites. The water table was 0.3 – 1 m deep, and apart from a few sites with silty till soils the soils were clay sediments with textures ranging from light to medium clay. The most frequent clones were OP-42 (*P. maximowiczii* Henry *x P. trichocarpa* Torr. & Gray), followed by balsam poplar (*P. balsamifera* L.), black cottonwood (*P. trichocarpa* L.) and Boelare (*P. trichocarpa x P. deltoides* Bartr. & Marsh.). In three cases, there was no information concerning the provenance and clone of the planted hybrid poplars. The soil types and clones at the sites used in the studies are described in detail in Papers I-IV. The sites and stands cover a variety of characteristics, as summarized in Table 1.

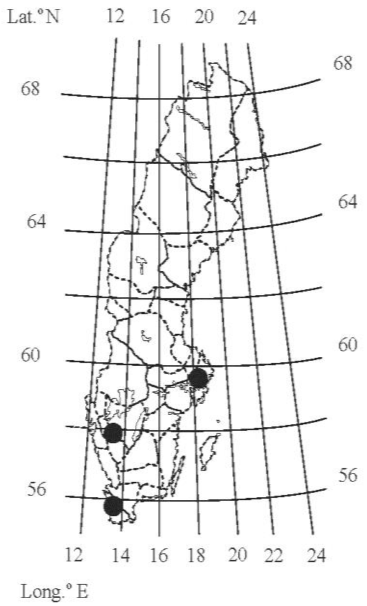

Figure 3. Map of Sweden showing locations of the three sampling areas used in Studies I-IV.

Table 1. *Summary of the main characteristics of the hybrid poplar stands*

Study	No. of sites	No. of sample trees	Age, yrs	Dom. Height,m	DBH, cm	No. of stems·ha^{-1}	Basal Area m^2
I	37	69	21±1.1	23.9±0.5	24.7 ± 1.0	984±125	38.5 ± 13.3
II	37	72	21±5.6	23.4±3.9	25.0 ± 5.5	940±776	34.6 ± 15.4
III	40	117	21±5.6	23.1±4.4	23.2 ± 4.0	954±686	33.9 ± 13.1
IV	6	72	20±2	25.3±4.1	28.8 ± 1.8	1151±1082	37.5 ± 13.4

3.2 Modelling data (Papers I-IV).

The sampled trees were subjectively selected due to restrictions imposed on the forest owner regarding future management of the stands. Generally, the selected trees had a diameter between the arithmetic mean DBH and the mean basal area-weighted DBH of the stand, and all selected trees were healthy, undamaged, with fairly straight, single stems, and neither border trees nor suppressed trees.

Studies I and II

The data used for modelling in Studies I and II were collected mainly from the same sites and the same sample trees. At each site one to four trees were selected for measurements for developing the stem taper equation and one to five trees for developing the volume equation. The measurement routines were identical in both cases. The total height of each sample tree was measured (in m), and its stem diameter on bark at breast height and the middle of the 1 m-section of the stem were measured by cross-calipering (in cm). Following standard routines for yield studies at SLU's Department of Energy and Technology, the diameters at six relative heights of the tree (1, 10, 30, 50, 70, and 90%) were also cross-callipered. The total age was determined by counting annual rings from a disc cut at stump height (0.2 m) and adding 1-2 years, or from information about planting dates and seedling ages provided by the owner. The volume of the sampled trees was calculated by summarizing the volume of the 1 m sections using the Smalian formula. The relative diameter and height points of the data set used in Study I and the paired volume-diameter data points used in Study II are shown in Figure 4.

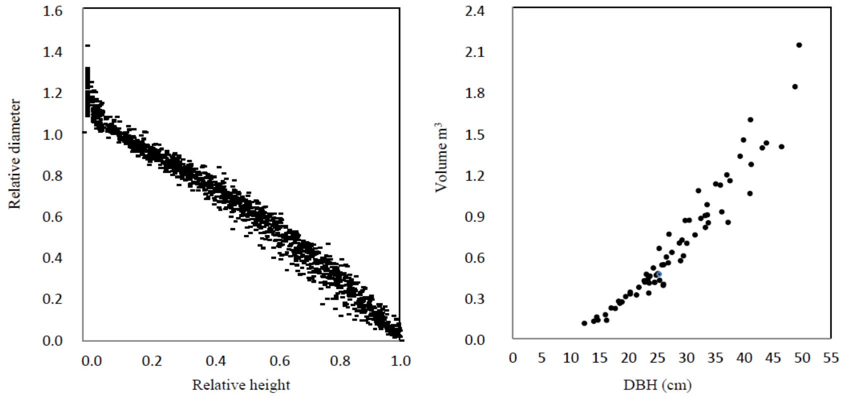

Figure 4. Paired data points of relative heights and relative diameters used in the stem taper study (left) and diameters at breast height (DBH) and volumes for the stem volume study (right).

Study III

Most of the sites and sample trees used in Studies I and II were also used in this study, except that sites older than 23 years were excluded as the aim was to develop models for stands with ages within, or close to, rotation ages set by the subsidiary framework. Today the framework stipulates bioenergy plantations to be harvest before 20 years of age (Jordbruksverket, 2014). In addition complementary data were collected from 10 younger stands (6 – 15 years). Thus, the total ~~ages~~ of the studied plantations ranged from 6 to 23 years, and their areas from 0.14 to 6.8 ha. In each stand, a sample plot was established at a randomly selected location, but avoiding areas with large gaps between trees and borders of the plantations. The sample plots contained 50-100 stems, and 5 582 in total. Thirteen of the stands had been previously thinned. The DBH of all stems within each plot area was measured by cross callipering, and the height of 1-10 selected trees was destructively measured. In total stem height and DBH measurements were obtained for 117 trees. The distributions of the data are shown in Figure 5.

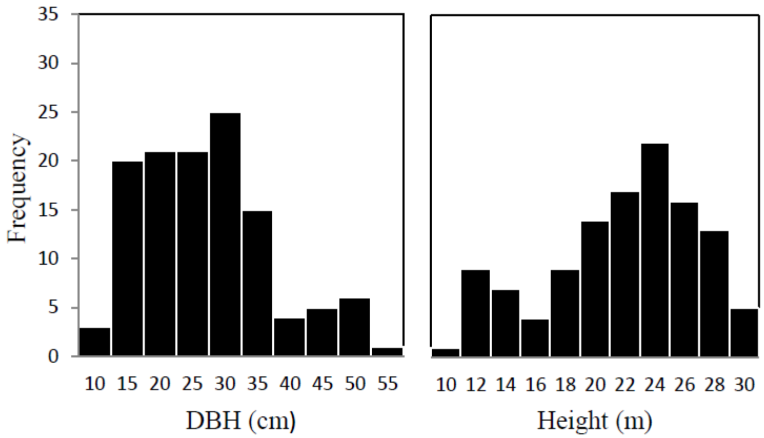

Figure 5. Frequency distributions of the DBH (cm) and height (m) measurements for model fitting (N = 117 trees). (III: Fig.2).

Study IV

In each of six stands 12 trees were evaluated prior to felling and their stumps were excavated after felling. Because of the restrictions imposed, the trees had to be sampled in a strip around the stand as close as possible to the edge (within ≈ 5 m). After initial recording of stems and stem diameter in the stands, the trees were divided into four diameter classes, representing the diameter distribution of the stand. Three trees representing each diameter class were selected for harvesting. Based on stem diameter, the stem and total aboveground biomass for individual poplar trees were estimated using the biomass equation presented by Johansson & Karačić (2011). Then the stands were either thinned or clear cut. The stumps of the previously evaluated trees were subsequently identified and their diameters were recorded (Table 2).

Table 2. *Summary of the characteristics of poplars used in the study*

DBH, mm	Height m	Biomass, above ground, kg d.w. [(1)]	
		Total[(2)]	Stem
257 ± 93	23.9 ± 3.6	284 ± 228	216 ± 174

[(1)] Estimated by Johansson and Karačić; [(2)] Total: stem + branches + leaves.

The fresh weight of each stump was recorded in the field. The roots were cut and separated into three diameter classes: >20 cm, 10–20 cm and 5–10 cm. The length and fresh weight of the roots in each diameter class were recorded. Dry weight to fresh volume ratios (densities) of the debarked stumps and roots were then calculated. Using the dry weight of stump and root samples, their dry masses were calculated as percentages of the total dry weight of the stumps and roots (Table 3). Their dry mass was also calculated as a percentage of fresh weight using the sample data.

Table 3. *Summary of fresh and dry mass production (kg) and percentage of stump and root weight.*

	Stump diameter, mm	Fresh weight, kg			Dry weight, kg		
		Total	Stump	Roots	Total	Stump	Roots
Mean ± SD	294 ± 109	133 ± 117	99 ± 85	34 ± 37	59 ± 52	45 ± 39	14 ± 16
Range	87–587	2–621	2–420	0.4–201	1–291	1–185	0.2–87
			% of total fresh weight			% of total dry weight	
Mean ± SD			76 ± 10	24 ± 10		76 ± 11	24 ± 11
Range			43–95	5–57		40–96	4–54

3.3 The Models.

3.3.1 Taper and volume equations (Studies I & II)

One polynomial taper equation was constructed (1). In addition, a number of published taper equations were initially tested, five of which (I:2-6) were selected for a final evaluation, including three simple equations (Kozak *et* al., 1969; Ormerod, 1973; Benbrahim & Gavaland, 2003), one segmented equation (Max & Burkhart (1976) and one variable exponent equation (Kozak (1988). Only the equation by Benbrahim and Gavaland was fitted on data from poplar plantations. One volume equation was constructed (3). In addition, a number (21) of published volume equations were initially tested, seven of which (Børset, 1954; Eriksson, 1973; Anon, 1976; Scott, 1979; Popovich, 1986; Fowler & Hussain, 1987; Opdahl, 1992), and a mixed form (Børset, 1954;

Fowler & Hussain (1987) were chosen for further analysis and evaluation. All of the published volume equations have been developed for poplar or aspen, solely or as one of a selection of species. All volume equations including the constructed equation had DBH and H as independent variables, which are the most frequently used independent variables in stem volume equations. Two taper equations (Kozak, 1988 and the constructed taper equation) and the constructed stem volume equation, shown below, were finally recommended in Papers I and II. For detailed information on the other taper and volume equations used in the studies, see the respective papers.

Stem taper equations recommended in Paper I:

Constructed (Hjelm, 2013) $d=(b_1q^2-b_2q+b_3((H-h)/h)+b_4)\text{x}(D/(1-k/H))^b5$ (1)

From Kozak (1988) $d=b_1D^{b2}b_3^D((1-q^{0.5})/(1-p^{0.5}))^A$ (2)

$A=(b_4q+b_5\ln(q+0.001)+b_6q^{0.5}+b_7e^q+b_8(D/H))$

Volume equation recommended in Paper II:

Constructed (Hjelm and Johansson, 2012) $V=b_1^{(2+(D/H))}+b_2H^2+b_3DH^2$ (3)

where D = diameter at breast height, cm; Db = diameter at stump height, cm; d = stem diameter, cm, at height h; H = total height, m; h = height, m, from ground to top diameter (d); $q = h/H$, relative height; HI = height, m, of the inflection point from the ground; $p = HI/H$; k = breast height (1.3 m); V = stem volume, dm^3; b_i = regression coefficients

3.3.2 Mixed effect diameter-height models (Study III)

Diameter-height models were first constructed based on the linearized versions of the Korf (1939) equation (equation 4) and an allometric model (equation 5). It was assumed that trees growing on the same plot would share common allometric features, since they often belong to the same clone and were under the same management regimes and growth conditions. Therefore, in order to address this hierarchical structure of the data (e.g.: trees growing in a stand, stands located on an estate, estates located in a region, region located in a province or country etc., Fig 6.), a mixed model approach was applied, incorporating random between-plantation effects (μ_j), identically distributed with mean 0 and constant variance σ^2_j, applied to the intercept, the slope, and both, was tested.

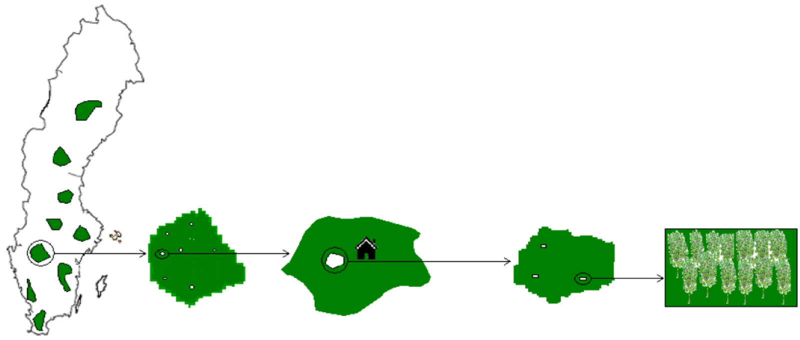

Figure 6. Example of hierarchical data structure

The fixed effect parts of the mixed models used were:

$$\ln(H_{ij} - 1.3) = \beta_0 + \beta_1 D_{ij}^{-1} \quad (4)$$

$$\ln(H_{ij} - 1.3) = \beta_0 + \beta_1 \ln(D_{ij}) \quad (5)$$

where H is the height (m) and D the diameter at breast height (cm). β_0 *and* β_1 are parameters to be estimated. Subscripts i, j refer to tree i growing in plantation j.

To convert the logarithmic predictions of the models to an arithmetic scale, an empirical estimator for bias correction was used (Snowdon, 1999). The estimator was based on the ratio of the mean height to the mean back-transformed height predicted by the model.

3.3.3 Biomass equations for poplar stumps and roots (Study IV)

The dry mass production per stump and root system was calculated using a power equation (6) describing the correlation between DBH and dry mass production (kg), derived from data collected from all of the measured stump and root systems. A power model is frequently used to describe such relationships (Johansson, 1999, Payandeh, 1981).

The power function tested was:

$$M = \beta_0 D^{\beta_1} \qquad (6)$$

where M = dry mass, kg stump^{-1} or roots^{-1}; D = diameter at breast height, over bark (ob), mm; β_0 and β_1 are parameters.

3.4 Statistical Procedures

All regression analysis presented in Papers I-II and IV was carried out using the SAS statistical package (SAS, 2006), applying the NLIN procedure for fitting and developing the constructed models, estimating parameters and evaluating the previously published models considered. For calculations used for fitting and evaluating models presented in Paper III the *nlme* (Pinhero *et al.*, 2014) module in R software (R Core Team, 2014) was used. The following statistics were used to assess the fit to the data of the models addressed in Papers I -IV:

$$R^2 = 1 - \Sigma(y_i - \hat{y}_i)^2 / \Sigma(y_i - \bar{y})^2$$ Papers I-IV (7)

$$bias = \frac{\sum(y_i - \hat{y}_i)}{n}$$ Papers I-II (8)

$$absolutebias = \frac{\sum| y_i - \hat{y}_i |}{n}$$ Papers I-III (9)

$$absolutebias\% = 100 \times \frac{\sum| y_i - \hat{y}_i | / n}{\sum \hat{y}_i / n}$$ Paper I , III* (10)

$$RMSE = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-1}}$$ Paper I -IV (11)

$$RMSE\% = 100 \times \frac{\sqrt{\sum(y_i - \hat{y}_i)^2 /(n-1)}}{\sum \hat{y}_i / n}$$ Paper III (12)

$$SSRR = 1 - \Sigma(Diff / \hat{y}_i)^2$$ Paper I (13)

Where R^2 = Coefficient of determination, RMSE = Root Mean Square Error, SSRR = Sum of Squared Relative Residuals, n = number of observations, y_i = observed values, $\hat{y}_i$ = predicted values. * eq (14)

The sum of squared relative residuals (SSRR) is an important statistic in analyses of differences between outcomes of taper equations (Figueiredo-Filho *et al.*, 1996), while absolute bias and SSRR provide clear indications of models' relative ability to describe and predict datasets (Parresol *et al.*, 1987). To test further the validity of the volume equations, paired student T-tests (TTEST procedure in the SAS package) of the significance of differences between measured values and predicted values were applied in Paper II.

The models in Papers I-II were validated by a leave-one-out cross procedure (Kozak & Kozak, 2003), i.e. each of the stands was excluded, one at a time, and the parameters were estimated for the reduced data-set. For the tree diameter-height modelling (Study III) an independent validation was created, consisting of diameter-height measurements of fifty trees (n=50).

Multicollinearity can cause major problems when constructing taper and volume equations that include complex polynomial and cross-product terms. The major multicollinearity problems that may occur are (Kozak, 1997):

1) minor variations in the data may substantially affect parameter estimates,
2) the regression coefficients may have high standard errors,
3) or the wrong coefficient sign.

The level of multicollinearity of the equations tested in Papers I and II was determined by calculating condition indices, CI (the square root of the ratio of the largest eigenvalue to each individual eigenvalue using the PROC REG procedure (SAS, 2006).

4 Results and Discussion

Prior to this study, no taper or volume equations had been developed specifically for poplars, nor biomass equations for poplar stumps or any height models for estimating stand volumes of poplar plantations grown under Swedish conditions. The ability to predict taper and volumes of poplar stems, biomass of poplar stumps, and volumes of plantations using the mentioned equations and models will be valuable because of the increased interest in the exploitation of poplar for biofuel in Sweden. However, the datasets used have several limitations, as discussed in the following section.

4.1 Limitations of available data

The models developed and evaluated in Studies I-IV are based on relatively few data points compared to some other taper, volume and height modelling studies. There are two reasons for this. Firstly, the data were collected from relatively few (37, 37 and 40) sites for the analyses presented in Papers I-III, because the total area used for growing poplars (ca. 1 000 hectares) and the number of existing poplar plantations in Sweden are small. The sites used in the studies are all that were found in an initial probe. Secondly, the number of sample trees per site was small due to restrictions set by the plantation owners.
With a few exceptions we were only allowed to cut a few trees per site. A systematic selection of sample trees was necessitated by the owners'

restrictions, although it can cause bias in the obtained regression coefficients and lead to greater errors than a random selection strategy (Kozak, 1997). However, these problems should be especially considered if the trees have been grown under various conditions within a site, and have a wide range of sizes. In Studies I-IV this problem was minor since all stands were clonal plantations on former farmland, thus the conditions within the stands were nearly homogenous and the range of tree sizes was small.

Forest management parameters (cleaning intensity and thinning regimes) can affect the form and taper of individual trees (Steven & Benee, 1988; Karlsson, 2005). Analysis of the slenderness (diameter/height) of poplars examined in Studies I-III revealed, as expected, that despite the scarcity of sites with densities of 1500-3000 stems per hectare slenderness values were negatively correlated with the number of trees per hectare (Fig. 7). This indicates that, as found in previous studies (Gafta & Crişan, 2010) slenderness and stem taper are correlated with the stocking and closure. Thus, future planting and management strategies for poplar plantations intended to produce timber should take into account the effect of stocking density on average stem diameter.

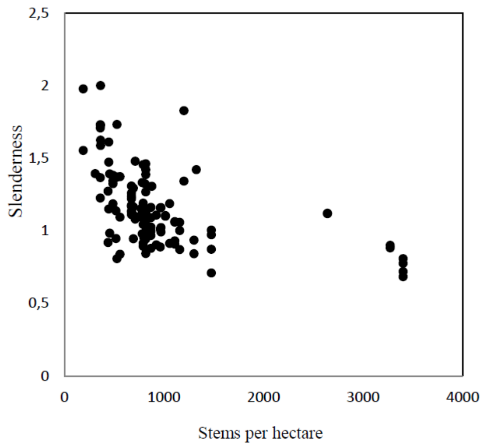

Figure 7. Relationship between the poplar trees' slenderness and numbers of stems per hectare in the sites used in Studies 1-III

Data for the stump and root biomass study (Paper IV) were collected from 12 final cuts or thinned trees at six sites in central and southern Sweden. Fewer sites were included than in the other studies because they were the only recently harvested or thinned sites available. Furthermore, the extraction, handling and measurement procedures for each stump are very time-consuming, which restricted the collection of data to 12 stumps per site, due to resource and time constraints.

4.2 Stem section lengths

Although numerous defined section lengths have been used for diameter measurements in other studies, the diameters of trees considered in Papers I and II were measured at 1-m intervals, together with their DBH, and the diameters at six relative heights. In Paper II the observed volume of the sample trees was calculated by applying Smalian's formula, $Vol=(Area_1 + Area_2)/2) \times length$, to data for 1-m sections, and summing the results, then compared with calculated volumes based on 2-m and 3-m sections. The calculated volumes for the 2-m sections had almost negligible deviations from the "true" volumes calculated from the data collected from 1-m sections (<1% of the volume for 69 % and <2% of the volume for 94 % of the sampled trees).However, the deviance between volume calculations based on the 1-m and the 3-m section lengths were larger: < 1% of the volume for 46 % and < 2% of the volume for 76 % of the sampled trees. These findings indicate that recording diameters at 2-m (but not 3-m) intervals may provide sufficiently reliable data to generate accurate taper and volume equations.

4.3 Statistical Evaluation

4.3.1 Taper equations

All six taper equations considered in Paper I yielded high determination coefficients between predicted and measured diameters (R^2 = 0.99). The exponent variable Equation (2) developed by Kozak (1988) had the lowest RMSE and AB values (0.91 and 0.64, respectively), and the lowest SSRR values for the upper part of the bole (I: Table 4). The constructed simple taper equation (1) had RMSE and AB values of 1.20 and 0.86, respectively, and a low level of multicollinearity. According to Parresol et al. (1987), AB and SSRR provide clear distinctions between examined equations and are important statistics when deciding the suitability of equations for use in practical surveys. The variable exponent equation (2) presented by Kozak (1988) was ranked most highly according by the evaluation statistics and thus recommended. However, the equation is complex and affected by multicollinearity (although this does not generally reduce its predictive capacity) and less user-friendly from a practical perspective. The complexity and relatively low user-friendliness are considered in recommendations in another study (Sakici *et al.*, 2008) that evaluated several taper equations including equation (2). In highly computerized and automatized systems the equation's complexity can be ignored and the model favoured, but when a less complex equation is required and larger bias is accepted, the constructed taper equation (1) may be a better option.

Equation (I:4), developed by Benbrahim & Gavaland (2003), shows larger residuals based on the data used in Paper I than in the cited study (up to 6 cm versus <1 cm), possibly due to differences in the data structure. Data applied in the latter were collected from young trees (7-8 years) with a mean height of 13 m and mean DBH of 12 cm, while the fitting data applied in Paper I were obtained from trees growing in stands with a mean age of 22 years (range 14-43 years), mean height of 23 m and mean DBH of 23 cm. Further, structure was observed in the residuals in Figure 3 in Paper I, while Benbrahim and Gavaland observed no such structure. Generally, young poplars, such as those included in the study of Benbrahim & Gavaland, have not developed butt-swells, unlike older trees such as those examined in Study I. None of the studied equations could fully grasp this butt-swell, but the magnitude of residuals related to the stump region is negatively related to the simplicity of the equations (I: Figure 3).

4.3.2 Volume equations

All of the nine studied volume equations had high determination coefficients ($R^2 \geq 0.98$, II: Table 3). However, the RMSE and AB values indicated that the constructed equation (2) and the equations presented by Eriksson and by Scott (II:3 and II:5) provided the best performance, and good predictions of stem volume. Furthermore, a paired Student's t-test indicated that differences between observed diameters and diameters predicted by these equations were non-significant. There were minor differences in the t-test statistics for all of the equations except equation (II:2), which had a notably higher SE value and larger range than the other equations, indicating weak accuracy and precision. The t-test results supported the ranking trend and are in line with the other evaluation statistics (R2, RMSE, B and AB) in Paper II.

There are small differences in the evaluation statistics between these three equations, but detailed comparison of B, AB and RMSE values and min-max ranges in the t-test showed that equations (II: 3 and 5) were marginally superior to the constructed volume equation (2). However, indications of ‘‘overparameterization’’ (multicollinearity) in these equations were detected, which is disadvantageous since at least one coefficient is likely to be small (close to zero) and/or have high standard errors (Burk *et al.*, 1989; Kozak, 1997), which is the case for equation (II:5). Generally, this does not affect the prediction capability (Kozak, 1997). Accordingly, both equations (II:3 and 5) performed well in the volume predictions, but they are complex, requiring estimates or five and six parameters, respectively. Thus, if slightly higher AB and RMSE values are accepted, equation (3) can be recommended since it is less complex, with only three parameters. An additive polynomial structure like that of equation (3), has been applied in various published volume equations, including the other equations addressed in Paper II, developed using data for a range of plantation species. A slenderness factor (diameter-height ratio) is not frequently used, but is a potential significant explanatory variable that may enhance stem volume predictions.

Table 4. *Estimated parameters and evaluation statistics of the recommended stem taper and volume equations (Papers I and II)*

Parameter	Parameter estimates	Standard errors of parameters	R2	RMSE	Bias	Absolute Bias	Absolute Bias %	RMSE[1]
Equation (1) Constructed polynomial taper equation (Paper I)								
*b*1	-0.4396	0.0198	0.996	1.20	0.04	0.86	5.2	1.20
*b*2	0.8477	0.0250						
*b*3	0.0020	0.0001						
*b*4	1.2892	0.0247						
*b*5	0.9130	0.0053						
Equation (2)Exponent variable taper equation by Kozak (1988) (Paper I)								
*b*1	0.7626	0.0451	0.998	0.91	-0.01	0.64	3.9	0.91
*b*2	1.1054	0.0242						
*b*3	0.9954	0.0008						
*b*4	1.0144	0.1129						
*b*5	-0.1997	0.0260						
*b*6	1.2213	0.2444						
*b*7	-0.6353	0.1331						
*b*8	0.2491	0.0079						
Equation (3): Constructed volume equation (Paper II)								
b1	4.40550	0.0742	0.997	46.27	-0.12	32.90	NA	46.49
b2	-0.63170	0.0354						
b3	0.05570	0.0019						

1) Obtained from leave-one-out cross validation

4.3.3 Mixed Effect Models for estimating tree heights

Autocorrelation of observations imposes general constraints on modelling procedures and can be addressed using a mixed model that eradicates these constraints. This model approach take into account random effects and generally handle hierarchy in the data well, when differences among groups due to latent factors are not explicitly incorporated in the models. It was observed at an early stage that the diameters of individual trees provided insufficient explanatory effect to predict the trees' heights (Fig. 8). Therefore six common additional site predictors (mean diameter, median diameter, mean height, dominant height, stand density and age) (Sharma & Parton, 2007) were considered for inclusion in equations (4) and (5) to improve the models' fit and predictive power. After including these predictors, one by one, and their interactions, it was found that the stand mean diameter and age provided the highest contributions to explanatory power and were included in the final diameter-height models. Adding the random effects to either the intercept or slope improved the predictive power, but adding to both provided no further significant improvement. The final models included a random error term $e_{i,j}$, a random effect μ_j for plot j with mean0 and variance $\sigma^2_{,j}$. The two additional variables (stand mean diameter and stand age) and their interaction significantly improved predictive capacity, as well as adding the random effect to the intercept or slope. Equation (14) shows the height-diameter model with age as an additional predictor and the random effects added to the intercept.

$$\ln(H_{ij} - 1.3) = \beta_0 + \mu_j + \beta_1 D_{ij}^{-1} + \beta_2 \ln(Age_j) + \varepsilon_{ij} \qquad (14)$$

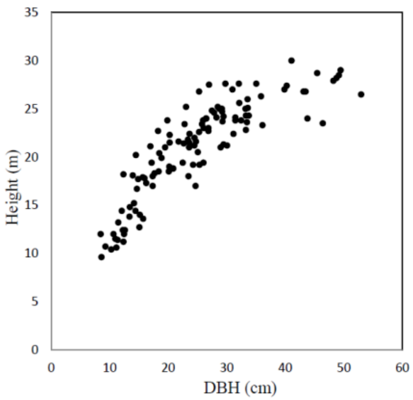

Figure. 8. Height-diameter relationships for the dataset applied in Paper III, n=117

R^2 values for the fixed part of the height models were between 0.85 and 0.87 (III: eqs. 8, 9 and 10). When the random effects were included the resulting coefficients of determination were >0.96 in all cases. This improvement of coefficients of determination values (R^2) is illustrated in Figure 9 by the plots of observed heights versus heights predicted with and without random effects. The dispersion and variance are notably smaller when the models include the random site factor. A summary of the statistical assessment and parameter estimates for equation (14) with the additional age predictor is presented in Table 5. For a detailed description of the statistical assessments of the models with stand mean diameter and the interaction with age as additional predictors see eqs. (8 & 10) and Table 3 in paper III.

Table 5. *Estimates, standard errors (S.E.) and significance level of the parameter estimates and the statistical assessments of the fixed effect and total model, including random effect for equation (14).*

Parameter	Estimate	S.E.	*d.f.*	t	*p-value*
β_0	*2.580*	*0.137*	*76*	*18.784*	*<0.001*
β_1	*-8.448*	*0.567*	*76*	*-14.913*	*<0.001*
β_2	*0.281*	*0.043*	*38*	*6.512*	*<0.001*
$\sigma_{plot\,(\mu_0)}$	*0.070*				
σ_{tree}	*0.065*				

	Fixed effect	*Total Model (incl random effect)*
bias	*-0.209*	*0.001*
Absolute bias	*1.391*	*0.791*
Absolute bias %	*7.219*	*4,001*
RMSE	*1.819*	*0.999*
RMSE %	*9.257*	*5.086*
R^2	*0.870*	*0.961*
Snowden ratio	*1.00230*	

S.E. Standard Error of the estimates
p-value: Significance of the parameter estimation.

The inclusion of a random site component remarkably reduces the absolute bias in both arithmetical and relative terms (%). This indicates that a random component effectively (but not totally) accounts for random site effects that are not captured with the explanatory variables and improves both the accuracy and precision of the height estimates, reducing the absolute bias by 42 % (from 1.39 m to 0.79 m on average), or in relative terms from 7.2% to 4.0%.

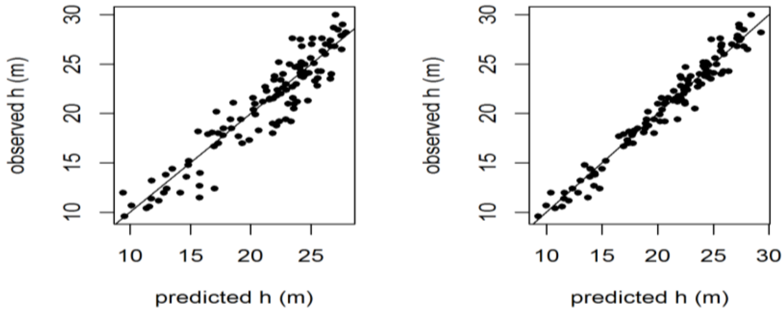

Figure 9. Measured tree heights in the fitting data and predicted heights obtained using solely the fixed part of the model (left), and both fixed and random parameters (right) for the selected Eq. (14).

The fit of the height model (eq. 14) to an independent validation data set (mean bias, 1.79 m) is shown in Figure 10.

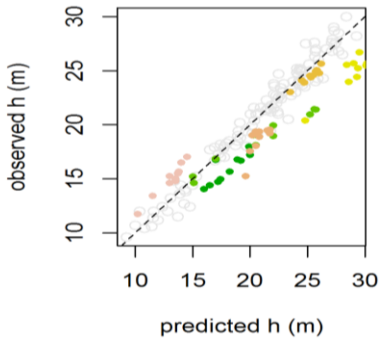

Figure 10. Measured tree heights in the independent validation data set versus heights predicted using the selected Eq. (14) Each color represent different sites.

If the model has to be applied to a new plantation, few new tree measurements are needed to estimate a locally calibrated height–diameter curve, which simplifies the data sampling. The approach in this study corrected and calibrated the general trend for each plantation, reducing biases, increasing accuracy, and adjusting the trend to model the relationship within the plantations more robustly.

4.3.4 Equations for estimating stump and root biomass

The interest in using residuals (branches and tree tops) and stumps after harvest as a bioenergy resource has increased in recent years. Several studies have examined techniques for excavating, handling and storing stumps (Anerud, 2012; Persson, 2012). The biomass of stumps of numerous species has also been assessed, but few studies have considered the biomass of poplar stumps. Usually the biomass of limited numbers of stumps (with or without various root fractions) has been measured, then the results have been extrapolated to stand or hectare level. Furthermore, few predictive models for stump biomass estimates based on independent variables such as DBH or diameter at ground level (e.g. stump diameter) have been developed, generally and for poplar in particular. Predictive models for estimating above ground biomass and stem volume are essential tools in forest management and planning operations, and there is a need for similar tools for estimating the biomass of poplar stumps, such as the model presented in Paper IV. It should be noted that the viability of excavating and utilizing stumps from forested land has been questioned, from environmental perspectives (Kardell, 2007; Berch *et al.*, 2012). Further studies on the environmental consequences of stump excavation in short rotation poplar plantations are required before its commercial-scale introduction.

The stump and root biomass modelling presented in Paper IV was based on data obtained from poplar plantations located in southern Sweden. In total, 72 stumps and root systems were excavated, separated, and the roots were further divided into three diameter classes: 50-100, 101-200 and >200 mm. Models based on the independent variable DBH and a power equation (4) were used to predict the stump- and root (>50 mm diameter) biomasses. Predictive curves generated by the models fitted the data well (Figure 11), although they were more accurate for the stump biomass than for the root biomass, as shown by the coefficients of determination (R^2) and RMSE values presented in Table 6.

Table 6. *Coefficients of equation (4) for estimating dry weights of poplar stumps and roots (Paper IV).*

Components	Coefficient	Coefficient estimates	Standard errors of coefficient	R^2	RMSE, Kg	Pr > F
Stump	β_0	0.000116	0.000096	0.93	15.9123	<0.0001
	β_1	2.290300	0.140200			
Roots	β_0	0.000010	0.000015	0.80	9.6435	<0.0001
	β_1	2.529000	0.259900			

4.3.5 Biomass Structure of Stumps and Roots for Trees and Stands

The mean dry stump and root weights were 45 and 14 kg; 76% and 24% of the total dry weight of the stumps and root systems, respectively. The mean dry weights of the stump and roots as a percentage of fresh weight were 45 and 42 %, respectively (Table 3), and their mean basic densities were 0.333 g cm^{-3} and 0.313 g cm^{-3}, respectively. For detailed descriptions of their fresh and dry biomass, and basic density, at each of the sites see Tables 3 and 5, respectively, in Paper IV. For individual stumps the mean length of all roots thicker than 50 mm was 6.71 m, of which 63, 23 and 14% of the total root length was associated with roots of 50–100, 101–200 and >200 mm diameter, respectively. For a detailed description of the mean root weight and length for each root diameter class and percentage of total root weight and length see Table 6 in Paper IV.

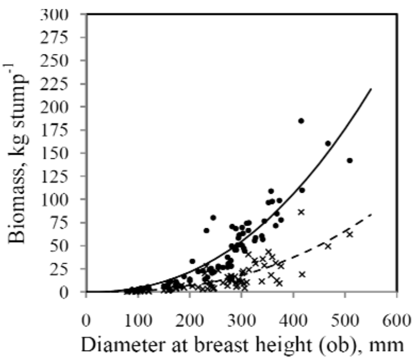

Figure 11. Dry mass per tree, kg tree^{-1}, in relation to diameter at breast height (DBH; mm) of stumps (—·) and roots (--×) of 72 sample trees.

Generally, the stump wood of conifers has higher basic density than the stem wood. However, Young & Chase (1965) found that the mean basic density of poplar stump-root systems was somewhat lower (0.336 g cm^{-3}) than that of the stems (0.381 g cm^{-3}). Similarly, in a study of planted poplars on former farmland in Sweden the basic density of stems was found to be 0.349 g cm^{-3} (Johansson & Karacic, 2011). These values are consistent with findings in Study IV that the stem, stump and root basic densities were 0.328, 0.333 and 0.313 g cm^{-3}, respectively. Several studies have found that the biomass of poplar stumps amounts to about 20% of the stem biomass (Richardson *et al*., 2002; Shyam *et al.*, 2011). Accordingly, in the material examined in Study IV, the stump and roots biomass corresponded to 21% and 6.5% of the stem weight. The results of the present study regarding the belowground biomass percentage of the total biomass also correspond well with findings of international studies. Fang *et al*. (2007) found that the belowground biomass of two poplar clones in China amounted to 20% of the total tree biomass, while studies of an 8-year-old and a 9-year-old stand of Eastern cottonwood in India found corresponding values of 18% (Lodhiyl *et al*., 1992) and 16% (Das *et al*., 2011).

The mean dry mass production for the studied stands was calculated based on the stem number per hectare of each stand. The mean total dry mass of stump + roots was 46.9 tDM ha^{-1} (34.9 for stumps and 12.0 tDM ha^{-1} for roots) (Figure 4 in Paper IV). The belowground biomass (stump + roots) per hectare was correlated to the aboveground biomass ha^{-1}. Puri *et al*., (1994) reported a similar relationship between root biomass and aboveground biomass for Eastern cottonwood.

4.4 Validation of the Taper, Volume and Diameter-Height models

The validity of the models presented in Papers I-II could have been assessed using independent data-sets (Kozak & Kozak, 2003), an approach that has been applied in numerous modelling studies. For example, in the comparative taper model study by Sakici *et al*. (2008) 24% of the total dataset (n=115) was used an independent validation data set. However, the number of available stands was even lower for the taper and volume studies presented in Papers I and II.

Therefore, the models were validated by a leave-one-out cross validation procedure (Kozak & Kozak, 2003), i.e. each of the stands was excluded, one at a time, and the parameters were estimated for the reduced data-set (Table 3 in paper I and Table III in paper II). As this procedure did not increase RMSE values in Study I and marginally increased them in Study II, the rankings of the models remained the same (Table 4). For the tree diameter-height modelling (Study III) additional tree diameter-height data had been collected from new sites resulting in a larger total number of available data. It was therefore decided that an independent dataset should be created, consisting of diameter-height measurements of ten trees each from five different sites (n=50) while the dataset for evaluating and fitting consisted of measurements from 117 trees from 40 different sites. The developed diameter-height models fitted the data well, and the validation plot (Fig. 10) showed that they had general applicability.

5 Conclusions

Poplars generally grow rapidly in Sweden, and in the best sites in southern Sweden their yields are comparable to those in southern Europe.

No assortment standards have been set for poplar wood as yet in Sweden. Thus, most harvested poplars have been sold as biofuel, but other assortments (pulp, veneer logs, saw timber etc.) could probably be sold as commercial products by the plantation owners. The recommended taper and volume equations are useful for estimating relevant wood properties, and the developed diameter-height models are useful for generating stand estimates when measurements of tree diameters are available, but not height measurements.

The diameter-height models developed in Paper III were improved by applying a mixed effect approach, including calibration for random site variability. Furthermore, site-specific predictions of future biomass and volume can be conducted more time and cost efficient and estimates for new plantations can be easily calibrated using a limited number of measurements based on the modelled structure.

Models for estimating Stump and root biomass are few (compared to the other model types studied in this thesis). The developed stump and root biomass model is therefore a useful tool in estimations of below ground biomass estimation in poplar stands.

6 Future Work

The minimum numbers of observations required to develop mixed models that provide sufficiently reliable predictions of the focal variables require further study. A potentially fruitful approach is to collect data on trees of several size classes, e.g. trees representing each quartile in the diameter distribution and preferably at least one replicate from each quartile to capture possible variation.

The models are based on limited datasets, and ideally they should be validated using larger total and clone-specific datasets, when available.

Plantation owners are often uncertain about the optimal time to harvest their poplar stands, and current guidelines are set by subsidiary frameworks rather than relevant physiological and site factors. Thus, studies on optimal rotation periods in Sweden are also required.

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