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Highlights

- We assessed the possibilities for a forest energy business in a case study.
- Semi-mechanized supply chain with proven technological choices was suggested.
- Due to small tree size and low stand-level removal the supply costs were high.
- Raw material base should be increased in order to lower the costs.

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Research paper

Availability, supply technology and costs of residual forest biomass for energy – A case study in northern China

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ABSTRACT

In theory, China has vast potential forest resources for production of energy, but utilization on an industrial scale has been negligible. We assessed the practical possibilities and barriers for a forest energy business in a case study in northern China. The specific objectives of the study were 1) to assess the availability of forest biomass for energy production, 2) to determine feasible supply chains, and 3) to estimate the biomass fuel supply costs. Based on the case study results, the stand-level removals of the intended feedstock were low and the supply costs were relatively high. Suggestions for increasing the raw material basis, lowering the costs and further research and development were given. We conclude that although the case study area may not be promising from the feedstock point of view, the development could be started with small steps and proven technology. In order to avoid expensive mistakes further research for transfer of know-how and technology is needed.

1. Introduction

1.1. Background and objectives

Due to its huge population and fast-growing economy China has become the number one energy consumer in the world [1]. As a net importer of oil, gas and coal there is interest in China to develop bioenergy production as a domestic energy source. Use of modern bioenergy would also help China in reaching the recently announced target to cap its rapidly growing carbon emissions by 2030.

Forest energy, i.e., bioenergy produced from the residues of wood production of the forest industry, has drawn the attention of SFA (Table 1). SFA is motivated by the following facts:

- Forest energy is considered green and environmentally friendly,
- There is a need for heat production in the north of China,
- Use of forests for energy production could improve the public image of state forests, and
- Increased wood harvesting would offer work opportunities for the declining population in remote areas.

At the national level, forest energy or bioenergy generally does not currently play a major role. China's 12th Five-Year Plan sets a binding target to increase the use of non-fossil fuels in primary energy consumption by 3.1% between the years 2010 and 2015 [2]. Although biomass energy is mentioned, hydro power and solar energy are clearly prioritized as renewable energy sources.

According to China's energy policy, however, power generation using woody biomass in forested areas is promoted, as well as distributed energy production [3]. Also another government white paper discusses power generation using biomass, but heat generation is not mentioned [4]. Nevertheless, Kahrl et al. [5] argue that bioenergy development policies have so far focused on large-scale, centralized biomass conversion for transport fuels and electricity. Yet, focussing on the local scale and utilizing forests for producing clean energy with modern technology for the rural population might be a wiser way [5].

According to China's Medium- and Long-term Development Plan for Renewable Energy, the raw material base for woody biomass based energy is large: of about 900 million tonnes of dry waste from forestry and forest product processing available every

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Table 1
Nomenclature and abbreviations.

SFA	State Forestry Administration of China
m^3	Solid cubic metre
RES8	Supply chain of logging residues (the minimum top diameter of a roundwood bolt 8 cm)
RES12	Supply chain of logging residues (the minimum top diameter of a roundwood bolt 12 cm)
WHT	Supply chain of whole trees

year, nearly 300 million tonnes could be used for energy production [6]. A specific objective in the plan was to raise the share of all renewable energy to 15% of total primary energy consumption by 2020. In 2012, the share of renewables was 9% [7]. Of this, hydropower accounted for nearly 90%.

The potentials given in the plan may, however, be rather optimistic: Qiu et al. showed that for crop residues, when taking the competing uses and the economic viability of bioenergy plants into account, the real availability could be less than half of the potential stated in the plan [8]. Zhou et al. estimated the total forest residue potential – including both primary and secondary residues – at 197 million tonnes [9]. Even this estimate could be questioned as the competing use of residues was apparently not considered.

Gosens studied the economical prerequisites for biomass power projects in China [10]. He concluded that without increasing the feed-in-tariffs from the current level of 90.9 € MWh^{-1} the economic viability of future projects cannot be guaranteed.

The results of a survey carried out among the heads of bureaus of forestry and county leaders responsible for forest programmes indicated that training and education in forest bioenergy should be increased [11]. The attitudes among these professionals were positive towards renewable energy in general, but less positive towards forest bioenergy. The professionals also felt that future development in the implementation of forest bioenergy requires cooperation between the government and enterprises.

It seems, therefore, that although the theoretical potential and general prerequisites for forest energy in China have been evaluated there is a lack of knowledge about the realistic possibilities of starting energy production based on residual forest biomass. Before making a decision on starting a biomass-fuelled plant, it is crucial to find out how much feedstock would be available, how it could be harvested and what would be the supply cost. These questions cannot be evaluated with a nation-wide assessment, but one must start in a carefully selected location with a more thorough case study.

The objectives of this study were 1) to assess the availability of logging residues for energy production, 2) to determine feasible supply chains, and 3) to estimate the biomass fuel supply costs. As the interest of SFA lay in Daxing'anling prefecture, the study was solely focused there. Within Daxing'anling Mohe county was determined as the target area.

1.2. General operating environment in the study area

Daxing'anling prefecture is located in the northernmost corner of China (Fig. 1). It mostly belongs to Heilongjiang province, but also partly to Inner Mongolia province. Daxing'anling is a special forestry area and administratively directly under SFA meaning that all the forests in the prefecture are owned by the state. The total area of the prefecture equals 83,000 km^2. The topography in the area is characterized by undulating, eroded mountains with slope angles mostly between 15° and 30°. The mean altitude in Daxing'anling region is 573 m, ranging from 180 m to 1528 m. The soil is mainly brown forest soil. According to the local forest authorities about 80% of the forest area is dominated by Dahurian larch (*Larix gmelinii*), 10% by white birch (*Betula platyphylla*) and 4–5% by Scots pine (*Pinus sylvestris* L. var. *mongolica* Litv.).

The climate in Daxing'anling is continental, and in Mohe county subarctic (Dwc in Köppen climate classification system [12]). The winters in Mohe are cold (average temperatures in January −36.2 to −21.5 °C) and long, and summers short and warm (average temperature in July 11.7–25.8 °C). The frost-free period lasts only approximately three months, which keeps tree growth low. Long winters also mean that the heating season is long, at least eight months. Currently, households in Daxing'anling are heated with charcoal.

Forestry and the forest industry are vital for the economy and employment of the region. In 2010, the production of sawn wood in Daxing'anling was 275.6 dam^3 [13]. There are no specific figures on the forest industry in Daxing'anling, but in the whole Heilongjiang province there were approximately 2000 wood processing enterprises with a total annual processing capacity of 9.6 hm^3 at the end of 2012. The main products include solid wood furniture, wooden doors and windows, floors, laminated wood, chipboards, fibreboards and wooden craft products. Due to the small size of harvested trees, the wood-products industry carefully utilizes the scarce resources. In addition to harvests from its own forests, Heilongjiang province imports annually around 10 hm^3 timber from Russia.

Currently, the use of forest chips in energy production in Daxing'anling is limited. Wood processing residues such as sawdust, bark and offcuts are partly utilized as energy, but part of the residues is treated as waste. At the end of 2013, there were two energy production facilities which were able to utilize woody biomass as feedstock.

One of the plants was located in Tahe city and was established in 2012. The main products of the plant were electricity and activated charcoal. The heat was utilized for drying the chips and heating the premises. The target was to raise the level of power production to 10 MW. The consumption of fresh wood chips amounted to 100,000 t, while the targeted use was even 250,000 t. Supply of chips was outsourced to 4–5 companies delivering the feedstock at a price of 37–39 € t^{-1} (average rate of RMB 8.165 in 2013).

The other plant, located in Songling, was built in 2011. The main product of this plant was charcoal, but the aim was to purify and sell the process gases as well. The daily feedstock consumption totalled 24 t which equals 6000–9000 t annual consumption depending on the utilization rate of the plant. The raw material cost at plant was 24–32 € t^{-1}.

2. Material and methods

The assessment of the availability of forest chips (chips made from logging residues) for energy was based on the SFA's statistics on the area, the growing stock and harvesting quota in Mohe county and on two thinning trials with the following steps: 1) estimation of thinning removals of stemwood, 2) estimation of stand-level removal of residues, and 3) combining the results of the former two to estimate the technical harvesting potential for forest chips.

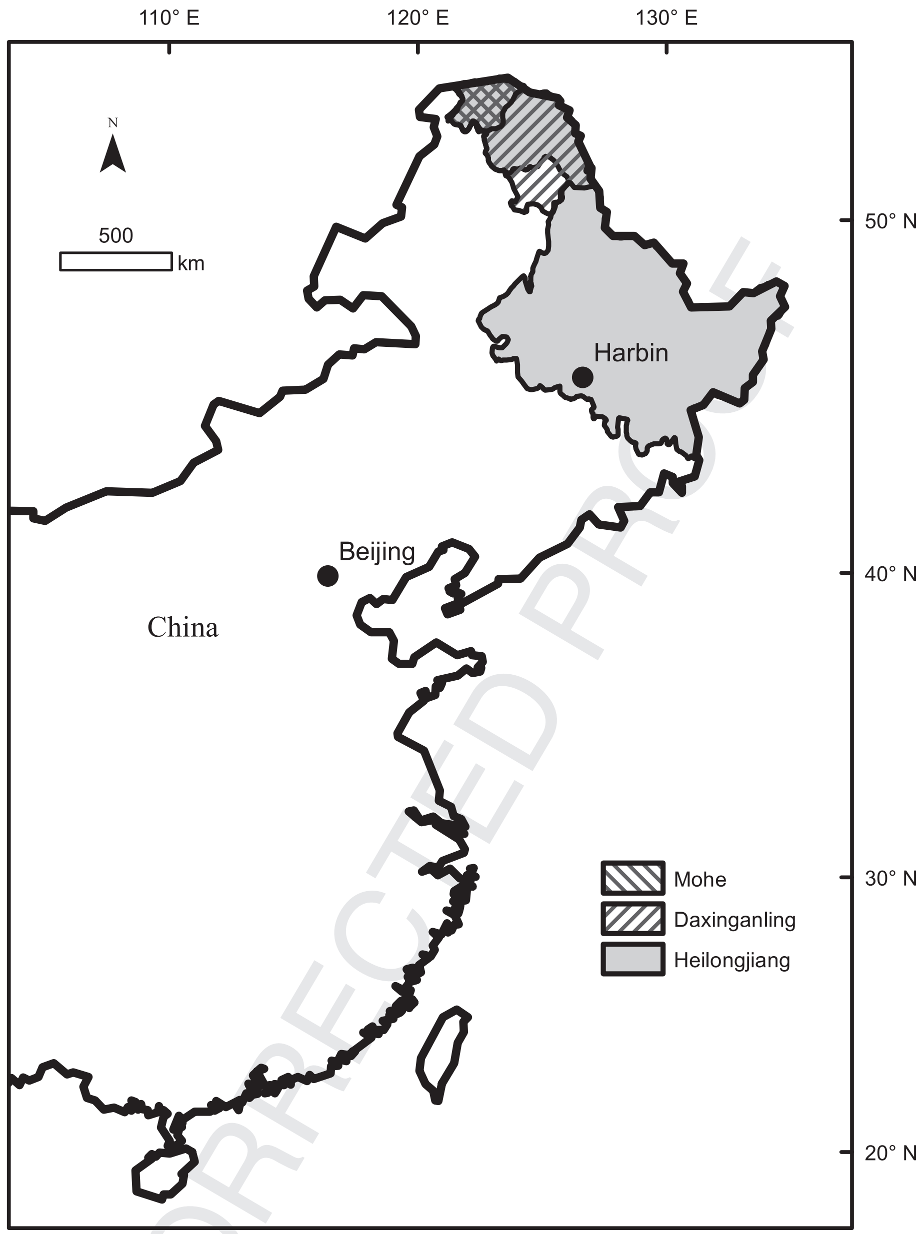

Fig. 1. Location of the case study region. Map data courtesy of ESRI Data & Maps, 2006, from ArcWorld Supplement.

According to the authorities the raw material base of forest chips would consist of thinning residues in young and middle-aged forests. Clear cuts are not allowed. The maximum legal thinning intensity is 20% of the total volume of the growing stock. At the moment, all the stemwood meeting the quality and size criteria of merchantable roundwood is directed to the wood-products industry. The minimum top diameter of a roundwood bolt is between 8 and 12 cm and the minimum length 2 m. Thus the technical harvesting potentials of residues were estimated using both 8 and 12 cm top diameter. Based on the thinning trial data described below, the removals may be very low. Therefore, an additional estimate of the technical harvesting potential of whole trees was calculated. Consequently, both the potentials and supply costs were estimated for the following supply chains: *RES8*, *RES12* and *WHT* (see Section 3.2 for the description of the chains).

The county consists of three forest bureaus and the total area of the county is 18,000 km^{-2}. In Mohe, 91% of the total area is covered by forests. Of these, 92% are natural forests and the rest are planted. The average volume of growing stock is 72 m^3 ha^{-1}. In young forests (conifers < 40 yrs, broadleaved < 30 yrs) the average volume varies between forest bureaus from 15 to 28 m^3 ha^{-1}. In middle-aged forests (conifers 41–80 yrs, broadleaved 31–50 yrs) the average volume varies between 78 and 102 m^3 ha^{-1}.

The annual quota for thinnings in Mohe is only 56,000 ha (3.4% of forest area). In young and middle-aged forests the planned thinning areas are 22,000 ha (4.6%) and 34,000 ha (4.2%), respectively. The actual thinning area was, however, only 47,800 ha in 2011 and 48,600 ha in 2012. Subsequently, the maximum thinning removals were estimated as follows:

$$V_i = 0.2 \cdot \widehat{V}_i \cdot A_i$$

where0.2 = thinning intensity$\widehat{V}_i$ = average volume on thinning area in age class i (m^3 ha^{-1})A_i = thinning quota in age class i (ha).

The stand-level removal of logging residues in thinnings was estimated based on data of two sample plots from Xilinjie forest bureau – one said to represent a typical young thinning stand and the other a typical middle-aged stand (Table 2). Note that the volume of growing stock in the young stand is actually considerably higher than the average in Xilinjie (41 m^3 ha^{-1} vs. 15 m^3 ha^{-1}), but in the middle-aged stand lower than the average (80 m^3 ha^{-1} vs. 102 m^3 ha^{-1}). As a matter of fact, the lowest average volume in young forests can be found in Xilinjie, but also the highest average volume in middle-aged forests (Fig. 2).

The intensity of thinnings seems to be relatively low, even compared to the legal maximum. In order to estimate the technical potential, a thinning was simulated for the sample plot representing middle-aged stands with 20%-removal of volume. In each diameter class the removal of birch was increased proportionally to the actual removal until the maximum removal was reached.

Next, the order of magnitude of thinning residues was estimated based on the size requirements of industrial roundwood, sample plot data on the maximal thinnings and biomass models. Due to missing local models, Finnish models for taper curve and biomass were applied. Models of Scots pine (*P. sylvestris*) were used for larch and of birch (*Betula pendula* and *Betula pubescens*) for white birch [14–16]. To mitigate the effect of using Finnish taper curve models the volumes obtained with the Finnish models were scaled to match the ones in the data set at tree-species level. Dividing the residue volumes with the roundwood volumes resulted in expansion factors for logging residues.

Finally, the thinning removals were multiplied with the expansion factors to obtain the technical harvesting potentials for logging residues. In middle-aged stands not all the crown biomass is available, since part of the needles, leaves and branches fall off before the point of utilization. Here, a reduction of 5% in the potentials of thinning residues and whole trees was assumed.

Feasible supply chains for forest chips were defined based on the field study observations and experiences in countries that are advanced in the utilization of forest chips. Among the feasible chains two were selected for further determination of supply costs. The costs were estimated for a middle-aged stand (Table 2) assuming 20%-thinning intensity with models developed for Finnish conditions [17,18]. The productivity of manual felling and bunching of whole trees was estimated with models by Vastamäki and Örn [19]. For the time consumption of hauling of logging residues and whole trees the models by Ranta [20] and Laitila et al. [21] were used, respectively. The time consumption of truck transportation was estimated with the model by Nurminen & Heinonen [22]. Local data were utilized where available; otherwise the input values were estimated based on expert opinions (Table 3).

The overhead cost was assumed to be at the same level as in roundwood procurement in Finland in 2012. Although the cost of labour in China is considerably lower than in Finland, more efficient organization of operations in Finland levels the difference. The cost of manual felling and bunching is based on local data. Stumpage

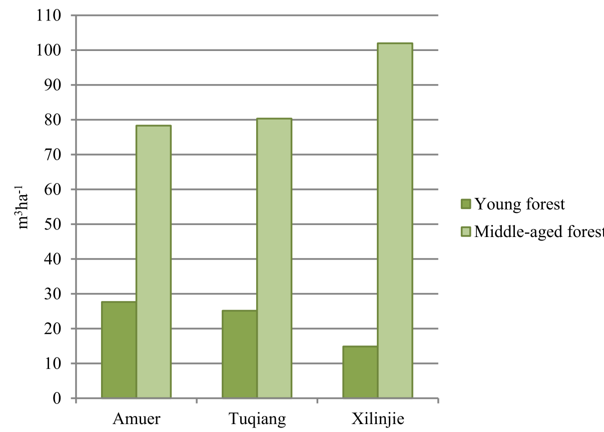

Fig. 2. Average volumes of growing stock in Mohe by forest bureau.

price is not included in the costs.

Machine costs consist of labour cost, capital costs and operational costs. Regarding capital and operational costs there are probably no major differences between the two countries. E.g. the prices of forest machines are about the same globally and the price of diesel in Mohe approximately at the same level as in Finland. The main difference lies, therefore, in labour costs. This is why the following procedure was applied to estimate hourly costs of machines: First, the up-to-date costs for forwarders, chippers and chip trucks in Finland were taken from recent, unpublished studies by the Finnish Forest Research Institute. The costs for forwarding, chipping, loading/unloading of a truck, and driving were set as 68 € h^{-1}, 170 € h^{-1}, 73 € h^{-1} and 102 € h^{-1}, respectively. Second, the labour cost was reduced to the level in Mohe. In Finland, the share of labour costs in forwarding, chipping, loading/unloading of a truck, and driving is 42%, 25%, 54% and 35%, respectively [23]. Finally, the estimates of hourly costs in Mohe were obtained by summing up the reduced labour costs and the unchanged capital and operational costs.

3. Results

3.1. Availability of forest biomass for energy in Mohe county

Assuming maximal thinning intensity (20%) and the average volume on thinning area we get the thinning removals of stemwood as in Table 4.

The simulated thinning with maximum thinning intensity in the middle-aged sample plot resulted in removal of 16 m^3 ha^{-1} and 7 cm mean diameter of the removed trees. The diameter distributions of the original and removed trees are illustrated in Fig. 3.

In the young stand, no industrial roundwood could be harvested because of the small tree size. Crown biomass would increase the

Table 2
Key attributes of the sample plots.

		Young stand	Middle-aged stand
	Plot area (ha)	0.34	0.31
Before thinning	Stem number (ha^{-1})	2465	2377
	Stem volume (m^3 ha^{-1})	41	80
	…larch (m^3 ha^{-1})	19	23
	…birch (m^3 ha^{-1})	22	57
	Mean diameter (cm)	6	8
After thinning	Removal (m^3 ha^{-1})	2.4	6.3
	Intensity (%)	6	8
	Mean diameter of removal (cm)	5	7

Table 3
Input data used in the cost calculations.

Parameter	Value	Unit	Source
Removal, residues	11/15	$m^3\ ha^{-1}$	This study
Removal, whole trees	20	$m^3\ ha^{-1}$	This study
Average whole-tree volume	34	dm^3	This study
Moisture of fresh wood	55	%	Expert opinion
Forwarding distance	150	m	Local data
Distance between strip roads	20	m	Expert opinion
Overhead costs	3	€ m^{-3}	Expert opinion
Cost of manual felling and bunching	23	€ d^{-1}	Local data
Load capacity, forwarder, residues	4	m^3	Expert opinion
Load capacity, forwarder, whole trees	6	m^3	Expert opinion
Gross effective/effective time ratio, forwarder	1.2		Expert opinion
Hourly cost, forwarder	52	€ h^{-1}	This study
Transferring cost, forwarder	52	€	Expert opinion
Productivity, chipper, residues (loose volume per effective hour)	65	$m^3\ h^{-1}$	[23]
Productivity, chipper, whole trees (loose volume per effective hour)	85	$m^3\ h^{-1}$	[23]
Hourly cost, chipper	133	€ h^{-1}	This study
Transferring cost, chipper	67	€ h^{-1}	Expert opinion
Volume of load space, truck	64	m^3	Expert opinion
Loading and unloading cost, truck	39	€ h^{-1}	This study
Driving cost, truck	72	€ h^{-1}	This study
Unloading time	0.5	h	Expert opinion
Auxiliary time	0.3	h	Expert opinion

harvestable biomass by some 40%. This would total 3.3 $m^3\ ha^{-1}$ of energy wood.

In the middle-aged stand, the volume of crown biomass is roughly 20% of stem volume. With 20% thinning intensity and 8 cm top diameter about 40% of stemwood would meet the size requirements of industrial roundwood and the rest, together with crown biomass, could be harvested for energy. This would total 7 $m^3\ ha^{-1}$ of roundwood and 12 $m^3\ ha^{-1}$ of residues. With 12 cm top diameter only about 20% of stemwood would be large enough for industrial use. Consequently, the total roundwood removal would remain at 3 $m^3\ ha^{-1}$ whereas the residue removal would sum up to 16 $m^3\ ha^{-1}$. Finally, if whole trees were harvested for energy, the removal would be approximately 20 $m^3\ ha^{-1}$.

The technical harvesting potentials of energy wood are given in Table 5. Per area of middle-aged forest, the potentials totalled 52 $m^3\ km^{-2}$, 70 $m^3\ km^{-2}$ and 84 $m^3\ km^{-2}$ for *RES8*, *RES12* and *WHT*, respectively. Because of the negligible removal in young stands, the potentials were only calculated for middle-aged forests. The technical potential of industrial roundwood in Mohe would total 250 dam^3 and 114 dam^3 for *RES8* and *RES12*, respectively. For comparison, according to the local authorities the actual annual removal of industrial roundwood in Mohe is only 79 dam^3.

Table 4
Forest areas and maximum thinning removals of stemwood.

Forestry bureau	Forest area km^2	Young forest dam^3	Middle-aged forest dam^3	Quota, total dam^3
Amuer	5080	37.184	171.952	209.136
Tuqiang	4650	36.441	160.924	197.365
Xilinjie	6950	24.594	258.678	283.272
Mohe, total	16,680	98.295	591.540	689.835

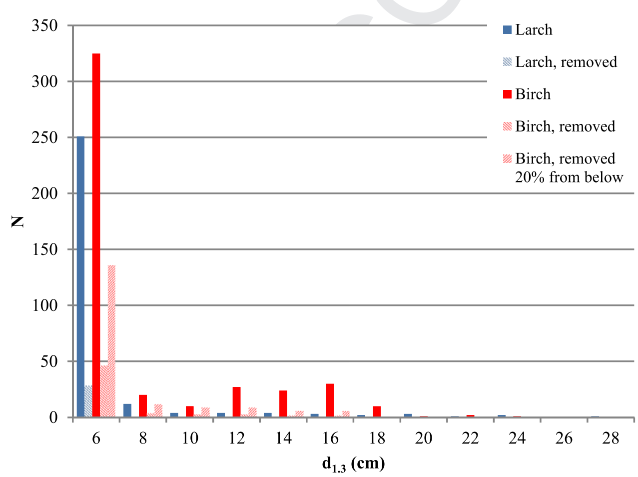

Fig. 3. The diameter distributions of the original and removed trees in the middle-aged sample plot.

3.2. Feasible supply chains and supply costs in Mohe county

At the moment, timber harvesting is based on the shortwood method consisting of the following work phases: motor-manual felling, delimbing and bucking; manual hauling to the roadside; and truck transport to the point of utilization. Because of manual hauling, harvesting is limited to within 200–300 m from a road. The harvesting season starts in October continuing till February-mid-April. In summertime road conditions are the limiting factor for harvesting and forest workers are then usually employed by the tourism business. The road network is relatively sparse and no forest roads exist. South from Mohe there is a wood terminal with a railway connection.

If the raw material base for energy use was logging residues from thinnings, manual hauling is out of the question. In that case either a farm tractor-based or purpose-built forwarder should be used for hauling. Otherwise proven, mechanized supply chain designs are to be recommended (see e.g. Refs. [24,25]). Chipping can be done at the roadside or at the place of utilization with a mobile

Table 5
The technical potentials of middle-aged forests in Mohe (dam^3).

	RES8	RES12	WHT
Amuer	121	164	197
Tuqiang	113	154	184
Xilinjie	182	247	296
Mohe, total	417	565	678

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chipper, mounted either on a trailer or on a truck. Should chipping take place at the roadside, the chips are transported to the point of utilization by a chip truck. In case of chipping at the point of utilization the residues are transported by a biomass truck equipped with solid side panels and bottom.

Currently, harvesting possibilities in Mohe are not being fully utilized. Increasing harvests could enable the use of whole trees or stems for energy. If the raw material base was whole trees or stems from thinnings, a similar supply chain could be utilized as with logging residues.

The costs were estimated for two different supply options: supply of logging residues from thinnings and supply of whole trees from thinnings (Fig. 4). For logging residues the costs were assessed for both 8 and 12-centimetre top diameters. Hence, tree distinct supply chains were defined: RES8, RES12 and WHT. All the supply chains include the following work phases: organizing of the procurement activities, hauling by forwarder, chipping at roadside landing and transportation to plant. In addition, chain WHT includes manual felling and bunching.

The break-down of supply costs by main work phases is illustrated in Fig. 5. With 30-km transport distance the supply costs at plant total 32, 29 and 29 € m^{-3} for supply chains *RES8*, *RES12*, and *WHT*, respectively. The corresponding technical potentials within this range are 25 dam^3, 34 dam^3 and 41 dam^3. Due to lower removal the costs for chain *RES8* are higher than with the two other chains. The additional cost of felling and bunching in chain *WHT* is compensated by lower costs in chipping and transport compared to chain *RES12*.

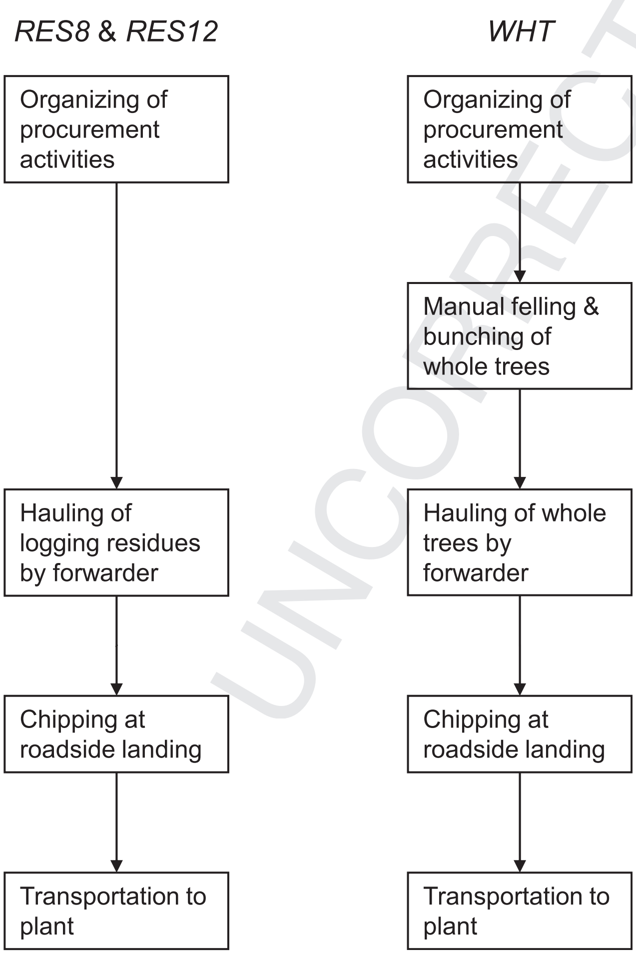

Fig. 4. Supply chains in cost calculations.

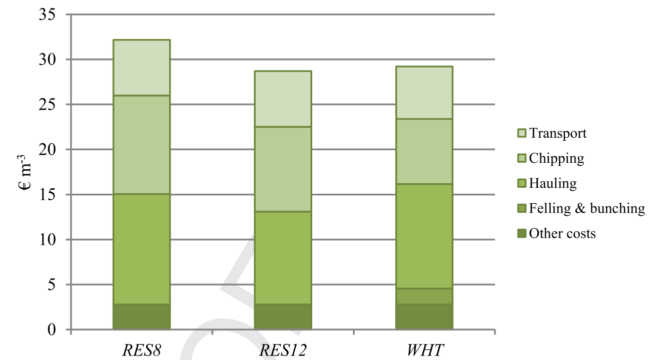

Fig. 5. Cost structure of forest chip supply. Transport distance for all the chains was 30 km. Residue removal for chain *RES8* was set at 11 m^3 ha^{-2} and for chain *RES12* at 15 m^3 ha^{-2} corresponding to minimum top diameters of industrial roundwood of 8 cm and 12 cm, respectively.

Increasing transport distance increases the technical potential of energy wood, but with higher supply costs (Fig. 6). There are no significant differences in supply costs between chains *RES12* and *WHT*, whereas the cost for chain *RES8* is considerably higher.

4. Discussion

The methodology used in this study was practice-oriented bottom-up approach that gives deep insight in the resources and sourcing of forest biomass for energy. Another approach would have been energy and forest policy oriented, top-down approach giving broader view to forest-based energy production. The scope of the study, however, was to produce information of operating conditions for technology providers for harvesting and transport operations. Thus, bottom-up approach was selected.

When it comes to the assessment of the availability of woody biomass for energy, forest inventory data would have been very helpful. Instead the calculations were actually based on data on thinning areas and volumes of growing stock at the level of the forest bureau. The data on constraints for energy wood procurement were rather limited, which means that the potentials should be considered as technical limits and by no means economic potentials.

In estimation of stand level removals of thinning residues, the data were available only for two sample plots. This raises a question about the representativeness of the plots. Furthermore both of the plots were birch dominated, although 80% of the forest area is dominated by larch and "all the forests are available for harvest".

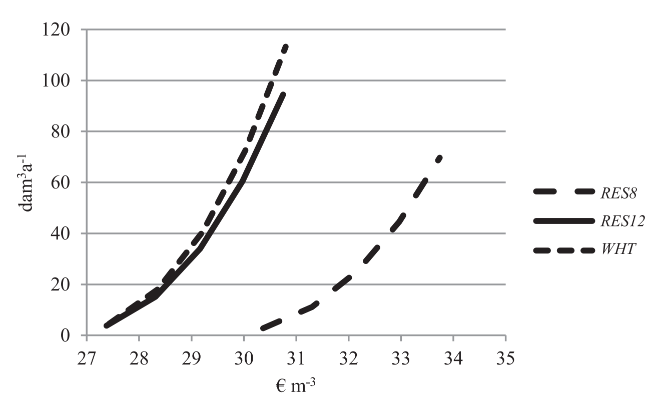

Fig. 6. Technical potential as a function of supply costs for the three different supply chains.

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Naturally if the amount of logging residues was considerably higher in reality, the profitability of operations would increase. The use of Finnish models for taper curve and biomass estimation is probably a minor source of inaccuracy as the volumes obtained with the Finnish models were calibrated with the local data. Moreover, the aim was to estimate the order of magnitude.

For comparison, the average volume of growing stock in young forests in Mohe corresponds to the one in advanced seedling stands in northern Finland [26]. Furthermore, the range of average volumes reported for middle-aged forests in Mohe is represented in young thinning stands from northern Ostrobothnia to central Finland. Anttila et al. [27] have estimated the technical harvesting potential of whole trees in young thinning stands in central Finland at 45 m^3 km^{-2} and in northern Ostrobothnia at 56 m^3 km^{-2}. Elsewhere in Europe the European Forest Sector Outlook Study II [28] assessed the development of various forest resource indicators under different scenarios. The amount of annually extracted residues (dry mass on forests available for wood supply) varied from 0.07 Mg ha^{-1} to 0.15 Mg ha^{-1} in 2010 and from 0 Mg ha^{-1} to 0.42 Mg ha^{-1} in 2030 depending on scenario. When seen in the light of these figures the potentials in Mohe (84 m^3 km^{-2} or 0.45 Mg ha^{-1} for *WHT*) are not low at all. In terms of energy content the estimated technical potentials in Mohe equal 3–5 PJ. The total energy demand in Mohe is not known, but for comparison the energy consumption of enterprises larger than 11 employees consumed 0.13 PJ in the first quarter of 2014 [29]. However, one should be cautious when drawing conclusions based on different biomass assessments because of differing assumptions on constraints for extraction. The more numerous and stringent constraints are set, the smaller is the potential [30]. In this study very few constraints could be quantified. Therefore, the actual implementation potential in Mohe would probably be much lower than the one in, e.g., Finland.

The constraints for extraction should reflect sustainable harvesting practises. With sustainable practises utilization of forest residues can provide benefits at local, national as well as global scales [31,32]. The guidelines for harvesting of forest chips should be formulated so that all three pillars of sustainability – environmental, social and economic – are covered. As an example of environmental sustainability criteria part of the residues should be left at the stand maintain the productivity of the soil. E.g. in the Finnish guidelines for energy wood harvesting 30% in total of the residues are advised to be left in the forest [33]. When it comes to social sustainability care should be taken to consider industrial use of stemwood and labour conditions. Finally, the economic sustainability requires that the supply of forest chips is profitable in the long run.

A fact that favours using whole trees or delimbed stems instead of logging residues is the quality of feedstock. The best fuel for a small-scale plant (with which the operation should be started), is stemwood. This is because needles contain high quantities of alkali metals and chlorine which, when condensing on heat transfer surfaces of the boiler, slow down the heat transfer and cause the risk of high-temperature corrosion [34].

The evaluation of feasible supply chains was based on the short study tour and the authors' expertise on feasible supply chains in other countries. One should bear in mind that the real design of a supply chain should be done in cooperation with Chinese companies over a longer period of time. Technically there seemed to be no restrictions for mechanization of harvesting. Although slopes may be steep on hills and mountains, large areas are completely flat. Bearing capacity is not a problem, because harvesting only occurs in wintertime. The forests seen during the trip were not especially stony. Basically manual hauling would still be possible if the stems were crosscut before hauling. Mechanized hauling would, however, make it possible to enlarge harvesting areas further from the roadside. Special attention should be paid to storing energy wood as roadside storages are subject to theft. One possibility would be to store stemwood at the point of utilization or in a terminal.

In contrast to harvesting potential, two other main factors affecting harvesting costs – stand-level removal and size of removed trees – were found to be rather low. The consequences of the forest fire in 1987 can still be seen in the age class structure of the prefecture. The area of the conflagration was more than 13,000 km^2 [35]. In addition to the age class structure another factor affecting the observed small tree size is illegal logging. Large trees are often harvested illegally. These three factors have a direct effect on the costs: small tree size and low stand-level removal increase cutting and hauling costs. Furthermore, because the real availability is lower than the technical potentials given here, the actual transport cost is higher than estimated.

The estimation of supply costs relied on expert estimations. The productivities of manual felling and bunching and chipping were set at the same level as in Finland. In reality, especially when starting a new practice, the productivities are lower, but should increase in the long run. Yet even after the learning phase there can be big differences between operators: a good one can be twice as productive as a weaker one [36]. Spatially explicit data were not available to estimate the transport distances or terrain slope. Neither were there data on overhead costs, truck load size or loading/unloading times. For comparison, the overhead costs of harvesting in Leningrad region in North–West Russia were 2.08 € m^{-3} [37]. Dees et al. [38] estimated the machine costs for several European countries. The costs of forwarding and chipping in some of the low-cost countries were 42 € h^{-1} and 113 € h^{-1} (Serbia), 42 € h^{-1} and 124 € h^{-1} (Ukraine) and 43 € h^{-1} and 114 € h^{-1} (Turkey), respectively. These numbers suggest that the overhead cost and the hourly cost values used in this study may have been overestimated. On the other hand, this levels the probable overestimation of productivities. However, the results indicate the order of magnitude of and the effect of different factors on the costs.

Comparable cost estimates in China are hard to find. The power plants visited estimated their fuel costs to be between 24 and 39 € t^{-1} (wet basis). Gosens has collected an extensive database of biomass power projects in China [10]. In 2010–2012 the average fuel cost was approximately 35 € t^{-1} (wet basis), but as the data covers a wide range both geographically and with respect to raw material the variation in costs is huge. Assuming a density of 800–900 kg m^{-3} for the fuel as received, the cost in this study would be between 30 and 42 € t^{-1} depending on the transport distance and supply chain. Considering the fact that the plants visited were using mainly industrial wood residues, these costs are not very high. Nonetheless, industrial residues are in practise cheaper as feedstock than forest residues and should be, if available, preferred in consumption. The average given in Ref. [10] also fits within the range of cost estimates obtained in this study. Because of the various origins direct comparisons are, however, difficult.

There are a number of topics where further research and training would be needed in order to start a forest energy business in Daxing'anling. Many of these are related to data availability as stated above. To make the calculations of energy wood availability and supply costs more accurate, spatially explicit forest inventory data would be needed. According to the department of forest resource management of SFA, China has a two-level inventory system. The first level consists of the national forest inventory, which provides national and provincial information on the status and changes of forest resources. The second level is composed of local inventories (city, county, enterprise, etc.), which support management and administration. Unfortunately, the inventory data were not available for this study.

Further research would be needed to study real productivities and machine costs of manual felling and bunching, hauling with a farm tractor and a forwarder, chipping and truck transport in local conditions. Local data would increase the reliability of the cost calculations. The participation of Chinese research organizations in all further research activities is indispensable.

5. Conclusions

In theory, China has vast potential resources for energy wood supply, but utilization on an industrial scale has been negligible. In practice, however, the higher demand of the forest industry compared to available resources does not allow significant growth prospects for forest energy.

SFA is trying to attract Chinese companies to invest in the forest energy business in Mohe county based on thinning residues. However, due to low removal at stand-level, the economic viability of such operations is questionable. From the raw material base point of view, the study area is not promising. More forested areas and especially forest areas with higher availability of biomass per unit of land area would lower the supply costs.

At the moment all the stemwood in Daxing'anling goes to the forest industry. Therefore, to start using stemwood in energy production, the raw material base should be increased. This can be done 1) by increasing the intensity of thinnings up to the legal maximum of 20% and 2) by increasing the thinning area. The thinning area can be increased 1) by mechanizing the hauling of wood so that the harvesting area can be expanded further from a road, and/or 2) by building forest roads or winter roads enabling harvesting in currently inaccessible areas. Finally, with increased raw material base, stemwood or whole trees can be harvested for energy without endangering the wood supply of the forest industry.

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