Energy 35 (2010) 3717–3721

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Modeling stump biomass of stands using harvester measurements for adaptive energy wood procurement systems

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A R T I C L E I N F O

Article history:
Received 21 January 2010
Received in revised form
5 May 2010
Accepted 8 May 2010
Available online 11 June 2010

Keywords:
Energy wood
Planning system
Forest harvester
Adaptive methods

A B S T R A C T

The value and volumes of industrial stump fuel supply are increasing for energy production. Accurate estimates of aboveground and belowground biomass of trees are important when estimating the potential of stumps as a bioenergy source. In this study two stump biomass equations were adapted and tested using them as calibrated stump biomass models computed as the cumulative sum by a local stand. In addition, variables derived from stem measurements of the forest harvester data were examined to predict stump biomass of a stand by applying regression analysis. The true stump yield (dry weight) was used as the reference data in the study. Both biomass models performed well (adjusted R^2~0.84) and no advance was found in using other stem dimensions as independent variables in the model. The stand-level model can be used in innovative stump biomass prediction tools for increasing efficiency of energy wood procurement planning to stands within a certain area. In practice, wood procurement managers would need to adapt developed system and decide whether the degree of accuracy/precision provided by the models is acceptable in their local stand harvesting conditions.

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1. Introduction

In Finland stump wood became a potential raw material for energy and pulpwood production during the energy crisis of the 1970s, but technical and financial factors limited the usage of stump wood. As growing demand for increasing the use of renewable energy sources, stumps have again become a potential source for bioenergy [3,4,9]. Nowadays, stump lifting is common practice and new cost-efficient methods have been developed and soil cultivation operations are also combined with stump lifting. To date, planning problems of the stump procurement have been addressed using advanced models at the strategic level. However, accurate estimates of stump biomass (both aboveground and belowground wood) of stands are also needed at the operational working level. This is becoming an important factor when quantifying the amount of energy wood of forests.

In Finnish forests stump lifting is carried out only on fertile clear cutting areas where the main tree species is Norway spruce (*Picea abies*). In addition, the suitable areas should fulfill the criteria set by the company for the harvesting, e.g., forest haulage and delivery to mills. Typically, the harvested areas should not be located further than 100 km from the energy production site [5]. Therefore, in order to obtain reliable predictions of the stump biomass for wood procurement management, local models should be applied. Otherwise, there is a risk of systematic prediction error resulting from the application of models that are too general: i.e. the distributions of the tree characteristics deviate from that of the research data of larger areas collected for estimation parameters of the regional models.

Root BEFs (biomass expansion factors) have been developed for estimation of biomass components of regional energy wood resources [6]. For the stump and root UN ECE/FAO [7] reports a BEF of 0.10 for all tree species. Lehtonen et al. [8] have developed BEFs using data from the Finnish National Forest Inventory in 1985–1986 and Marklund's [10] equations. These BEFs aimed to provide more accurate estimates of biomass components for large inventory areas. Lehtonen et al. [8] reported a stump and root BEF of 0.18 for Norway spruce. In theory, the local variation of forests would require site specific calibration of BEF figures using local measurements. In this respect, depending on the local stand characteristics, the regional BEF models are also biased for operational planning at the local level.

In addition to different conversion factors, tree specific biomass regression equations have been developed for estimation of stumps and belowground biomass of stands. The regression based biomass equations can be constructed in such a way that estimates are

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doi:10.1016/j.energy.2010.05.017

Nomenclature

B_{stump}	total yield of stump biomass, kg/stand (dry weight)
h_u	length of the top part of a stem, mm
d_{stump}	diameter at stump height, mm
$d_{1.3}$	diameter at breast height, mm
h_k	measured length of the stem, mm
d_p	top diameter, under bark, cm
ln	natural logarithm
n	number of selected trees in stand
ns	number of stands
Y_i	observed biomass values of stand i
$\hat{Y}_i$	predicted biomass values of stand i
e_i	random effect in stand i

calculated directly using local measurements. However, the sampling of roots is very laborious. Several studies have been carried out on tree biomass in the Nordic countries, but only a few of them have targeted at stump biomass. Stump biomass has been studied, e.g. by Hakkila [11–13], Kuitto [14], Marklund [10,15], Petersson and Ståhl [1], and Repola et al. [2]. Some studies have indicated that the stump biomass equations tend to underestimate the stand-level biomass of stumps [1,14,16]. Obviously, the number of measured stumps has been rather modest, e.g. 31 spruces from the southern Finland in the study of Repola et al. [2]. In Sweden, however, Marklund [10] studied 311 spruces, but Petersson and Ståhl [1] noticed that Marklund's equations also tend to underestimate the total belowground biomass, and therefore Petersson and Ståhl [1] designed new equations using Marklund's [10] calibrated data with additional inventory of 31 spruces from 12 stands (six stands from the northern part of the Sweden).

One explanation for the underestimation of stump biomass is that the final harvesting is carried out in older stands where trees are bigger, and thus the cutting heights may be above the theoretical cutting point [1,14,17–19]. Also the site conditions and snow cover may affect the cutting height. Therefore, the aboveground stump biomass is greater, and the stump diameters measured by a harvester are smaller than the equations expect. The existing equations for stump biomass do not take site fertility into account, and this may have an affect on belowground biomass [16].

The purpose of this study was to evaluate the usability of the latest biomass equations of Petersson and Ståhl [1] and Repola et al. [2] at the operational working level, and to construct a locally calibrated biomass model to predict stump biomass yield of a stand for energy production. The research problem is solved using forest harvester data as the source of information. The major focus was to apply stem related information recorded by harvesters and the potential of diameters of absolute heights and relative heights (relative to total height) as independent variables in the applicable biomass model. True dry weight of lifted stumps by same stands was used as the reference data.

2. Materials and methods

The data were collected in Central Finland from 38 logging sites where the share of spruce was more than 50% of the total removal and the stumps were lifted. The clear cuttings were conducted using forest harvesters. The areas of the clear cutting sites varied from 0.5 to 10.8 ha (mean 2.8 ha). The total removal of timber by stand varied from 217.1 m^3 to 2173.2 m^3 (mean 652.0 m^3).

The stands were felled and only selected spruce stumps were lifted. The productivity of stump lifting increases with increasing stump diameter [20], and therefore stumps with a diameter of less than 15 cm were not lifted. Moreover, due to watershed protection reasons, 25% of the total amount of the smallest tree stumps was left in the forest. Then stumps were piled up, shaken and moved to the heap where they stood over the summer. The material was finally transported into storage where it dried for a year. The stumps from each stand were stored separately, so that the materials from different stands could be weighed separately at the energy production mills.

The stump material was delivered by trucks to the energy mill storage between January 2006 and October 2007. Before delivery to the mill the stump material was weighed by delivery lots. The measurements and calculations were made by the company's laboratory workers. Thus the dry weight was determined by delivery lots at the energy plant in accordance with the definitions of the measurement agreement of energy wood of Finland [21]. The amount of external material (i.e. sand and stones) could not be defined by a delivery lot; this was taken into account with the help of a mean factor based on regular inspections made at the energy mill.

The methodological focus of this work has been to develop algorithms to synthesize data for stand level to enhance stump biomass models. The most promising method was a data-dependent biomass model calibration method. This algorithm adaptively estimates the potential of stumps as a bioenergy source and fills the parameters of calibrated biomass model using a linear least-squares estimator. Stand-level parameters of the model are filled in to predict stump biomass of a stand with a stump biomass equation, and this performance is enhanced with the method. In respect to stump weighing, the adaptive method is virtually implemented using this algorithm in real-time hardware for inclusion in a future ERP (Enterprise Resource Planning) system build.

The harvester data consisted of 55 490 stems – spruces (78.8%), pines (7.1%) and birches (14.1%). The measurements of each stem were stored in files which were transmitted daily into the ERP systems via a mobile network connection. The harvester's sensor recorded stem diameters along a stem at 10 cm intervals, starting from the lowest cutting point and ending at the last cutting height of the stem. In this study, the stem data were combined into one file, consisting of information about tree species, stem diameters (in mm) and height (in cm). In addition, we calculated diameter at breast height ($d_{1.3}$) and the height of the uppermost measurement point.

In order to derive the relative diameters, the total tree heights need to be estimated. Hence we computed an estimate for the length of the top part of the stem for each tree using the equation published by Varjo [22]. The applied Eq. (1) for spruce was of the form.

$$h_u = e^{F(x)},$$

$$\begin{aligned} F(\text{spruce}) = {} & 0.463881 + 0.006171\ h_k + 0.034721\ d_p \\ & + 0.120016*\ln(h_k) - 0.608647\ \ln(d_{1.3}) \\ & + 1.036332\ \ln(d_p) + 0.014675 \end{aligned} \tag{1}$$

where h_u = length of the top part of a stem, m; F(spruce) = length of the top part of spruce stem, m; h_k = measured length of the stem, m; $d_{1.3}$ = diameter at breast height, mm; d_p = top diameter, under bark, cm; ln = natural logarithm.

The average bark thickness at the top height of spruces was assumed to be 2.5 mm [21]. The total tree height was computed as the sum of the top height and the estimate of the length of the top part of the stem.

The trees were classified into two groups: 1) the trees whose stumps were probably collected, and 2) the trees whose stumps were probably left in the forest. The trees with collected stumps were identified from the data following the company selection criteria. The rule to select stumps was following:

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