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Combining GIS and Forest Modelling in Estimating Regional Supply of Harvest Residues in Norway

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New and ambitious targets for renewable energy production put attention to increased supply of biomass. Harvest residues are only to a limited extent demanded by the traditional forest industries and represent an unutilized resource for increased production of renewable energy in Norway. The overall objective of this paper is to study how GIS and forest modelling can be combined to improve estimates of the supply of harvest residues, taking different environmental and economic constraints into consideration. The analyses are based on a case study of a forest area of more than 40 000 ha in Southern Norway divided into about 500 private forest properties. The study was carried out by computations of timber harvest using the forestry scenario model SGIS based on extensive forest inventory data at stand level. In the studied area energy utilization of harvest residues is not profitable below an energy price of about €3.2/GJ (NOK 0.10 /kWh) when the distance from roadside to industry is 20 km. Above this level supply increases rapidly over a rather narrow price range and is nearly inelastic above €4.1/GJ (NOK 0.12/kWh). We did not find significant negative shifts in the residues supply caused by changes in location of roundwood harvest over time. Exclusion of collection from stands with a site index (H_{40}) below 14 reduced the potential supply of residues by 16–27%. The optimisation method combined selection of exogenous variables in order to map observed harvesting level and is probably the best approach to map future harvest.

Keywords bioenergy, SGIS, supply functions, forestry

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1 Introduction

New and ambitious targets for renewable energy production put attention to increased biomass supply. Growing stocks in European forests have been increasing over the last decades, mainly because of an increasing discrepancy between fellings and increments (UN-ECE/FAO 2000, Nabuurs et al. 2003). However mobilising complementary or increased fellings would in the short run demand that the forest owners get at least the market price for pulpwood in order to supply roundwood for energy use. Harvest residues – i.e. branches, tops and stems left over from harvest – are at least in the short run the most feasible part of the forest resources for energy production. Karjalainen et al. (2004) estimated the available potential harvest residues in EU-25 to be around 63 mill m^3 with an energy content of around 125 TWh/450 PJ.

In addition to overall renewable energy and energy saving targets, the Norwegian government has proposed a national target of 14 TWh/50 PJ increased use of bioenergy by year 2020, a doubling of the current level of 7.3% for the stationary energy consumption (Statistics Norway 2010a). Forest resources represent the main biomass potential, due to limited availability for agricultural land, high utilisation of waste and modest utilisation of relatively vast forest resources. Internal use of harvest residues in the forest industries (4.8 TWh/17.4 PJ in 2007) and firewood consumption in private households (6.9 TWh/24.9 PJ), represent the major current use. The use of wood chips for energy production is low, and 0.6 TWh/2.2 PJ used for district heating represents the major use (Statistics Norway 2010a). Studies of Norwegian market conditions have found bioenergy based on forest fuels to be moderately competitive in some market segments and only minor changes in market conditions could substantially increase the potential of bioenergy against electricity and oil (Bolkesjø et al. 2006, Trømborg et al. 2007).

Harvest residues are only to a limited extent demanded by the traditional forest industries in Norway, and it represents an unutilized resource for increased production of renewable energy. The potential for residues utilization is closely linked with timber harvest – it may be said to be a by-product of timber harvest. Thus, the volume and location of timber harvest in a given area are the decisive factors for the economic availability of harvest residues. The costs of collection, transport, chipping and storage and the demand for the residues decide the actual harvest of residuals, within the potential given by the actual roundwood harvest. In addition to a price that covers the direct costs involved in the production process, the forest owner might also demand a “stumpage fee” to compensate for perceived non-market costs of deliveries. Bohlin and Roos (2002) found that concern for loss of soil productivity is the major reason why some forest owners did not want to deliver harvest residues.

The overall objective of this paper is to study how GIS and forest modelling can be combined to improve estimates of the supply of harvest residues from non-industrial forest owners at regional level in Norway. First, we model the location of future roundwood harvest by using a forest model and historical harvesting level. Second, we analyse the supply of residues and how this supply is affected by environmental restrictions. Third, we study how the supply shifts over time as a consequence of changed location of timber harvest, and finally, we analyse how the supply of residues is affected by fuel prices and distances from forest roads to energy plants. The analyses are based on a case study of a forest area of more than 40 000 ha in Southern Norway divided into about 500 private forest properties. The study was carried out by estimating the roundwood harvest using the forest scenario model SGIS that computes the harvesting level based on economic optimisation and extensive forest inventory data at stand level. The model determines the distribution of roundwood harvests both in space and time based on given assumptions regarding timber prices, harvesting costs, interest rate and management strategies and these results are in turn used to estimate the supply of harvest residues. Methodology and results are presented and discussed in the following sections.

Table 1 Standing stock by relative age class (30 year classes) and site index (H_{40}).

	Relative age classes							
Site index	I	II	III	IV	V	Sum	%	% Norway
6	8	143	540	5 290	24 593	30 574	0.8	4.7
8	932	4 499	19 468	127 080	271 075	423 054	10.6	17.1
11	1 491	5 845	135 262	240 501	394 656	777 755	19.6	21.7
14	2 072	7 032	362 840	398 652	427 578	1 198 174	30.1	23.5
17	1 250	4 840	253 689	479 659	245 388	984 826	24.8	18.0
20	418	2 063	102 978	204 414	71 973	381 846	9.6	9.9
23	129	653	44 536	96 768	37 069	179 155	4.5	5.3
Sum	6 300	25 075	919 313	1 552 364	1 472 332	3 975 384	100.0	100.0
%	0.2	0.6	23.1	39.0	37.0	100.0		
% Norway	0.8	5.0	18.5	27.4	48.3	100		

2 Material and Methods

2.1 Study Area

Data for the study was collected from the area of a local forest owner's association, namely Norderhov (60°10′N 10°15′E, 100–700 m a.s.l), in southeast Norway. The forest area analysed in this study covers 42 150 ha, owned by 474 forest owners and dived into 974 parcels and 23 890 stands of productive forests. Annual harvest for industrial use has been increasing from 94 000 m^3 in year 2005 to 114 000 m^3 in 2008.

The forest inventory in Norderhov was carried out in the period 1989 to 2002. In the inventory, common forest parameters were registered and the area divided into homogeneous forest stands where stand attributes such as tree species, age, site quality, vegetation-type, mean stand height, basal area, number of trees and volume were registered.

The forest is covered by equal parts of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) both with regards to area and standing stock, with only a small proportion of broadleaves, mainly birch (*Betula pendula* Roth, *B. Pubescens* Ehrh.). There is a relatively even distribution of relative age classes compared to the typical situation in Norway. About 10% of the forest area had high site quality ($H_{40} > 18.5$), 50% had medium site quality ($H_{40} = 12.5–18.5$) and 40% had low site quality ($H_{40} < 12.5$). Site quality is presented according to the H_{40}-system, i.e. dominant height in meters at breast height age 40 years (Tveite 1977, Braastad 1980). The distribution of standing stock is shown in Table 1.

2.2 Modelling of Roundwood Harvest

The future roundwood harvest is computed with the SGIS forestry scenario model (Næsset et al. 1997). SGIS is a Visual Basic application for ArcView (ESRI Inc.), giving a windows user interface for the stand simulator GAYA (Hoen and Eid 1990) and the optimisation tool J (Lappi 1992, Lappi 2003). The forest stand map with associated stand characteristics is handled in the ArcView environment, and each treatment unit is thus an identifiable polygon with respect to stand characteristics. Standard GIS tools may then be applied when producing input to the simulation/optimisation model and presenting results in a GIS-format. The location of forest management activities including timber harvest is geographically identifiable at the stand level, which offers an opportunity to model the supply of harvest residues.

The model applies standard methodology (Johnson and Scheurman 1977, Garcia 1990, Siitonen 1993) for simulating treatment schedules for the individual management unit (Hoen and Eid 1990, Hoen and Gobakken 1997) and solves the management problem at forest level by linear programming (Lappi 1992, Lappi 2003). Thus, numerous treatment schedules with different thinning programmes, rotation periods, etc., are simulated for each treatment unit (stand) (Hoen and Eid 1990, Hoen and Gobakken 1997). Projections of forest development, and the corresponding economic calculations are provided by using a stand growth model with the basal area mean diameter, mean height weighted by basal area and number of stems per ha as the basic entities. Projections are driven by diameter (increment functions: Blingsmo 1984, height development models: Tveite 1977, Braastad 1977 and a mortality model: Braastad 1982).

The planning horizon applied is 50 years, divided into 10 periods of equal length, with treatments taking place in the middle of each period *. The simulations produce all feasible combinations of pre-defined treatment options, where treatment options comprise various kinds of pre-commercial thinning, thinning, regeneration cutting, and final felling, in addition to "no treatment" which involves undisturbed growth. Each treatment option has a set of feasibility criteria based on stand characteristics. Final felling is always followed by regeneration of a new stand, by either "intensive" regeneration options involving planting or "extensive" options involving natural regeneration. The choice of regeneration option is based on economic profitability. Regeneration includes clearcutting with retention of seed trees in pine-dominated stands, and shelterwood cutting or regeneration established by bordercuttings or small clearcuts in stands dominated by spruce. Each stand is assigned to one of four mutually exclusive classes of regeneration conditions according to vegetation type, and the attributes of the new forest, such as length of the regeneration period, vary between classes. Final felling includes clear-cutting and removal of seed and shelter trees. The various silvicultural options used in the current study were mainly defined as described by Eid et al. (2001). Environmental considerations at stand level and protection of key habitats are incorporated in the model through a reduction of the net harvesting volume by 5%.

Price and cost levels were chosen to reflect a realistic expectation of future prices, and correspond to the levels experienced in the area (Trømborg and Bergseng 2003). Timber values delivered road side are estimated from gross price functions (Blingsmo and Veidahl 1992), and harvest costs from functions based on a tariff agreed upon by employers' and employees' organisations (Overenskomst mellom ... 1996). The levels of these are calibrated according to timber qualities and operating conditions and local expertise to correspond to the general level in the area.

The net present value (NPV), including the land expectation value of the ending inventory, is calculated for all treatment schedules. The ending inventory values are based on predetermined treatment schedules given for each dominating species and varying with site index. A 3% p.a. rate of return is applied in order to reflect the observed harvesting level in the area. As no relative changes for prices and costs over time are assumed, the rate of return is constant and in real terms.

The forest management problem is specified as a linear programming (LP) problem and solved in the LP-system J (Lappi 2003). All optimisations assume maximisation of NPV for each property. The required non-decreasing harvest path at the property level is the only "real" constraint except for standard constraints on weights and non-negativity. The region level result is thus the sum of results for individual properties, each maximizing their profitability under the constraint of non-declining harvest over time.

We are hence not modelling timber supply, but use the model to predict the future roundwood harvest in the region based on constant timber prices and other assumptions that mimic the observed roundwood harvest in the region.

2.3 Availability and Costs of Harvest Residues

2.3.1 The Estimation of Harvest Residues

This section outlines how the supply functions for harvest residues for energy purposes are estimated. The location of harvest, the volume harvested and stand characteristics in each period is determined by SGIS, and these results together

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* In the estimation of the supply functions we have used 10 years periods instead of 5 years. This is done in order to ease the presentation of the results. As will be shown, there are only small differences between the periods.

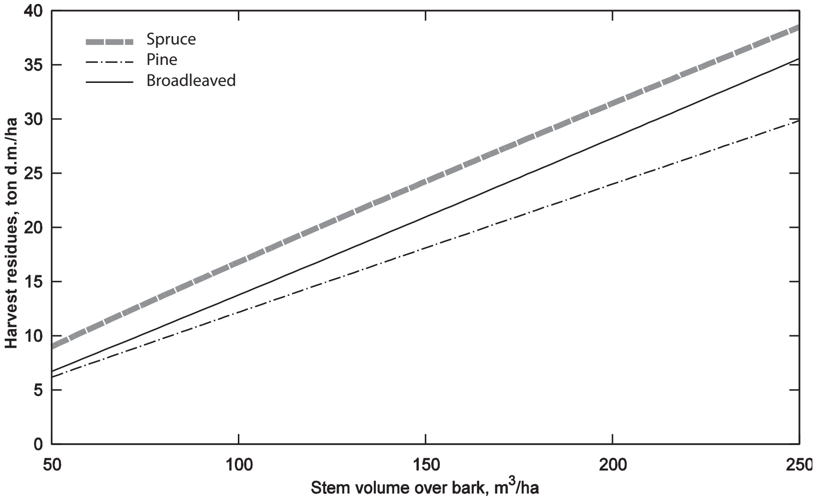

Fig. 1. Harvest residues as a function of standing volume over bark. Functions are based Lehtonen et al. (2004).

with estimated cost of forwarding residues to roadside are used to calculate the supply functions. The supply analyses thus focus on the costs delivered roadside. As will be shown below, these costs vary substantial between stands – due to differences in hauling distance and other stand characteristics. Other studies have focused on the costs of transportation from landing to industry (e.g. Nord-Larsen and Talbot 2004, Panichelli and Gnansounou 2008) assuming in-forest costs more or less constant. The cost of road transport is of course important, but given the large variability of terrain transport costs, it is also important to model this properly. The importance of capturing this variability, essentially the level and shape of the supply functions, is unknown a priori. Estimating the variability of in-forest cost can be said to be the major contribution of this paper.

Harvest residues are only to a very small degree utilized for energy purposes in Norway meaning that data on real costs are lacking. We have therefore used an engineering approach when estimating these costs, as described in more detail below.

We have used biomass functions from Lehtonen et al. (2004) when estimating the quantity of stand level harvest residues. Functions are estimated for Scotch pine, Norway spruce and broadleaved species and for different parts of the trees (tree compartments), e.g. roots, branches, stem, bark and foliage, and have the following functional form:

$$W_i(V) = a_i V^{b_i} \tag{1}$$

where $W_i(V)$ is total biomass (ton d.m./ha) for tree compartment i, V is stem volume (m^3/ha), and a_i and b_i are parameters. When estimating these functions Lehtonen et al. (2004) have used stand data from Finish NFI and biomass functions from Marklund (1988). In our estimations we have assumed that the total usable amount of harvest residues equals 10% of the stem biomass and bark – in order to account for tops and other stem parts not usable as sawn or pulp wood – plus biomass in living and dead branches. Foliage is not included since we assume that these will drop off during forwarding and storing/drying at landing. However, foliage biomass is included when estimating forwarding costs, as it is assumed that the residues are forwarded immediately after roundwood harvest. This means that our estimate of total harvest residues available for energy purposes is calculated as:

$$\mathrm{BM}_{\mathrm{residues}} = \sum_{i=1}^{4} \tau_i W_i(V) = \sum_{i=1}^{4} \tau_i a_i V^{b_i} \tag{2}$$

where $\mathrm{BM}_{\mathrm{residues}}$ is biomass in residues (ton d.m./ha), i is the different tree part included (stem, bark, living and dead branches), τ_i is the assumed fraction utilized (0.1 for stem and bark, 1 for living and dead branches), and the rest of the terms as previously defined. The resulting functions are plotted in Fig. 1.

The residue calculations are based on total standing volume per ha before harvest, and the quantity of harvested residues is assumed to be proportional to the fraction of roundwood harvested. This is done since the functions estimated by Lehtonen et al. (2004) are functions for whole stands.

The functions depicted above represent the upper bound for the quantity of harvest residues. However, it is neither physical possible nor profitable to harvest all the residues. In a field trial Nurmi (2007) reports recovery rates between 60 and 80%, depending on the single-grip harvester work methods studied. In addition to harvesting method, the optimal recovery rate will also depend on site characteristics like stand age, main tree species, terrain, etc. The lack of data concerning recovery rates prevents us from including these factors in the analysis. In the supply analyses below, we have assumed a fixed recovery rate of 60%.

Three different scenarios (Base, All, and Environmental) regarding what types of forest stands to include are studied. In the **Base** scenario we have assumed residues collection in all harvested stands except thinned stands. Harvesting of residues in thinned stands may be a viable option, but given the current low state of residues utilization in Norway, we consider this to be of less importance. We have however included thinnings in the **All** scenario, which otherwise is the same as Base.

The removal of residues means that a larger amount of the nutrients stored in trees is removed from the forest. Soil fertility was documented as the main disincentive to collect harvest residues in Sweden (Bohlin and Roos 2002) and is therefore a key area of research. As a large part of the nutrients in trees are located in the needles and branches, removing these will reduce nutrient supply to the soil. In the long run this might both increase the risk for nutrient imbalance and reduced forest production (Raulund-Rasmussen et al. 2008). There seems to be ambiguities in the literature regarding this (see e.g. Wall 2008, Åström et al. 2005). In addition, other environmental aspects like species richness may be affected by the removal of residues (Åström et al. 2005).

There are currently no guidelines that restrict the collection of harvest residues in Norway. In order to illustrate how such concerns may affect the biomass supply, we have run a separate scenario, **Environmental**. This scenario is the same as Base except that we have excluded residues collection in stands with a site index (H_{40}) less than 14. We emphasize that this limit is set rather arbitrary and as knowledge about these effects improves, other criteria than the site index may turn out to be more appropriate. It should also be mentioned that some environmental concerns are taken into account in all scenario through the 5% reduction in roundwood harvest, as mentioned above.

2.3.2 *The Estimation of Harvest Costs for Residues*

Lacking empirical data on operation costs, we have used an engineering approach when estimating the harvest costs for the harvest residues, based on productivity data in the literature. The costs are estimated in monetary units (NOK)* per ton dry matter harvest residues excluding foliage.

The transportation of the harvest residues from the stand to the landing may be split into four operations: loading of the residues on to the forwarder, terrain transport to the road landing, unloading and driving empty back to the stand. The terrain transport cost of driving (average of loaded and empty) expressed in NOK/ton d.m. (excluding foliage) is calculated as:

$$\mathrm{C}_{\text{transport}} = w\frac{2fd}{v}\frac{1}{\gamma ls}\alpha \tag{3}$$

where w is the operating cost (NOK/E_0–h), fd is the average forwarding distance (km), i.e. distance from the stand to landing, v is driving speed (km/h), ls is load size (ton d.m. including foli-

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* The average exchange rate between Norwegian kroner (NOK) and Euro (€) in the period from February to mid June 2009, was NOK 8.8/€. This exchange rate was used whenever results are presented in Euros.

age), γ is a factor correcting for foliage which is assumed to drop off at landing and thus will not be utilized for energy purposes and α is a factor to take into account local conditions. The latter is estimated at stand level and reflects deviations from the general cost level (see the section on modelling of timber harvest above). We have assumed a constant operating cost of NOK 500/E_0–h. The distance from the stand to landing is estimated in SGIS. γ (the ratio of biomass excluding and including foliage) is estimated using the biomass functions from Lehtonen et al. (2004). Load size and driving speed is to a large degree dependent on the forwarder characteristics. Regarding the former, Laitila et al. (2007) reports an average load size of about 2.6 ton d.m. assuming 50% moisture content in whole tree forwarding in pre-commercial thinnings, while Nurmi (2007) reports an average of about 4.4 ton d.m. when forwarding harvest residues using a large forwarder. In our estimations we have used a load size of 3.5 ton d.m. The average driving speed is assumed to be 2.5 km/h.

Loading productivity (ton/hour) depends mainly on forwarder characteristics (e.g. grapple size), harvest residue density (ton/100 m skip road) and harvester work technique (manual felling, piling or not of residues, etc). Regarding the latter, Nurmi (2007) finds a positive (10–20%) and significant effect of piling residues. We assume that felling and delimbing is done using a harvester in the conventional manner. The effect of residue density is documented in the literature for whole tree forwarding (Asikainen et al. 2001, Laitila et al. 2007) and for bundling of residues (Kärhä and Vartiamäki 2006), but data on loading loose residues is lacking. We have therefore used data from Laitila et al. (2007) to estimate the relative effect on loading productivity and data from Nurmi (2007) on (absolute) productivity. This resulted in the following calculation of loading cost (NOK/ton d.m.):

$$\mathrm{C}_{\mathrm{loading}} = \frac{w}{\gamma pl_0 \left(\dfrac{d}{d_0}\right)^{\lambda}} \beta \tag{4}$$

where pl_0 (ton d.m./E_0–h) is the base loading productivity given base harvest residue density d_0 (ton d.m./ha), d (ton d.m./ha) is harvest residue density, λ (without unit) is a parameter, β is a factor taking into account local conditions (ref. α above) and the other terms are as defined above. pl_0 (=10.1) and d_0 (=52) are calculated from Nurmi (2007), while λ (=0.52) is estimated based on Laitila et al. (2007). d is estimated for each stand according to the procedure described above.

Unloading at landing constitutes roughly 20% of the total hauling time consumption (Laitila et al. 2005, Nurmi 2007, Laitila et al. 2007). The productivity (ton d.m./E_0–h) is mainly linked to conditions at the landing and machinery characteristics. For simplicity we have assumed this productivity fixed, and based our estimate on Nurmi (2007). The cost of unloading (NOK/ton d.m.) is estimated by:

$$C_{unloading} = \frac{w}{\gamma pu} \tag{5}$$

where pu is unloading productivity (=24 ton d.m./E_0–h) and other terms as previously defined.

The total hauling cost is the sum of the three expressions above, i.e.:

$$\mathrm{C}_{\mathrm{hauling}} = \mathrm{C}_{\mathrm{transport}} + \mathrm{C}_{\mathrm{loading}} + \mathrm{C}_{\mathrm{unloading}} = \frac{w}{\gamma}\left(\frac{2fd\alpha}{vls} + \frac{\beta}{pl_0\left(\dfrac{d}{d_0}\right)^{\lambda}} + \frac{1}{pu} \right) \tag{6}$$

2.3.3 Estimation of the Harvest Residues Supply Functions

A supply function basically gives the amount supplied at different prices. For a profit maximizing firm in a competitive market, the firm's short run supply function is the upward sloping part of the marginal costs curve that lies above the average variable cost curve. The industry total supply function is simply the sum of the individual firm supply functions (Varian 1992).

The aim of our economic analysis is to estimate the supply of harvest residues for bioenergy given the quantity of roundwood harvest and different residue prices. Technically this is done in the following way. First, we estimate the hauling costs and harvested residues for each harvested stand.

The latter is estimated by:

$$\mathrm{BM}_{\text{harvested residues}} = ar\,\kappa\,\mathrm{BM}_{\text{residues}} \tag{7}$$

where ar is stand area (ha), κ is the recovery rate, assumed to be 0.6, based on Nurmi (2007). Next, we sort the stands according to the quantity of harvest residues they provide in ascending order of hauling costs, thus obtaining the accumulated quantities of harvest residues harvested as a function of harvest costs. This procedure is similar to Joutz (1992). Estimations are done separately for each 10-years period and scenario. Finally, we regress accumulated harvested biomass of harvest residues – expressed as yearly harvest – on residues harvest costs to obtain the (period and scenario specific) basis supply functions. These functions can be viewed as industry marginal cost curves. Assuming profit maximizing forest owners, these functions give the amount of harvest residues (in ton d.m.) that is profitable to "harvest" given the road side price of harvest residues (in NOK/ton d.m.).

These functions may easily be converted to energy terms – by assuming a constant energy density of the dry matter – or be modified to include other costs in the supply chain. Details are given below.

Since the results showed a sigmoid like shape, we have used a logistic functional form when estimating the supply curves (ton d.m./year) as a function of hauling cost:

$$\mathrm{S}(\mathrm{C}_{\text{hauling}}) = m + \frac{n}{1 + o\,e^{p\,\mathrm{C}_{\text{hauling}}}} \tag{8}$$

where m, n, o and p are parameters to be estimated, e is the base of the natural logarithm and $\mathrm{C}_{\text{hauling}}$ is hauling cost. Details about the supply function estimations are given in the result section.

We have so far expressed supply in terms of ton d.m., but it is rather straight forward to convert the supply functions to energy terms. The (upper) heating value of biomass depends on the composition (C, N, O, H, S and ash content) of the biomass, and this may be different for different tree species and different parts of the tree. However, this variation is far less than the uncertainties in the rest of the analyses, and we will therefore assume a fixed lower heating value equal to 5320 kWh/ton d.m. (19.2 GJ/ton d.m.). The residues are assumed to be stored and dried at landing, and we assume that the moisture content is 30% (of green weight) when processed and shipped to the end user. This means that the effective heating value delivered end user, i.e. exclusive of energy use efficiency, is 5029 kWh/ton d.m. (18.1 GJ/ton d.m.). By multiplying supply by this factor we get the supply in kWh (GJ).

3 Results

3.1 Roundwood Harvest

Projected net timber harvest is shown in Fig. 2, assuming non-decreasing yield and 3% p.a. real rate of return. The share of commercial thinning varies between 12% and 18%. The projected harvest levels are adjusted for environmental considerations, e.g. protection of key habitats. The estimated harvesting levels can be compared to the observed level for the same area. This is shown in Table 2 and illustrates that the SGIS with base-line assumptions to a large extent gives a realistic scenario for the harvesting level in the area, given that timber prices remain relatively stable.

3.2 Supply of Harvest Residues

The supply functions (Eq. 8) were estimated using PROC MODEL in SAS version 8.2 (SAS Institute 1999). In addition to estimating period specific functions we also estimated a function for all periods using the data generated for each period. Thus, these functions represent the average supply function for the whole planning period. Parameter estimates, goodness of fit indicators (root mean square error and adjusted R^2), and the number of "observations" are shown in Table 3. All parameters are significant at 1% level.

The table shows that the estimated functions fit the data very well. This is also shown in Fig. 3 where both selected data points (in order to make the plot readable) and estimated functions for the Base scenario are plotted. The fit is poorest, but still good, for the average functions (period equal

Table 2. Observed industrial harvest 2004 to 2008 in Norderhov in m^3. Firewood not included. Source: County Governor in Buskerud.

Specie	Assortment	2004	2005	2006	2007	2008
Pine	Pulpwood	17 605	27 481	17 373	15 923	27 570
	Sawlogs	20 123	35 799	21 696	23 430	25 607
	Other	9	55	49	32	33
Total pine		37 736	63 335	39 118	39 385	53 209
Spruce	Pulpwood	27 188	48 664	31 734	35 155	38 803
	Sawlogs	21 292	38 217	24 192	28 434	28 374
	Other	907	1 345	906	964	1 325
Totalt spruce		49 386	88 225	56 831	64 552	68 502
Non-coniferous	Pulpwood	627	1 218	956	1 300	1 411
	Sawlogs	10	10	22		41
Total non-coniferous		637	1 228	978	1 300	1 452
Total		87 759	152 788	96 927	105 237	123 163

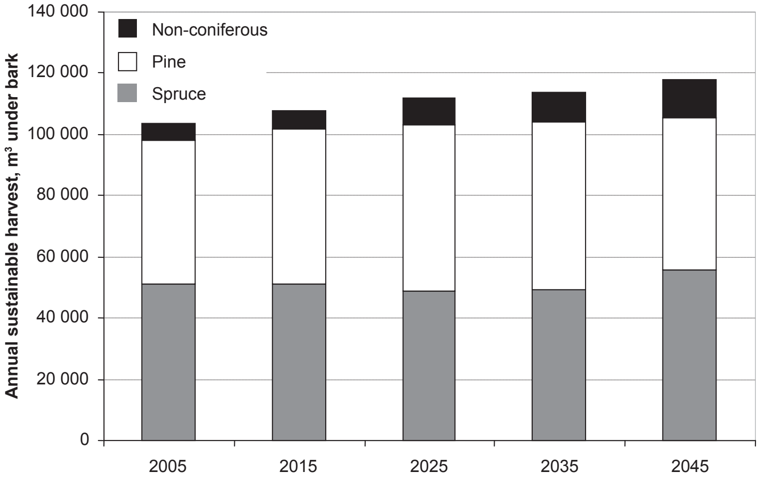

Fig. 2. Projected annual timber harvest in Norderhov.

to “Mean” in the table). This is clear from the figure, since these functions are estimated on all observations. The figure also reveals that supply is increasing over time for the Base scenario. This also holds for the other two scenarios. This is in line with the results presented in Fig. 2 where the timber harvest is increasing over time. Harvest residues are almost linear in harvested volume (Fig. 1) leading to more biomass in residues as harvest increases. In addition, there are no large changes in factors affecting hauling costs. The differences in hauling costs increase as the residues level increases, and below about 10 000 ton d.m. the differences are rather small.

The increase in the maximum potential over time, i.e. maximum amount of residues available, may also be inferred from Table 3. Since the parameter p is larger than zero in all cases, the parameter m is the upper asymptote of the estimated functions. As can be seen from the table, m is increasing over time.

The maximum amount of residues in Base is lower than in All since thinning are excluded in Base. Using the parameter m in Table 3, we see

Table 3. Parameter estimates for harvest residues supply functions (standard errors in parenthesis), goodness of fit indicators and number of observations. All parameters are significantly different from zero at 1% level.

Scenario and period	Parameter estimates				RMSE	R^2-adjusted	N
	m	n	o	p			
Base							
1	10772 (5.2)	–13750 (33.5)	0.0075 (0.00013)	0.0465 (0.00012)	122	0.999	4678
2	11075 (3.9)	–15175 (44.6)	0.0214 (0.00034)	0.0389 (0.00011)	130	0.999	5000
3	11336 (3.1)	–15921 (47.3)	0.0340 (0.00049)	0.0372 (0.00009)	130	0.999	5649
4	11592 (3.0)	–15396 (38.8)	0.0230 (0.00032)	0.0410 (0.00010)	130	0.999	5667
5	12273 (4.2)	–18724 (85.9)	0.0468 (0.00089)	0.0369 (0.00012)	195	0.997	6279
"Mean"	11603 (8.8)	–15326 (101.0)	0.0260 (0.00092)	0.0378 (0.00024)	748	0.960	27273
All							
1	11422 (5.7)	–15741 (49.8)	0.0172 (0.00030)	0.0395 (0.00012)	142	0.998	5456
2	11824 (5.3)	–19376 (100.6)	0.0673 (0.00127)	0.0303 (0.00011)	171	0.998	5921
3	12010 (3.9)	–20314 (101.9)	0.0945 (0.00157)	0.0294 (0.00009)	164	0.998	6602
4	12353 (3.9)	–19703 (90.7)	0.0726 (0.00121)	0.0318 (0.00010)	176	0.998	6913
5	13244 (4.5)	–26564 (196.2)	0.1636 (0.00314)	0.0274 (0.00009)	211	0.997	7698
"Mean"	12414 (8.8)	–19141 (159.4)	0.0713 (0.00222)	0.0299 (0.00018)	750	0.963	32590
Environmental							
1	8180 (5.4)	–9489 (19.6)	0.0009 (0.00002)	0.0677 (0.00019)	84	0.999	3099
2	8119 (3.0)	–9731 (19.3)	0.0027 (0.00005)	0.0603 (0.00015)	79	0.999	3213
3	8712 (2.8)	–10720 (22.1)	0.0060 (0.00010)	0.0560 (0.00013)	87	0.999	3601
4	9720 (3.9)	–12500 (34.5)	0.0114 (0.00021)	0.0501 (0.00014)	118	0.999	3791
5	9600 (4.4)	–12005 (39.7)	0.0050 (0.00013)	0.0606 (0.00023)	166	0.997	4134
"Mean"	9142 (12.9)	–11163 (95.8)	0.0084 (0.00053)	0.0505 (0.00049)	814	0.925	17838

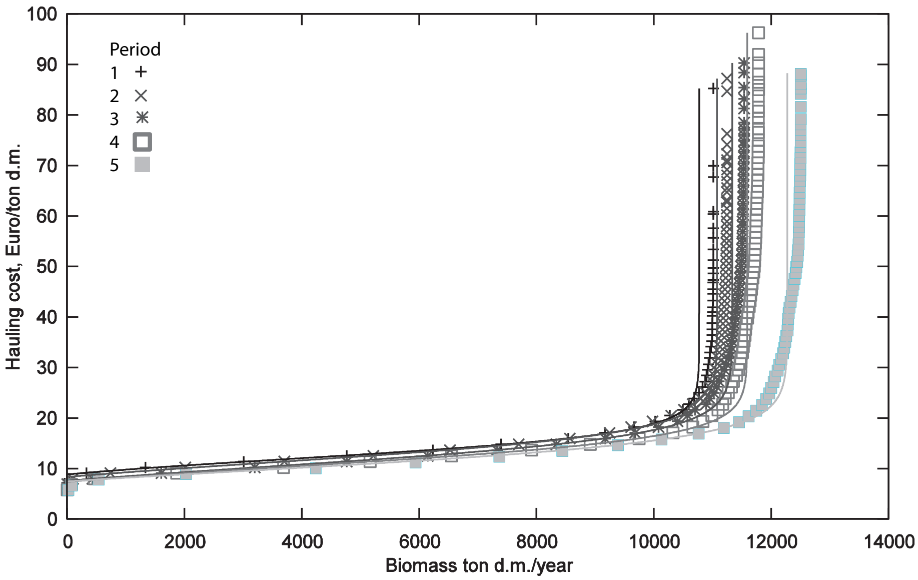

Fig. 3. Estimated biomass supply as a function of hauling cost (from stand to landing) for the Base scenario. Markers indicate "observations" (estimated as described in the text), while lines are estimated regression lines. In order to make the figure more readable, a large portion of the "observations" are deleted.

Table 4. Comparison of maximum residue potential (upper asymptote) for the different scenarios. Calculations are based on figures in Table 3.

Period	Environmental/Base	Environmental/All	Base/All
1	76%	72%	94%
2	73%	69%	94%
3	77%	73%	94%
4	84%	79%	94%
5	78%	72%	93%
"Mean"	79%	74%	94%

Table 5. Additional costs of producing energy chips from harvest residues.

	€/GJ	NOK/kWh	NOK/lm^3
Administration and compensation to forest owner	0.41	0.013	10
Chipping and storage	1.77	0.056	45
Road transport 20 km	0.63	0.020	20
Total additional costs	1.81	0.089	75

a reduction in the asymptote of 6–7% (see also Table 4). The supply in Base and All are close to equal up to a hauling cost somewhere in the range of €17–23/ton d.m. (NOK 150–200/ton d.m.) or about €3.8/GJ. Fig. 4 shows this for the mean, and the situation is quite similar for all periods (not shown).

The Environmental scenario illustrates how environmental restrictions may affect residue supply. In addition to thinnings we have also excluded collection from stands with a site index (H_{40}) below 14. The values of the parameter m indicate an increase in maximum potential over time, but not a monotonic increase as for the two other scenarios. Timber harvest increases up to period four, while there is a slight decrease between the two last periods. The general effect of increased harvest is offset by an increase in pine harvest. Pine results in less harvest residues (Fig. 1).

Comparing the parameters for the different scenarios in Table 3, it is clear that the environmental restriction may affect supply. If we use the estimated asymptotes as an indicator, the potential reduces by 16–27% (Table 4) compared to the Base scenario.

Combining the heating value with the potential residue supply for the whole planning period (asymptotes for "Mean" in Table 3) the annual potential energy from harvest residues is 210 TJ (58.4 GWh) for the Base scenario, 230 TJ (62.4 GWh) for All and 166 TJ (46.0 GWh) for Environmental. These figures correspond roughly to the heating demand of 3400 to 4640 average households *.

The argument in the supply functions above is the hauling cost in NOK/ton, but we want to express supply in terms of energy prices (NOK/kWh). This is done by replacing hauling cost ($C_{hauling}$, NOK/ton d.m.) by the energy price (p_{energy}, NOK/kWh) multiplied by the heating value. In addition we need to include some other costs, since we have so far only included costs delivered roadside. These other costs include administration and compensation to the forest owner, chipping and storage and transportation from landing to end user. If we subtract these costs from the energy price, we get what is left to cover the hauling cost, i.e. the argument in the supply functions. Our assumptions regarding the additional costs are summarized in Table 5. The figures are based on data collected from suppliers of forest fuel in eastern Norway.

Combining these factors we arrive at the following supply function (kWh/year):

$$\mathrm{S}(\mathrm{P}_{\mathrm{energy}}) = hv\left(m + \frac{n}{1 + oe^{p\,hv(P_{\mathrm{energy}} - ac)}}\right) \tag{9}$$

where p_{energy} is the (end user) energy price (NOK/kWh), *hv* is heating value as received (=5029 kWh/ton), *ac* is additional costs (=NOK 0.089/kWh) and other terms are as defined earlier. It is straight forward to transform Eq. 9 to e.g. estimate supply in terms of GJ and prices/costs in €/GJ terms. This is achieved by using heating value (hv) in GJ/ton and by multiplying prices and costs (in €/GJ terms) by the exchange rate (NOK/€). Fig. 4 shows estimated supply using the param-

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* The calculations are based on a yearly average household energy consumption of 77.9 GJ (21 644 kWh) (Statistics Norway 2010b) of which 50% is assumed to be for heating, and an energy use efficiency of 80% for harvest residues.

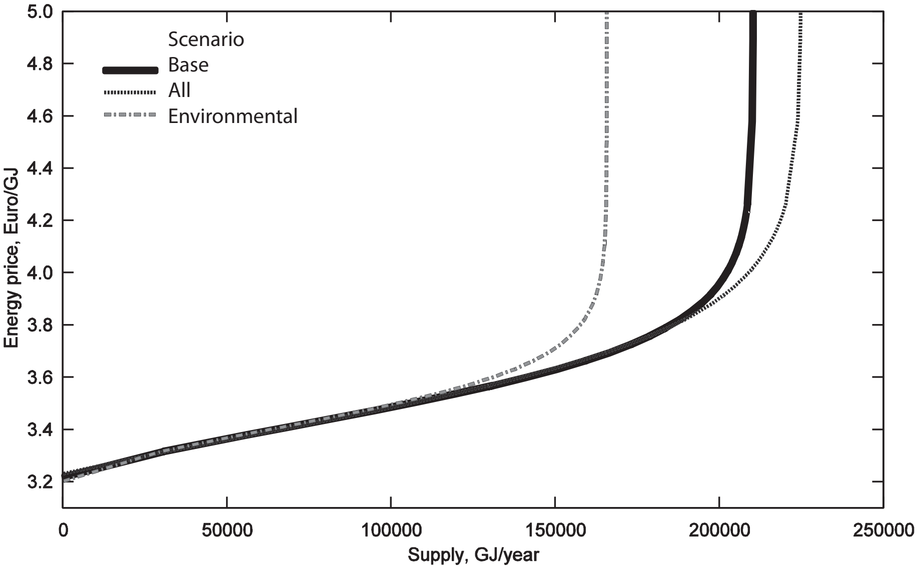

Fig. 4. Supply (based on the "Mean" functions in Table 3, and given the additional costs in Table 5) as a function of the energy price (as received).

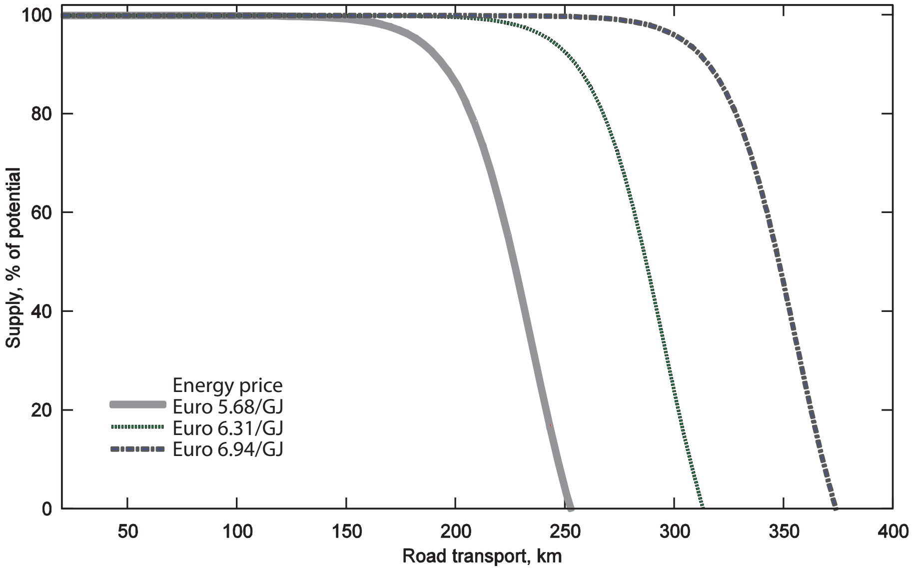

Fig. 5. Effect of road transport distance on supply. Energy price is as delivered end user. Supply estimates are based on the "Mean" functions for the scenario Base in Table 3 and the additional costs in Table 5 together with transport cost given in the text.

eters for the "Mean" functions in Table 3.

Eq. 9 is just a linear transformation of Eq. 8, i.e. a scaling of the axis. Thus, the general shape of the supply curves will not change. This of course also means that the relative differences between periods and scenarios discussed above are the same.

Given the assumptions, energy utilization of harvest residues is not profitable below an energy price of about €3.2/GJ (NOK 0.10 /kWh). Above this level supply increases rapidly over a rather narrow price range and supply is nearly inelastic above €4.1/GJ (NOK 0.12/kWh). This means that the full potential of residue supply will be utilized if prices are above this price range. From the figure we also see that the environmental constraint quickly becomes binding. According to NoBio (2009) the price for wood chips in 2007 was in the range of €4.0–9.5/GJ (NOK 0.128–0.301/kWh) with a weighted average of €6.1/GJ (NOK 0.195/kWh). The average price has been above €5.1/GJ (NOK 0.16/kWh) in the reported period (2004–2007). Given these average prices, it is clear that the potential would be nearly fully utilized in the study area. However, the rather wide price range in 2007 shows that the supply is highly sensitive to local conditions.

The distance dependent cost of road transport of forest chips in Norway is NOK 0.32/loose m^3–km, according to Grimsrud (pers. comm.). In order to analyse transport distance sensitivity we have combined this figure with the other additional costs in Table 5 for different road transport distances and for three different levels of the end user energy price. The price levels are centred round the current price, €6.31/GJ. The results are shown in Fig. 5.

Given the current fuel chip price, the full potential will be profitable up to road transport of about 200 km. At about 310 km road transport supply will be zero. A €0.63/GJ (NOK 0.02/kWh) increase (decrease) will increase (decrease) the point of full utilization by about 50 km.

4 Discussion and Conclusions

The objective of this paper has been to estimate the supply of harvest residues from non-industrial forest owners at a regional level in Norway, taking different environmental and economic constraints into consideration. Harvest residues are a bi-product of roundwood harvest and hence the future harvesting levels and spatial location of the harvest are decisive factors for the supply. Roundwood harvest is computed using the SGIS forestry scenario model where location of forest management activities including timber harvest is geographically identifiable at the stand level. The scenario parameters in SGIS like roundwood prices, interest rate and sustainable yield as the harvesting criteria are chosen to map observed roundwood harvest levels in the analysed area. The information is used to estimate the supply of harvest residues at a relatively detailed level. An engineering approach is used to estimate the harvest costs for the harvest residues, based on productivity data mainly from Finland.

The main advantage of GAYA-J/SGIS is that economically optimal forest management including location of harvest is found endogenously in the model based on assumptions concerning discount rate, prices and restrictions on harvests. All the results in our case study are dependent on the level and geographical location of future harvesting modelled by the forestry model SGIS. If the harvest levels in one period should differ from the projected level, the availability of harvesting residuals will change correspondently. Changes in timber prices, interest rate, weather conditions and individual preferences make it impossible to exactly map the level and location of future harvest. However, the optimisation method’s combined selection of exogenous variables in order to map observed harvesting level, is in our opinion a suitable approach to map level and location of future harvest.

We have used an engineering approach when estimating the supply functions for harvesting residuals. The estimated costs will probably differ from market prices if and when a market for harvest residues emerges and matures in Norway. One reason for this is that we have analysed the costs at stand level, and we have not taken into account that a contractor will also take into account the cost of moving the equipment between stands. This means that he/she may charge a higher price than the actual costs for one stand and a lower for an adjacent stand in order to get the contract for both. If this is the case the supply functions will tilt. We observe this tendency of price discrimination in the roundwood harvest market. Still, our cost estimates reflects the societal cost of utilization of harvest residues, except for moving equipment between stands.

It is also clear that we are not able to estimate accurately the supply functions at firm (forest holding) level. First, we treat each stand as a homogenous unit, i.e. we use estimated average cost for each stand. Second, the real costs at stand level may depend on site specific factors not captured by the model. Still, we believe that the model on average gives a good approximation of the real (technical) costs. At the aggregate level, i.e. aggregated over all stands and all years in each 10-years period, the supply will be more accurately estimated as, loosely speaking the law of large numbers applies. Also, at the aggregate level each stand can be said to be a marginal unit, meaning that we are closer to estimating the marginal cost function.

We have used parameter estimates – especially regarding productivity – from different sources, of which none are from Norway. Certainly, there are potential problems in doing so, as first of all, conditions may be different in Finland compared to Norway, and second, such parameters are to some extent anecdotal. However, more or less the same equipment is used in Norway as in Finland – standard or slightly modified forwarders. Also, the conditions for forestry activities in the study area are similar to conditions found in Finland. Finally, parameters from the different studies correspond rather well. In conclusion, we find it reasonable to use these parameters in Norway. It should also be kept in mind that modest errors in these parameters would not affect the general shape of the estimated supply curves, i.e. the sigmoid like shape where there is a large change over a small range. This shape is also reported in other studies, e.g. Nord-Larsen and Talbot (2004), Bjørnstad (2005), Panichelli and Gnansounou (2008).

Exclusion of collection from stands with a site index (H_{40}) below 14 – representing 31% of the productive forest land and 43.5% of the standing volume in the study area – reduced the potential supply of residues by 16–27%. This environmental restriction comes in addition to the assumed environmental considerations that effects roundwood harvest (5%) in the model. To what extent this constraint is binding is dependent on the price. Our results indicate that given the current prices, it is binding, i.e. reducing the (potential) supply of residues.

Harvest residues are barely used in Norway at the moment. The estimated cost functions imply only minor compensation to the forest owner. Hence, their attitude towards deliveries of harvest residues (reservation price) will affect the supplied volumes. Different reservation prices can easily be incorporated in the model when more empirical studies of observed behaviour are available.

In the study area energy utilization of harvest residues is not profitable below an energy price of about €3.2/GJ (NOK 0.10/kWh) when the distance from roadside to industry is 20 km. Above this price level supply increases rapidly over a rather narrow price range and supply is nearly inelastic above €4.1/GJ (NOK 0.12/kWh). This means that practically the full potential of residue supply will be utilized if the price is above this level. Since the price range in which supply changes is very narrow – about €1/GJ (NOK 0.03/kWh) – it is tempting to draw the conclusion that supply is "nothing or all" and that distance from landing to end user is a decisive factor for utilisation of harvest residues.

The methodology presented in this paper may be used to improve the estimates for harvest residue supply at national level. Such analyses must however be carried out with less precise data, mainly since we do not have complete coverage of digital inventory data at national scale. Instead, sample plots from national inventories may be analyzed using the same model as applied in this study. It is however important that historical harvesting volumes of roundwood are used to define the likely future roundwood supply in order to estimate residual supply. Collection of harvest residues will only to a limited extent affect roundwood supply.

The study area is characterized by higher site productivity and higher harvesting activity than the average for Norway (see Table 1). Also the average hauling distance is shorter, 145 m in Norderhov compared to around 450 meter as the average for the last 20 years of harvest in Norway. Based on an industrial harvest of 8 million m^3 and 60% utilization rate, the energy content of the harvest residues in Norway is around 14 PJ (4 TWh) annually. The cost function of this supply is yet not developed, but our results show that the supply function in the study area is rather flat in a large part of the supply interval. Hence, even when taking into account lower average productivity and longer average forwarding distances, harvest residues can be available in significant volumes at current wood chip prices. A national analysis would also gain from a more thorough analysis of timber supply, especially if prices/quantity relations are expected to change, see e.g. Kuuluvainen et al. (1996), Bolkesjø and Baardsen (2002), Pukkala et al. (2003), Størdal and Nyrud (2003), Bolkesjø et al. (2007), Bolkesjø et al. (2010).

Environmental restrictions regarding collection on sites with low productivity may reduce the national potential. 43.5% of the standing roundwood volume in Norway is located on sites with a site index of 11 and below, but as the utilization is lower and costs are higher on poorer sites, potential will be reduced less that indicated by these numbers. The current low utilization of harvest residues reduces the present need for introduction of environmental restrictions as collection on high productive sites are most feasible and will start first. Restrictions regarding collection on low productive sites might be needed if biomass prices increase and more research is available regarding long run impacts of collection of residues on different soil types.

The location of roundwood harvest decides available volumes and costs of harvest residues. The innovative element of this study is the application of a forest optimization model integrated in a GIS in order to provide relevant data for the estimation of supply functions for harvest residues. We did not find significant negative shift in the residues supply caused by changes in location of roundwood harvest over time as the slight increase in hauling distance is compensated by increased sustainable harvest.

As reference points for our results: The average electricity price for households for the period 1997–2007 has been €17.8/GJ (NOK 0.56/kWh), and the corresponding price for the energy intensive industry (excluding grid tariff) has been €4.2/GJ (NOK 0.13/kWh) (Statistics Norway 2010a). The results thus show that harvest residues can be an economic feasible resource for energy production in Norway with costs starting at biomass price of about €3.2/GJ (NOK 0.10/kWh). More research is needed to estimate the supply on a national level, including effects of environmental restrictions.

References

Asikainen, A., Ranta, T. & Laitila, J. 2001. Large-scale forest fuel procurement. In: Pelkonen, P., Hakkila, P., Karjalainen, T. & Schlamadinger, B. (eds.). Woody biomass as an energy source – challenges in Europe. EFI Proceedings 39: 71–78.

Åström, M., Dynesius, M., Hylander, K. & Nilsson, C. 2005. Effects of slash harvest on bryophytes and vascular plants in southern boreal forest clear-cuts. Journal of Applied Ecology 42: 1194–1202.

Bjørnstad, E. 2005. An engineering economics approach to the estimation of forest fuel supply in North-Trøndelag county, Norway. Journal of Forest Economics 10: 161–188.

Blingsmo, K.R. 1984. Diametertilvekstfunksjoner for bjørk-, furu- og granbestand (Diameter increment functions for stands of birch, Scots pine and Norway spruce). Rapport fra Norsk institutt for skogforskning 7. 22 p. (In Norwegian with English summary.)

— & Veidahl, A. 1992. Funksjoner for bruttopris av gran- og furutrær på rot (Functions for gross price of standing spruce and pine trees. Research paper. Skogforsk 8: 23 pp. (In Norwegian with English summary.)

Bohlin, F. & Roos, A. 2002. Wood fuel supply as a function of forest owner preferences and management styles. Biomass and Bioenergy 22: 237–249.

Bolkesjø, T.F. & Baardsen, S. 2002. Roundwood supply in Norway: micro-level analysis of self-employed forest owners. Forest Policy and Economics 5(2): 157–171

— , E. Trømborg & Solberg, B. 2006. Bioenergy from the forest sector: Economic potential and interactions with timber and forest products markets in Norway. Scandinavian Journal of Forest Research 21: 175–185.

— , Solberg, B. & Wangen, K.R. 2007. Heterogeneity in nonindustrial private roundwood supply: Lessons from a large panel of forest owners. Journal of Forest Economics 13(1): 7–28.

— , Buongiorno, J. & Solberg, B. 2010. Joint production and substitution in timber supply: a panel data analysis. Applied Economics 42(6): 671–680.

Braastad, H. 1977. Tilvekstmodellprogram for bjørk (Growth model computer program for Birch). Internal rep. Norw. For. Res. Inst. Division of Forest Management and Yield Studies 1. 17 p. (In

Norwegian.)

— 1980. Growth model computer program for Pinus sylvestris. Meddelelser fra norsk insitutt for skogforskning 35(5): 272–359.

— 1982. Naturlig avgang i granbestand (Natural mortality in Picea abies stands). Rapport fra Norsk institutt for skogforskning 12. 46 p.

Eid, T., Hoen, H.F. & Økseter, P. 2001. Economic consequences of sustainable forest management regimes at non-industrial forest owner level in Norway. Forest Policy and Economics 2: 213–228.

Garcìa, O. 1990. Linear programming and related approaches in forest planning. New Zealand Journal of Forest Science 20(3): 307–331.

Hoen, H.F. & Eid, T. 1990. En modell for analyse av behandlingsalternativer for en skog ved bestandssimulering og lineær programmering. Rep. Norw. For. Res. Inst 9. 35 p. (In Norwegian with English summary.)

— & Gobakken, T. 1997. "Brukermanual for bestandssimulatoren GAYA v.1.20." Unpublished user manual. Dept. of Forest Sciences, Agric. Univ. of Norway. (In Norwegian.)

Johnson, K.N. & Scheurman, H.L. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives – discussion and synthesis. Forest Science Monograph 18: 1–27.

Joutz, F.L. 1992. Biomass fuel supply: a methodology for determining marginal costs. Bioresource Technology 39(2): 179–183.

Kärhä, K. & Vartiamäki, T. 2006. Productivitiy and costs of slash bundling in Nordic conditions. Biomass and Bioenergy 30: 1043–1052.

Karjalainen, T., Asikainen, A., Ilavsky, J., Zamboni, R., Hotari, K.-E. & Röser, D. 2004. Estimation of energy wood potential in Europe. Working Papers of the Finnish Forest Research Institute 6.

Kuuluvainen, J., Karppinen, H. & Ovaskainen, V. 1996. Landowner objectives and nonindustrial private timber supply. Forest Science 42(3): 300–309.

Laitila, J., Asikainen, A. & Hotari, S. 2005. Residue recovery and site preparation in a single operation in regeneration areas. Biomass and Bioenergy 28: 161–169.

— , Asikainen, A. & Nuutinen, Y. 2007. Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. International Journal of Forest Engineering 18(2): 29–39.

Lappi, J. 1992. JLP: a linear programming package for management planning. Research Paper of the Finnish Forest Research Institute 414: 134 p.

— 2003. J-user's guide. Version 0.7.8, Desember 2003. Finnish Forest Research Institute, Suonenjoki.

Lehtonen, A, Mäkipää, R., Heikkinen, J., Sievänen, R. & Liski, J. 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management 188: 211–224.

Marklund, L.G. 1988. Biomass functions for pine, spruce and birch in Sweden. Swedish University of Agricultural Sciences, Department of Forest Survey. Report 45. 73 p.

Nabuurs, G.J., Schelhaas, M.J., Mohren, G.M.J. & Field, C.B. 2003. Temporal evolution of the European forest sector carbon sink 1950–1999. Global Change Biology 9: 152–160.

Næsset, E., Gobakken, T. & Hoen, H.F. 1997. A spatial decision support system for long-term forest management planning by means of linear programming and a geographical information system. Scandinavian Journal of Forest Resresearch 12: 77–88.

NoBio. 2009. Bioenergi i Norge – Markedsrapport – Pellets og Briketter 2008 (Bioenergy in Norway – Market report – Pellets and briquettes 2008, in Norwegian). Norwegian Bioenergy Association (NoBio), Oslo. (In Norwegian with English summary.)

Nord-Larsen, T. & Talbot, B. 2004. Assessment of forest-fuel resources in Denmark: technical and economic availability. Biomass and Bioenergy 27: 97–109.

Nurmi, J. 2007. Recovery of logging residues for energy from spruce (Picea abies) dominated stands. Biomass and Bioenergy 31: 375–380.

Overenskomst mellom Næringslivets Hovedorganisasjon og Skogbrukets Landsforening på den ene siden og Landsorganisasjonen i Norge og Fellesforbundet og vedkommende avdelinger av forbundet på den annen side. 1996. Lønnssatser. Oslo. 109 p. (In Norwegian.)

Panichelli L. & Gnansounou, E. 2008, GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities. Biomass and Bioenergy 32(4): 289–300.

Pukkala T., Ketonen, T. & Pykäläinen, J. 2003. Predicting timber harvests from private forests – a utility maximisation approach. Forest policy and Economics 13(1): 7–28.

Raulund-Rasmussen, K., Stupak, I., Clarke, N., Callesen, I., Helmisaari, H.-S., Karltun, E. & Varnagiryte-Kabasinskiene, I. 2008. Effects of very intensive biomass harvesting on short and long term site productivity. In: Röser, D., Asikainen, A., Raulund-Rasmussen, K. & Stupak, I. (eds.). Sustainable use of forest biomass for energy – a synthesis with focus on the Nordic and Baltic countries. Managing Forest Ecosystems 12. Springer.

SAS Institute. 1999. SAS/STAT User's Guide, Version 8. SAS Publishing, SAS Institute Inc., Cary, NC.

Siitonen, M. 1993. Experiences in the use of forest management planning models. Silva Fennica 27(2): 167–178.

Statistics Norway. 2010a. Focus on energy. http://www.ssb.no/english/subjects/01/03/10/energi_en/ http://www.ssb.no/energy_en (Accessed Oct 10, 2009–May 5, 2010).

Statistics Norway. 2010b. Energy consumption per household, 2006. http://www.ssb.no/english/subjects/01/03/10/husenergi_en/ (Accessed May 5, 2010).

Størdal S. & Nyrud, A.Q. 2003. Testing roundwood market efficiency using a multivariate cointegration estimator. Forest Policy and Economics 5(1): 57–68.

Trømborg, E. & Bergseng, E. 2003. Markedstilpasset skogbehandling og verdiskaping. Unpublished paper, Prevista, Kongsberg. (In Norwegian.)

— , Bolkesjø, T.F. & Solberg, B. 2007. "Impacts of policy means for increased use of forest-based bioenergy in Norway – a spatial partial equilibrium analysis". Energy Policy 35: 5980–5990.

Tveite, B. 1977. Bonitetskurver for gran. (Site index curves for Norway spruce (Picea abies (L.) Karst.)). Rep. Norw. For. Res. Inst. 33: 1–84. (In Norwegian with English summary.)

UN-ECE/ FAO 2000. Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand, Contribution to the Global Forest Resources Assessment 2000. In Geneva Timber and Forest Study papers. UN, New York and Geneva. 445 p.

Varian, H.R. 1992. Microeconomic analysis. Third edition. W.W. Norton and Company, New York, London.

Wall, A. 2008. Effect of removal of logging residue on nutrient leaching and nutrient pools in the soil after clearcutting in a Norway spruce stand. Forest Ecology and Management 256: 1372–1383.

Total of 47 references