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Comparison of Approaches to Integrate Energy Wood Estimation into the Finnish Compartment Inventory System

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The harvesting of energy wood from young stands is increasing as the demand for renewable wood fuel is growing. Energy wood consists of stems, tree tops, branches and needles, depending on the size of the trees and the logging method used. The current forest inventory and planning systems used in private forests in Finland do not produce estimates of energy wood components. In stands typical for energy wood harvesting, a large share of energy wood consists of trees smaller than the minimum size for pulpwood. In this study, energy wood was included into the calculation system of compartment inventory, and a procedure for simulating the thinning treatments in young stands was developed. The results for six inventory alternatives and prediction of energy wood were compared with the use of inventory material from 37 young stands that have plenty of energy wood. The measurement of additional stand characteristics and the use of a calibration estimation method was tested, as well as the use of plot-level inventory data instead of stand level data. The results showed that the measurement of the number of trees per hectare, in addition to stand basal area and mean diameter, improved the energy wood estimates. The additional minimum and maximum diameters improved the precision of the estimates, but did not affect bias. The removal estimates were more precise when plot-level data was used, rather than stand-level data. The removal estimates were higher with plot-level data. The results suggest that, in heterogeneous young stands, plot by plot prediction would give more accurate removal estimates than the calculation of a corresponding prediction at the stand-level.

Keywords calibration estimation, compartment inventory, diameter distribution, thinnings
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1 Introduction

Consumption of forest chips in Finland has increased rapidly from 0.75 mill. m^3 in 1999 to 2.7 mill. m^3 in 2004. Currently, energy wood is mainly collected from clear-cutting areas because of the low harvesting costs of logging residues and stump wood. The annual harvest of energy wood for forest chip production in thinning operations is approximately 0.7–0.8 mill. m^3. The National Forest Programme proposes that the annual consumption of forest chips should be increased to 5 mill. m^3 by 2010. Thus, energy wood procurement from young forests is likely to double from the present level by 2010.

Energy wood is defined by Pulkki (2006) as any part of tree biomass in any form to be used as fuel. Usually, energy wood contains tree species, stem sections and biomass fractions like branches and needles that do not fulfil the size or quality requirements for pulpwood. In young stands, the most important constraint in energy wood harvesting are high logging costs due to small stem size and low removal per hectare (Laitila et al. 2004, Heikkilä et al. 2005). Harvesting technology and procurement methods for operations in young forests are still developing rapidly. One way to reduce procurement costs is to use full tree and part tree harvesting methods, which increase the amount of harvested biomass. One application of the part tree method is the so-called topping method, where only the uppermost 1–2 meters of the tree is left in the forest in order to reduce nutrient removals.

About 80% of the harvested timber in Finland comes from private forests (Finnish Statistical Yearbook… 2005), which makes forest management data from private forests an important source of information for energy wood procurement. The annual forest management planning area covers over one million hectares of private forests. Field data for forest management planning are collected by using compartment inventory with subjective sampling complemented by visual assessment of some stand characteristics (e.g. Kangas et al. 2004). The basic idea of the method is to measure stand basal area samples from subjectively selected representative points in the stand. In each sample, the basal-area-weighted mean tree is visually selected for each tree species, and the diameters and heights of these trees are measured. Stand-specific estimates of stand characteristics are the averages of these plot-level assessments. Theoretical diameter distribution models, height models and taper curve models are further used to predict the volumes of timber assortments (Laasasenaho 1982, Kangas and Maltamo 2000b, Siipilehto 1999). Until now, only saw logs and pulpwood have been considered as timber assortments in the calculation systems. The development of the tree stock is predicted with individual tree growth and survival models (Hynynen et al. 2002). Similar forest inventory systems are also used in forestry planning in forest companies and in the state forests.

The accuracy of inventory by compartments has been found to vary between 15% and 40% in terms of the RMSE of the total stand volume (e.g. Anttila 2002, Haara and Korhonen 2004). At the tree species level, the accuracy can be considerably lower. Due to the use of diameter distribution models for stand basal area, description of the diameter distribution is imprecise for small trees (dbh < 10 cm) (e.g. Kangas and Maltamo 2000c).

One way to improve the prediction of diameter distribution is to use calibration estimation (Deville and Särndal 1992). The basic idea is to calibrate the predicted diameter distribution with the aid of additional measurements, such as number of stems, and minimum and maximum diameters (Kangas and Maltamo 2000a, Mehtätalo 2004). Calibration adjusts the predicted diameter distribution to ensure compatibility with the field-assessed stand variables. This may considerably improve the accuracy of volume estimates and description of the size structure of trees, when the true values of calibration variables are used (e.g. Kangas and Maltamo 2000a,c). However, when this method is applied to field-assessed stand variables the results have been less satisfactory (e.g. Haara and Korhonen 2004). For example, the field-assessed number of stems is often so imprecise that its use is questionable (Kangas et al. 2004).

Stands suitable for energy wood harvesting have several features that make forest inventory and the estimation of timber volume, harvesting removal and its distribution into different timber assortments more difficult than usual. The potential stands for harvesting energy wood have usually been regenerated for pine or spruce but insufficient tending has led to an admixture or even domination of fast growing broadleaved species like grey alder (*Alnus incana)*, aspen (*Populus tremula*), pubescent birch (*Betula pubescent*) and *Salix* species. Energy wood is usually harvested simultaneously with industrial wood and the thinning removal consists of several species and a wide range of tree sizes. Conifers and silver birch (*Betula pendula*) are usually favoured in thinning treatments. Thus, the selection of harvested stems should take into account both the trees' social status and the species' suitability for the site, which makes it difficult to simulate real harvesting operations. As the stands are dense with a high number of small stems, it is difficult to accurately measure samples for stand basal area or number of stems per hectare.

Whole tree and part tree methods are favoured in energy wood harvesting because they increase the harvesting removal and decrease the unit harvesting costs. Harvesting costs can also be reduced by preparing fewer timber assortments. For example, when the removal of a certain species is low, the whole removal of this species may be allocated to energy wood, using the whole tree method, even if part of the trees would meet requirements for industrial timber. The logging method, which greatly affects the profitability of the operation, is usually selected on the basis of inventory data. Therefore, accurate inventory data is a means to reduce harvesting costs.

Regional Forestry Centres, which are state-funded organisations, that advise forest owners and monitor the forestry laws, carry-out over 90% of private forestry planning. As the energy wood markets are developing, Forestry Centres have faced a growing demand for energy wood estimates. However, energy wood estimation is not yet included in the calculation system of inventory by compartments. Instead, Regional Forestry Centres train their staff to recognize and record stands suitable for energy wood harvesting. The surveyors evaluate if the stand fulfils the criteria for a special state subsidy for energy wood harvesting in young stands. They also recommend the timing of the thinning treatment on the basis of stand state and silvicultural recommendations, and estimate the total stem volume of the harvestable energy wood. The problem with this system is its inflexibility. The surveyors' recommendation for the timing of thinning may differ by several years from the eventual harvesting year, which causes errors in removal estimates. Changes in the logging method (e.g. delimbed stems vs. full tree logging), minimum dimensions of timber assortments, and government subsidies are additional reasons why the fixed field estimates can be easily inaccurate.

The general aim of this study was to compare different inventory and prediction methods for the estimation of harvesting removals of energy wood in young stands in Finland. The specific aims were:

1) To develop an algorithm for the simulation of harvesting in mixed un-thinned young stands and the calculation of removal estimates for both industrial timber and energy wood;
2) To compare alternative ways to conduct field inventories for improved energy wood estimation; and
3) To compare simulated energy wood removals with ocular field estimates.

2 Material and Methods

2.1 Materials

The material consists of data from 37 young stands that were classified by the Forestry Centre of North Karelia in Eastern Finland to be suitable for energy wood harvesting. The compartment and sample plot inventory was done in 2003. The first available stands from the on-going compartment inventory of the Forestry Centre that fulfilled the selection criteria were chosen for a detailed inventory by sample plots. All the stands had to be located within 50 km of the town of Joensuu, be larger than 0.5 hectares and have a recommendation for energy wood harvesting within five years from the inventory. The inventory data collected by the Forestry Centre also included, besides recommendations for silvicultural treatments, field estimates for the removal of industrial timber and energy wood.

Five to seven sample plots with a radius of 5.64 meters (100 m^2) were systematically placed in each stand. The mean area of the stands was 1.36 hectares (0.5–2.6 ha), and the total number

Table 1. The mean, range and standard deviation of some stand characteristics in the 37 stands used as study material. The mean diameter, height and age of the stand have been calculated with the use of tree basal area as a weight variable. Biomass refers to dry mass.

Variable	Minimum	Mean	Maximum	Standard deviation
Mean diameter, cm	8.0	13.5	18.5	2.5
Mean height, m	7.9	11.5	15.7	1.9
Mean age, a	15.0	28.3	43.7	6.2
Stand basal area, $m^2 ha^{-1}$	9.4	21.0	36.5	5.7
Number of trees, ha^{-1}	1586	2545	3371	461
Total volume, $m^3 ha^{-1}$	38	121	234	40
Pulpwood volume, $m^3 ha^{-1}$	3	86	192	41
Total biomass, tn ha^{-1}	20.5	70.1	142.1	23.5
Stem biomass, tn ha^{-1}	13.9	49.4	90.2	16.0
Energy wood stem biomass, tn ha^{-1}	5.1	12.8	35.7	6.1
Total crown biomass, tn ha^{-1}	6.6	20.8	52.7	6.6
Live branch biomass, tn ha^{-1}	5.8	15.3	34.5	6.4
Dead branch biomass, tn ha^{-1}	0.2	0.8	2.1	0.5
Needle biomass, tn ha^{-1}	0.4	4.7	18.3	3.9

of sample plots was 246. The forest site type was assessed at the stand level. The tree species and breast height diameter (cm) were recorded for every tree with diameters of at least 25 mm. The first three trees of each species in each sample plot were selected as sample trees. However, to make the sample more representative for height model calibration, the sample trees of a given plot and species had to differ in dbh class when trees with a different dbh class were available. The sample trees were measured for dbh (mm), age, height (dm), height to crown base (dm) and height to the lowest dead branch (dm). An electronic Vertex-device was used for height measurements and the crown base was defined according to the field instructions of the Finnish National Forest Inventory. The heights of trees other than the sample trees were predicted using Näslund's height model (Näslund 1937), which was fitted separately for every stand using all the height sample trees of the stand. Stand basal area and mean height were calculated both at the stand and plot levels, including stems of at least 45 mm at dbh. Trees smaller than 45 mm were ignored because they are often felled before the logging to reduce costs and damages for remaining trees.

The stands had no visible signs of earlier thinnings and the within-stand variation in respect to density (stems ha^{-1}) was large (Table 1). Almost every stand included sample plots in which the stand basal area exceeded the recommended limit for thinning (Hyvän metsänhoidon… 2001). Almost every stand also included at least one sample plot in which the basal area was lower than the recommended density after thinning. The stands were mixed stands, eight being birch dominated by basal area and volume, and the rest conifer dominated with a mixture of several broadleaved species. As broadleaved species were the smallest in dbh, they represented the largest share of the number of stems in most stands.

2.2 Methods

2.2.1 Inventory Data Alternatives

Six different approaches were considered concerning the availability of inventory data. In three cases, only stand level variables were available, corresponding to the current ocular forest inventory practice in Finland. The remaining three cases assumed that the variables measured in the individual inventory plots were available. Therefore, the six cases were as follows:

1 Only stand-level information available
  1.1 Basal (G) area and basal-area-weighted mean diameter (Dg) measured for every species

1.2 G, Dg and number of trees per hectare (N) measured for every species
1.3 G, Dg, N, and minimum and maximum diameters (D_{min} and D_{max}) measured for every species
2 Plot-level information available
2.1 G and Dg measured for every species (in every plot)
2.2 G, Dg and N measured for every species
2.3 Individual trees of the inventory plots were measured for species and dbh, and sample trees for height and crown length

2.2.2 Predicting Diameter Distribution

In all cases, except 2.3, the diameter distribution of every species present in the stand or plot was predicted. The range of diameters was divided into 30 classes of equal width, and the frequencies were calculated for class mid-point trees, which were taken to represent the entire class. In the case of 2.3, the trees measured in the field were used directly in calculations.

The diameter distribution was predicted from stand characteristics using the beta function as the theoretical distribution. Corresponding to the current practice in Finland, the diameter distribution of the stand basal area was used instead of the diameter distribution of the number of trees.

The beta density function is (e.g. Loetsch et al. 1973):

$$f(d) = c(d-a)^{\alpha}(b-d)^{\gamma} \quad (1)$$

where d is tree diameter, a is the minimum diameter, b is the maximum diameter, c is a scaling factor, and α and γ are exponents that determine the shape of the distribution. The parameters of the function were estimated as follows. Parameter a (minimum) was either the minimum observed diameter or 0.5 times the basal-area-weighted mean diameter (Dg), depending on which stand variables were assumed to be available as field measurements. Parameter b (maximum) was equal to the maximum observed diameter or, if this variable was not available, b was set to be equal to 1.3Dg. Parameters α and γ were calculated from (Loetsch et al. 1973):

$$\alpha = z(\gamma+1)-1 \quad (2)$$

$$\gamma = \frac{\dfrac{z}{s_r^2(z+1)^2}-1}{z+1}-1 \quad (3)$$

where

$$z = \frac{d_r}{1-d_r}; \quad d_r = \frac{D_{gM}-a}{b-a} \quad (4)$$

$$s_r^2 = \frac{s^2}{(b-a)^2} \quad (5)$$

where s is the standard deviation and D_{gM} the basal area median diameter of the empirical distribution. In this study, Dg was used as a surrogate of D_{gM}, since it was assumed that only Dg was available as a field measurement. The standard deviation of the diameter was predicted using the equations of Päivinen (1980). The frequencies of the 30 representative trees per species drawn from the predicted distribution were computed with the use of a scaling factor (c in Eq. 1) that makes the sum of the frequencies equal to the observed basal area of the species.

The scaled frequencies of representative trees were used in calculations for cases 1.1 and 2.1. This corresponds to the current way of using inventory data in the calculation systems of Forestry Centres. For cases 1.2, 1.3 and 2.2 the method was refined by calibrating the frequencies of the trees. This was done by solving the following optimisation problem with the Simplex method (see Deville and Särndal 1992, Kangas and Maltamo 2000):

$$\min \sum_{i=1}^{I}\left(s_i^- + s_i^+\right) + 50N^- + 50N^+ + 50D_g^- + 50D_g^+$$

subject to

$$\sum_{i=1}^{I} g_i w_i = G$$

$$\sum_{i=1}^{I} w_i + N^- - N^+ = N$$

$$\sum_{i=1}^{I} w_i d_i g_i + D_g^- - D_g^+ = GD_g$$

$$w_i + s_i^- - s_i^+ = f_i, \quad i = 1,...,I$$

where s_i^+ and s_i^- measure how much the calibrated frequency of diameter class i (w_i) exceeds (s_i^+) or falls short of (s_i^-) the non-calibrated frequency (f_i); N^+, N^-, Dg^+ and Dg^- are the corresponding goal variables for the total number of trees per hectare and mean diameter; I is the number of diameter classes; and g_i, w_i, f_i and d_i are, respectively, the tree basal area (m^2), calibrated frequency, non-calibrated frequency and mid-point diameter (cm) of diameter class i.

The purpose of calibration was to adjust the frequencies of the diameter classes so that the total number of trees per hectare (N), stand basal area (G), and mean diameter (Dg), when calculated from the representative trees, matched the input values of the corresponding characteristics. To be sure that the problem was always solvable, goal variables for N and Dg (N^+, N^-, Dg^+ and Dg^-) were added to the problem formulation. They were often zero because their weights in the objective function were 50 times greater than the weights of the deviations of the class frequencies. Calibration decreases the significance of the distribution function that is used to derive the first guesses for class frequencies.

2.2.3 *Simulation of Thinning*

The energy wood harvest was simulated by decreasing the stand basal area to the post-thinning basal area of the silvicultural instructions of the Forestry Centres (Hyvän metsänhoidon… 2001). The treatment was simulated as follows. The frequencies of all trees were first reduced by 15%; which corresponds to the opening of logging trails. It was then checked if the removal of trees other than pine, spruce and birch would keep the remaining basal area above the recommended post-thinning level, and if this was the case, all trees of the "non-timber" species were removed. If a complete removal of non-timber species would have reduced the stand density too much compared to the recommended basal area after thinning (Hyvän metsänhoidon… 2001), only a part of the trees was removed, so that the post-thinning basal area was exactly the same as in the recommendation. 25% of the removed basal area was removed by using an equal harvest percentage for all diameter classes. The remaining 75% of the removal was simulated as a thinning from below, i.e. the trees with the smallest dbh were removed until the stand basal area was at the recommended post-thinning level. If the stand basal area was higher than recommended after a complete removal of all trees of the non-timber species, the tree frequencies of the timber species (pine, spruce and birch) were reduced until the recommended post-thinning basal area was reached. Also, in this case, a combination of uniform (25% of removed basal area) and thinning from below (75%) was used, as described above. Only trees with a dbh greater than or equal to 4.5 cm were removed in the thinning treatment (smaller trees were not considered when calculating the removal or the remaining basal area).

The cutting was simulated in the inventory year (2003). However, when the simulated removal was compared to the field estimates of the Forestry Centre of North Karelia, the cutting was simulated in the same year as proposed in the management plan prepared by the Forestry Centre. This allowed us to compare the simulated energy wood removals to the removal estimates of the management plans. Our inventory data were from 2003, and the cutting was planned for 2005 or 2006. This means that the stand development had to be simulated for two or three years before simulating the "energy wood harvest" treatment. The stand development was simulated with the growth models of Nyyssönen and Mielikäinen (1978) and the survival models of Hynynen et al. (2002).

2.2.4 *Calculation of Assortment Biomasses*

The stems were divided into pulpwood and energy wood assortments. No saw logs were obtained in the rather young stands used in this study. The top diameter for pine, spruce and birch pulpwood was 6.3 cm and 9 cm for aspen. For energy wood, the minimum top diameter was 3 cm, except in the part tree logging method. The minimum diameters for pulpwood represent the average requirements in Finnish timber markets and the minimum diameter for energy wood logs corresponds to the practice of logging delimbed stems. For species other than pine, spruce, birch or aspen, the top diameter for pulpwood was set high enough that only energy wood could be obtained. The shortest acceptable length of pulpwood bolts was 2.7 m, and that of energy wood was 2 m. The volumes of these assortments were predicted through the taper models of Laasasenaho (1982). In addition, these taper models were used to find the starting and ending height of the energy wood part of the stem. This allowed us to estimate the branch biomass of the part of the tree that is used for energy wood.

The models of Marklund (1988) were used to predict the total branch mass (dry mass of living branches including needles). The model for birch was also used for aspen and alder. However, the predictions were corrected on the basis of the basic densities of the branch biomass of birch, aspen and alder. The correction factor was 450/530 for aspen (basic density of aspen divided by the basic density of birch) and 440/530 for alder and all other deciduous trees. The correction is based on the assumption that birch, aspen and alder of the same dbh and height will have an equal volume of branches. The models of Tahvanainen and Forss (2006) for the vertical distribution of branch mass were used to calculate the branch mass of the energy wood part (diameter > 3 cm) and the top (diameter 0–3 cm). Only living branches were included in the results.

All these calculations enabled us to estimate amounts for the following assortments:

- A Pulpwood
- B Energy wood from stems (Delimbing method)
- C Energy wood from stems with branches of the energy wood part of the stem (Topped full tree method)
- D The same as C plus tree top with branches (Part tree method)

Cases B, C and D represent the most common alternatives for harvesting energy wood from Finnish forests (Laitila et al. 2004, Heikkilä et al. 2005). The amounts of the assortments were reported in tons of dry mass. The volumes of pulpwood and energy wood from stems were converted into dry masses using the following basic densities (tons/m^3): pine 0.390, spruce 0.385, birch 0.490, aspen 0.395, alder and all other species 0.360.

The six alternatives for using field data were compared by predicting the average amount of biomass for the growing stock and the thinning removal for every alternative (in tons/ha). When plot-level inventory data were used, all predictions were conducted at the plot level, from which a stand level estimate was calculated by assuming that every plot represents the same area (stand area divided by the number of plots). In addition, the square root of the mean of squared errors (RMSE) of standing or harvested biomasses was calculated for every method. It was assumed that the estimate based on individual trees was the "reference" one, so the other estimates were compared to it when the squared errors were calculated.

3 Results

3.1 Standing Biomass

The use of the number of stems per hectare clearly improved the estimates for standing biomass compared to the alternative where only the stand basal area and mean diameter were known (Table 2). The use of only D_g and G overestimated the amount of pulpwood and underestimated the amount of energy stemwood. The addition of the minimum and maximum diameters did not further improve the estimates. Plot-level calculations only gave minor improvements compared to compartment-level data.

The ranking was different in terms of the RMSE (Table 3). If the individual tree alternative is taken as "reference", the combination of G, N, D_g, D_{min} and D_{max} was by far the best of the stand-level alternatives. In most cases, the use of plot-level information improved the estimates for energy wood compared to the corresponding stand-level data but the improvements were rather small. The pulpwood estimates also improved when plot-level data were used in the calculations.

Table 2. The average standing biomass (tons/ha) for different inventory and prediction methods (the most accurate method is in boldface).

Method	Inventoried variables (input for calculation)			
	Pulpwood (A)	Energy wood to 3-cm top (B)	B with branches (C)	C plus tree top with branches (D)
	Stand-level data			
1.1 *G*, *Dg* by species	37.8	11.1	16.6	20.0
1.2 *G*, *Dg*, *N* by species	35.8	13.1	18.5	22.2
1.3 *G*, *Dg*, *N*, D_{min}, D_{max} by species	36.0	12.8	18.3	22.0
	Plot-level data (5–7 plots per stand)			
2.1 *G*, *Dg* by species	37.2	11.6	17.1	20.7
2.2 *G*, *Dg*, *N* by species	36.1	12.8	18.2	21.9
2.3 Individual trees	**36.1**	**14.0**	**19.5**	**23.9**

Table 3. The RMSE for standing biomass (tons/ha) for different inventory and prediction methods if the most accurate method (individual trees) is taken as "reference".

Method	Inventoried variables (input for calculation)			
	Pulpwood (A)	Energy wood to 3-cm top (B)	B with branches (C)	C plus tree top with branches (D)
	Stand-level data			
1.1 *G*, *Dg* by species	2.18	2.35	3.34	4.25
1.2 *G*, *Dg*, *N* by species	1.54	2.14	2.15	2.77
1.3 *G*, *Dg*, *N*, D_{min}, D_{max} by species	0.63	1.59	1.65	2.41
	Plot-level data (5–7 plots per stand)			
2.1 *G*, *Dg* by species	1.42	2.70	2.64	3.45
2.2 *G*, *Dg*, *N* by species	0.59	1.66	1.64	2.38
2.3 Individual trees	**0**	**0**	**0**	**0**

3.2 Harvesting Removals

Plot-level data gave higher estimates for the total biomass removals and for pulpwood removals (Table 4). With the stand-level data, using *N* with or without D_{min} and D_{max} decreased the estimated pulpwood removals, and using *N* with D_{min} and D_{max} underestimated the removals of all biomass components.

The comparison of the RMSEs for the harvested amount of biomass clearly show a higher precision for the plot-level information compared to the stand-level combinations (Table 5). With plot-level data, the RMSEs for both pulpwood and energy wood were slightly smaller when *G*, *Dg* and *N* were combined, compared to when *G* and *Dg* only were used. At the stand-level, additional variables worsened rather than improved the precision of removal estimates. This is because the additional variables often led to an underestimated removal (Table 4).

3.3 Accuracy of the Field Estimates of the Forestry Centre

The Forestry Centre field estimate for energy wood harvest removal and an estimate that was predicted with the use of the Forestry Centre field data were compared to the corresponding estimate

Table 4. The average harvest removal (tons/ha) for different inventory and prediction methods (the most accurate method is in boldface).

Method	Inventoried variables (input for calculation)			
	Pulpwood (A)	Energy wood to 3-cm top (B)	B with branches (C)	C plus tree top with branches (D)
	Stand-level data			
1.1 G, Dg by species	9.1	6.2	8.7	10.1
1.2 G, Dg, N by species	6.9	7.1	9.5	10.9
1.3 G, Dg, N, D_{min}, D_{max} by species	6.6	6.3	8.5	9.8
	Plot-level data (5–7 plots per stand)			
2.1 G, Dg by species	11.4	6.1	8.6	10.0
2.2 G, Dg, N by species	10.2	6.8	9.2	10.8
2.3 Individual trees	**10.6**	**6.9**	**9.3**	**11.0**

Table 5. The RMSE for harvested biomass (tons/ha) for different inventory and prediction methods if the most accurate method (individual trees) is taken as "reference".

Method	Inventoried variables (input for calculation)			
	Pulpwood (A)	Energy wood to 3-cm top (B)	B with branches (C)	C plus tree top with branches (D)
	Stand-level data			
1.1 G, Dg by species	4.57	3.35	4.30	4.79
1.2 G, Dg, N by species	5.29	4.23	5.22	5.74
1.3 G, Dg, N, D_{min}, D_{max} by species	5.46	4.07	5.14	5.78
	Plot-level data (5–7 plots per stand)			
2.1 G, Dg by species	1.90	1.36	1.51	1.78
2.2 G, Dg, N by species	1.25	1.09	1.32	1.54
2.3 Individual trees	**0**	**0**	**0**	**0**

that was calculated by using the individual tree data (Table 6). The Forestry Centre field estimates (27.4 m^3/ha) were, on average, 75% higher than estimates based on individual tree data (15.6 m^3/ha). When the simulated estimate was based on the Forestry Centre inventory data (Fig. 1), the average estimate for energy wood removal was only 13.8 m^3/ha. On the other hand, pulpwood removal based on individual tree data was 8.5 m^3/ha higher than the estimate based on the Forestry Centre inventory data.

An examination of the inventory data showed that the trees had a rather large size variation and the plots often had some stems, usually broadleaved species, which were far higher than the rest of the trees. To reduce the effect of non-representative dominant trees, the thinning models were modified to use a basal-area-weighted mean height (H_g) instead of the dominant height to define the prior- and post-thinning basal areas ("Modified thinning model" in Table 6). The use of H_g in the thinning models increased the average energy wood removal to 21.2 m^3/ha, and pulpwood removal to 42.7 m^3/ha. When the top diameter for pulpwood was increased by 1 cm, the energy wood removal estimate further increased to 24.7 m^3/ha.

Table 6. The mean harvest removal of energy stemwood (m^3/ha) and pulpwood (m^3/ha) for different inventory and prediction methods.

Method	Energy stemwood	Pulpwood
Forestry Centre field estimate	27.4	-
Forestry Centre inventory data + simulation	13.8	23.2
Individual trees + simulation	15.6	31.7
Individual trees + modified thinning model	21.2	42.7
Individual trees + modified thinning model + increased top diameter (+1 cm) for pulpwood	24.7	39.2

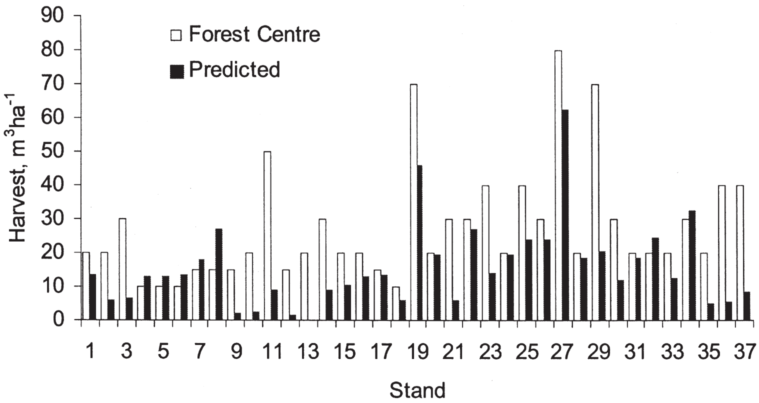

Fig. 1. Field estimate and simulated removal of energy wood harvest (energy wood from stems). The thinning has been simulated for the same year as proposed by the Forestry Centre (2005/2006).

4 Discussion

The results of this study showed that the estimation of different energy wood characteristics can be integrated into the operational compartment inventory and calculation system. The sample plots of this study were not actually thinned, so the "reference" harvesting removal is based on assumptions. However, the results suggest that the need for harvesting operations can be predicted, thinnings can be simulated and harvestable removals can be predicted with the use of inventory data and calculations. When accurate forest inventory was used, the calculated removal estimates were about at the same level as the ocular field estimates. However, when the removal was predicted using the field data of the Forestry Centre, it was much lower than the ocular field estimates and the prediction based on accurate inventory data.

The thinning procedure in un-thinned stands with several tree species is rather complex. The thinning procedure used in simulations has a strong effect on removal estimates. The un-thinned young stands in this study had a large variation in tree size, and the dominant height of a stand or plot was often based on trees that would largely be removed in the first thinning. The present harvesting models are designed for even-aged, one-canopy stands which have been thinned from below, and in which dominant height defines both the prior- and post-thinning basal area (Hyvän metsänhoidon… 2001). These thinning models may lead to overdue harvesting proposals and overly low harvestable removal estimates. The simulations in this study suggest that in un-thinned stands the removal estimates seem to be more realistic if the basal-area-weighted stand mean height (H_g) is used instead of dominant height for the prediction of the harvesting time and the post-thinning basal area.

The most important advantage in using the inventory data and calculation process to predict the harvesting removals, instead of ocular field estimates, is flexibility. As opposed to using field estimates, the removal can be estimated for any timing of the harvesting operation. The calculation approach is also more flexible with respect to changes in logging methods, size and quality requirements for timber assortments, and changes in the selection criteria of harvesting sites and harvesting subsidy requirements.

The results support the conclusion that the use of only *G* and *Dg* by species for the prediction of the diameter distribution gives imprecise and biased estimates for diameter distribution and biomasses of timber assortments in young, un-thinned stands. The share of small-sized stems is underestimated, which leads to an overestimation of pulpwood and an underestimation of energy wood. The biomass predictions can be improved by measuring the number of stems by species. The addition of the minimum and maximum diameters does not improve the estimates of means but it does improve the precision of the biomass estimates. However, when the calculation was done at the stand-level, the addition of more variables decreased rather than improved the precision of the predicted pulpwood and energy wood removals. This result corresponds to earlier studies (Kangas and Maltamo 2000c, 2002), in which it was shown that the measurement of the number of stems improves the description of the stand structure, but not the estimates for the assortment volumes.

The use of plot-level information improves the accuracy and precision of standing biomass prediction. In particular, underestimates in energy wood and overestimates in pulpwood biomasses, obtained with stand level data in heterogeneous stands, are eliminated when plot-level information is used. The results suggest that, in un-thinned young stands, plot by plot inventory and calculation would give more accurate results than those obtained with stand level data. Corresponding results have been obtained lately in the case of other stand characteristics, such as the volumes of traditional timber assortments (e.g. Mehtätalo 2005).

Plot-level calculation gives higher predicted removals than stand-level calculation. This is logical in heterogeneous stands in which the stand density and tree size can vary considerably in different parts of the stand before the thinning operation. The precision of the predicted removals was much better with plot-level data than in the stand-level calculation, if the plot-level calculation based on individual trees was considered as "reference". If only stand-level data are available, additional measurements do not offer any benefits compared to the use of only *G* and *Dg* by species for the prediction of the diameter distribution for harvesting removals.

The use of plot-level data particularly improves the estimates for harvestable removals and the benefit in using plot-level information seems to be higher than the benefit of additional measurements of the number of stems and extreme diameters by species. The number of stems is also quite difficult to measure correctly (Kangas et al. 2004). Additional field measurements also increase inventory costs, although it is worth noting that the additional measurements may only be useful for stands and species whose diameter distribution differs from the distribution of "normal" thinned stands.

Nowadays, the basal area samples are directly recorded onto electronic data collectors. The results suggest, that the use of the sampling point level information in calculations would improve the accuracy of standing biomass and removal estimates. However, the benefits of improved data should be compared to educational and other costs incurred when the inventory and calculation system is changed, along with possible extra costs in the fieldwork.

Further research is needed in order to be able to predict the accuracy of the harvestable removals compared to the real harvesting operations, and to be able to adjust the calculation procedures for the thinning simulations. Attention should also be paid to the self-thinning models used in simulation. In this study, the self-thinning models of Hynynen et al. (2002) were used to predict tree mortality between the inventory year (2003) and the thinning year (2005/2006). When there was self-thinning, mortality was greatest among small trees. An underestimate in the survival of small trees may explain a part of the difference between the Forestry Centre field estimate of energy wood removal and the estimates based on inventory data and calculations. Growth and development of young, mixed stands with great spatial and dimensional variation is more difficult to forecast in comparison to mature stands that have been treated with repeated thinnings. The older the inventory data are, the more uncertain the removal estimates become, even if the original data have been accurate. Thus, it is likely that a feasible time-span for forest inventory data of young, un-thinned energy wood harvesting stands would be less than 10–13 years, which is the common interval between field inventories in private forests.

Biomass models could also benefit from further development. The biomass models of Marklund (1988), which were used in this study, cover different sizes of trees, but the small trees mainly represent undergrowth in older stands. Their use in young stands might cause bias, the magnitude of which is hard to evaluate without additional biomass measurements in the field.

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