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Raul Fernandez-Lacruz [1], Fulvio Di Fulvio [1,2], Dimitris Athanassiadis [1], Dan Bergström [1], Tomas Nordfjell [1]

Distribution, characteristics and potential of biomass-dense thinning forests in Sweden

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Highlights

- Biomass-dense thinning forests (BDTF) cover 2.1–9.8 M ha in Sweden, which represents 9–44% of the country's productive forest land area, depending on the constraints applied.
- 65% of BDTF area is found in northern Sweden.
- Analyses revealed a yearly harvesting potential of at least 4.3 M OD t of undelimbed whole trees (3.0 M OD t of delimbed stemwood including tops).

Abstract

Understanding the characteristics of unutilized biomass resources, such as small-diameter trees from biomass-dense thinning forests (BDTF) (non-commercially-thinned forests), can provide important information for developing a bio-based economy. The aim of this study was to describe the areal distribution, characteristics (biomass of growing stock, tree height, etc.) and harvesting potential of BDTF in Sweden. A national forest inventory plot dataset was imported into a geographical information system and plots containing BDTF were selected by applying increasingly stringent constraints. Results show that, depending on the constraints applied, BDTF covers 9–44% (2.1–9.8 M ha) of the productive forest land area, and contains 7–34% of the total growing stock (119–564 M OD t), with an average biomass density of 57 OD t ha^{-1}. Of the total BDTF area, 65% is located in northern Sweden and 2% corresponds to set-aside farmlands. Comparisons with a study from 2008 indicate that BDTF area has increased by at least 4% (about 102 000 ha), in line with general trends for Sweden and Europe. Analyses revealed that the technical harvesting potential of delimbed stemwood (over bark, including tops) from BDTF ranges from 3.0 to 6.1 M OD t yr^{-1} (7.5 to 15.1 M m^3 yr^{-1}), while the potential of whole-tree harvesting ranges from 4.3 to 8.7 M OD t yr^{-1} (10.2 to 20.6 M m^3 yr^{-1}) depending on the scenario considered. However, further technological developments of the harvest and supply systems are needed to utilize the full potential of BDTF.

Keywords early thinning; small-tree harvesting; unthinned stand; GIS; wood fuel; bioenergy; biomaterial
Addresses [1] Swedish University of Agricultural Sciences (SLU), Department of Forest Biomaterials and Technology (SBT), Skogsmarksgränd, SE-901 83 Umeå, Sweden; [2] International Institute for Applied Systems Analysis (IIASA), Ecosystems Services and Management Program (ESM), Schlossplatz 1, A-2361 Laxenburg, Austria
E-mail raul.fernandez@slu.se
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1 Introduction

Bioenergy (solid, liquid and gaseous biofuels produced from biomass) provided 34% (130 TWh) of the energy consumed in Sweden in 2013 (Swedish Bioenergy Association 2014). Thus, it contributed most of the total share (52%) of renewables in Sweden's gross final energy consumption, which is one of the highest among European countries (Eurostat 2015). The main reason for the large use of bioenergy in Sweden is the carbon tax (Swedish Bioenergy Association 2013) and the use of by-products from the forest industry (sawmills and pulp and paper industries), which is already close to maximal in relation to their availability (Swedish Energy Agency 2012; Routa et al. 2013). Wood fuels (52 and 10 TWh of unrefined and refined wood fuels) and black liquors (45 TWh) accounted for 84% of all bioenergy produced in 2013 (Swedish Energy Agency 2015). However, political and economic goals are set to increase the use of bioenergy in Sweden, and the main source for this increase will have to be biomass extracted directly from the forest. Of the total amount of wood chips produced from primary forest biomass in Sweden (20 TWh or 9.8 M m^3), logging residues (tops and branches) from final fellings were the main raw material (53%), followed by roundwood (34%), small-diameter (undelimbed) trees (12%) and stumps (1%) (Statistics Sweden 2014). This material is mainly used by energy plants, i.e. heating plants and combined heat and power (CHP) plants (Swedish Energy Agency 2013). Routa et al. (2013) showed that half of the technical potential of logging residues is currently utilized, while only 20% and 2% of this potential is used for small-diameter trees and stump wood, respectively; these represent unutilized biomass resources that require significant technological development for realization of their full potential. Within a few more years, the amount of economically and ecologically available logging residues will probably be insufficient to supply the market if the bioeconomy grows as expected.

There is therefore a need to identify unutilized forest biomass resources, such as small-diameter trees from non-commercially-thinned forests, referred to in this study as biomass-dense thinning forests (BDTF) (i.e. early thinning stands and overgrown marginal land). The traditional management of BDTF in Sweden includes pre-commercial thinning (PCT), in which the trees are motor-manually cut and left on the ground, with the aim of obtaining a homogeneous stand of future crop trees that will produce a high quantity of sawtimber. Therefore, PCT or clearing may have been applied in the BDTF. However, statistics show that large areas of forest are not currently subjected to PCT for several reasons, notably high operational costs. According to the Swedish Forest Agency (2014a), about 1.4 million (M) ha of forests in Sweden are in urgent need of PCT, and this area increased by 35% between 2000 and 2013. This has led to a large increase in BDTF, in which motor-manual PCT is very costly and the first commercial thinning for pulpwood provides low returns. If, instead of PCT, new management and supply systems could be developed that harvest the biomass of whole trees regardless of tree size, it could be economical to use much more of the gross (theoretical) harvesting potential (Bergström 2009; Ulvcrona 2011; Karlsson 2013). According to Nordfjell et al. (2008), during the period 2001–2005 there was 2.8 M ha of BDTF with a tree height below 12 m and a biomass content above 30 oven-dry (OD) tonnes (t) per ha (12% of the Swedish productive forest land area), with a technical harvesting potential of at least 5 M OD t per year (yr) (11.8 M m^3 yr^{-1}). However, Routa et al. (2013) have suggested a technical harvesting potential of small-dimension wood from thinnings of 6.5 M m^3 yr^{-1} (2.7 M OD t yr^{-1}).

Some small-diameter trees could be extracted from stands growing on non-conventional forested land, such as abandoned agricultural land (overgrown arable land, meadows and pastures, etc.) and the edges of fields, roads, ditches, railways, power line corridors, etc., referred to collectively as marginal land . Such marginal stands sometimes have similar characteristics to BDTF on conventional forest land, and could therefore be harvested using similar technology, as shown by Fernandez-Lacruz et al. (2013), Bergström et al. (2015) and Jylhä et al. (2015). However, suitable harvesting technology and working methods must be identified for each marginal land type and set of conditions. In contrast to early energy thinnings on conventional forest land, the purpose of which is to improve the future production of high-value roundwood in the stand, the biomass on marginal land can be clear-cut (often regularly or thinned very intensely), sometimes resulting in larger volumes and higher productivities when harvested. For example, Emanuelsson et al. (2014) estimated potential harvests of 2.3 TWh yr^{-1} (1.2 M m^3 yr^{-1}) and 1.6 TWh yr^{-1} (0.8 M m^3 yr^{-1}) from overgrown pastures and arable lands, respectively.

Kempe and Fridman (2011) showed that about 200 000 ha of farmland was converted into forest in Sweden during 1985–2008 and similar trends have occurred over Europe (MacDonald et al. 2000; Romero-Calcerrada and Perry 2004; Gellrich et al. 2007; Keenleyside and Tucker 2010). Based on FAO statistics from the Global Forest Resources Assessment (Food and Agriculture Organization 2014), from 1980 to 2010 the total growing stock of forests in Europe (excluding the former Soviet Union) increased by 69% (more than 11 billion m^3 by stem volume) (cf. Melin 2014) and the forest land area increased by 25% (36 M ha). It is therefore likely that the area of BDTF in Europe will continue to increase. Note that the establishment of short-rotation energy crops, such as willow (*Salix* spp.), on arable land in Sweden does not change the land use, i.e. it is still classified as farmland. The arable land in Sweden covered by these crops accounts for 12 241 ha (Swedish Board of Agriculture 2015).

In Sweden, the two main industries that acquire small-diameter trees from thinnings (or clearings on marginal land) are pulp mills and energy plants, the former using delimbed stemwood for pulp production and the latter using undelimbed whole trees (and roundwood that does not meet the forest industry's quality requirements) for generating heat and/or electricity. Details of the biomass supply chains from forest to industry have been presented by Routa et al. (2013). Small-diameter trees provide higher quality wood chips than logging residues, with lower ash contents because of their higher stemwood contents (Flinkman and Thörnqvist 1986; cf. Ringman 1996). The minimum dimension requirements for the pulp mills are 2.9 m stock length and 5 cm top diameter under bark (VMF Qbera 2012), so only a small proportion of the volume of BDTF can be harvested as pulpwood (cf. Di Fulvio et al. 2011b). Small trees could supply future biorefinery industries producing new biomaterials, e.g. liquid biofuels for the transport sector and bioplastics, and such industries are likely to be located close to, or integrated with, current industries (Bergström and Matisons 2014). Several studies (Röser 2012; Petty 2014; Karttunen 2015; Windisch 2015) have addressed ways to increase the efficiency of biomass supply chains from forest to industry. BDTF harvesting costs account for the largest shares of cost in these supply chains (Laitila 2008; Laitila et al. 2010) and thus some of the main barriers to high cost efficiency (Bergström and Di Fulvio 2014a), but they can be potentially reduced (Petty 2014). Efficient long-distance transportation is also crucial for increasing the use of forest biomass in Finland and Sweden (Routa et al. 2013), as well as increasing the payload, i.e. maximizing the density of the transported biomass by compression or comminution (Belbo and Talbot 2014; Bergström and Di Fulvio 2014a; 2014b).

Thus, the aim of this study was to describe the areal distribution, characteristics and harvesting potential of BDTF (i.e. non-commercially-thinned forests) in Sweden.

2 Materials and methods

2.1 Forest dataset

The Swedish National Forest Inventory (NFI) provided a dataset containing details of forest inventory plots of productive forest land in Sweden (29 105 plots, clustered, with a radius of 7 or 10 m,

Table 1. Variables in each NFI plot used in analyses.

Variable	Explanation
Diameter at breast height (DBH)	Average of all trees, basal area-weighted.
Height	If height ≥ 7 m, the average height of all trees weighted by basal area; if height < 7 m, the arithmetic average of the dominant trees.
Tree density	Number of trees ha^{-1}.
Above-ground biomass density	OD t ha^{-1} of stemwood with bark and living branches including needles and fine fractions (calculated according to Marklund 1988).
Standing volume per ha	Stem volume over bark and above the stump, including the tops.
Maturity class	Cutting class according to Nilsson et al. (2011).
Stand age	Years
Composition of tree species	Proportions (%) of Scots pine, lodgepole pine, spruce and broadleaves.
Ground moisture, soil parent material	Classes using the Swedish terrain classification method of Berg (1992).
Pre-commercially thinned (PCT)	No / Yes
Commercially thinned	No / Yes
Previous land use other than forest	No / Yes (and use, e.g. pasture, arable land, gravel pit, etc.)

22.5 M ha) for the period 2006–2010, including their Cartesian coordinates (Axelsson et al. 2010). Nature reserves that do not exclude silviculture were included. The total forest land area represented by the plots within each county was indicated, ranging from 13 ha in southern Sweden (606 ha on average) to 2410 ha in the northernmost part of the country (993 ha on average). The variables in Table 1 were used in subsequent analyses (based on measurements from all the trees in a plot that had reached breast height, i.e. 1.3 m). The average stem volume of the trees in each plot was calculated by dividing the stem volume ha^{-1} by the number of trees ha^{-1} in the plot (arithmetic average).

2.2 Geographical analyses

The NFI dataset was imported into a geographical information system (GIS) using the software package ArcGIS®. Plots containing four categories of BDTF in the dataset were then identified and selected, by successively applying the following constraints:

A. non-commercially-thinned plots, with an average tree height > 3 m and average DBH < 20 cm;

B. plots of category A with an above-ground biomass density (growing stock) > 30 OD t ha^{-1};

C. plots of category B with an average tree height < 12 m;

D. plots of category C with an average stem volume (denoted v) of 10–120 dm^3, divided into five subclasses:

1. $10 \leq v < 20$ dm^3: typical PCT forest, normally cleared with a brush saw;

2. $20 \leq v < 30$ dm^3: energy wood thinning forest, normally harvested with accumulating felling heads (AFHs);

3. $30 \leq v < 40$ dm^3: thinning forest, either harvested as energy wood only or as pulpwood (using AFHs with or without rough delimbing or a harvester head with accumulating arms);

4. $40 \leq v < 60$ dm^3: thinning forest, either harvested as pulpwood only or integrated with energy wood in dense stands and heterogeneous tree sizes. Harvester heads with accumulating arms or AFHs with rough delimbing are normally used;

5. $60 \leq v < 120$ dm^3: pulpwood thinning forest. Harvester heads with accumulating arms are normally used.

Category A included all plots (11 823) with trees that had passed the regeneration stage and did not have very thick trees, because 2–4 m is the usual height for applying PCT in Sweden (Direct Knowledge 2012) and trees with a DBH ≥ 20 cm can be used to produce high-value roundwood (cf. Varmola and Salminen 2004). Category B included 8262 of these plots, excluding plots with trees that had a standing biomass < 30 OD t ha^{-1} (< 70 m^3 ha^{-1}) because it is reasonable to let such stands continue to grow to increase the biomass concentration (Nordfjell et al. 2008). Category C included 3437 plots, excluding plots with trees that were taller than 12 m on average because it is more economical to apply conventional first thinning and treat them as pulpwood rather than energy wood (Nordfjell et al. 2008; Heikkilä et al. 2009). Category D included just 2446 plots, excluding plots that had trees with an average stem volume ≥ 120 dm^3, because they can be treated exclusively as pulpwood rather than energy wood using conventional techniques, and plots with trees with extremely small stem volumes (< 10 dm^3), because these cannot be harvested effectively with current technology and even with anticipated technological developments their use is unlikely to be economical (Sängstuvall et al. 2012). Unless stated otherwise, the results (and discussion) refer to BDTF of category D (i.e. applying all selection constraints, A–D, to the overall NFI dataset).

Most analyses were performed at a regional level, following the historical division of Sweden: Norrland, subdivided into Northern Norrland (the northern half of the northernmost region of Sweden) and Southern Norrland (the southern half of the northernmost region); Svealand (the central region); and Götaland (the southernmost region) (Nilsson et al. 2011) (Fig. 1). More detailed calculations, such as of the area occupied by BDTF in relation to the total forest area, were performed at a county level, and some counties were subdivided into "landscapes" to provide the highest level of geographical detail. The term "counties" is used in the text to refer to both county and landscape levels, even though the resulting maps may show the subdivisions, when applicable. Calculations indicating the characteristics of the BDTF are presented as cumulative percentages. The area and growing stock of BDTF occurring on difficult terrain (classes 4 and 5, according to the Swedish terrain classification method of Berg 1992) were determined, where class "1" indicates very firm, stable ground and "5" indicates very soft ground with a low bearing capacity. The average age of the BDTF within each county and the area of BDTF growing on abandoned agricultural land were also determined.

2.3 BDTF harvesting potential

The technological harvest potential from BDTF was calculated considering technological restrictions (i.e. limitations of the ground-bearing capacity) and ecological considerations (i.e. removal of only the yearly growth or a percentage of the standing biomass). Usually, in energy-thinnings in Sweden, about 30–40% of the basal area or about 50% of the standing volume is removed (Di Fulvio et al. 2011b). In our study, the technological harvest potential from BDTF was calculated by considering the removal of 100% of the annual increment in stemwood volume. The calculations were carried out for four scenarios, after filtering the dataset by applying selection constraints A–C and A–D, and considering 100% and 70% of the area of BDTF accessible to machines (i.e. with good ground-bearing capacity). The mean annual increment in stem volume (m^3 ha^{-1} yr^{-1}) was provided by the Swedish NFI for each county and NFI maturity classes "B3"+"C1". Stem volume refers to the volume over bark above the stump to the top, excluding branches and needles. A basic stemwood density of 402 OD kg m^{-3} was used to convert solid cubic metres to oven-dry tonnes, using WeCalc (Nylinder and Larsson 2013) according to the proportions (%) of tree species within the BDTF (Table 4). The potential of whole-tree harvesting was also calculated, as this can be suitable in many BDTF. Stemwood represented about 70% of the dry weight of standing biomass within the studied BDTF, while branches and needles represented 30%. The potential of whole-tree harvesting was based on these proportions, considering a basic density of 479 OD kg m^{-3} for the branch fraction (obtained using the same principles as for the stemwood).

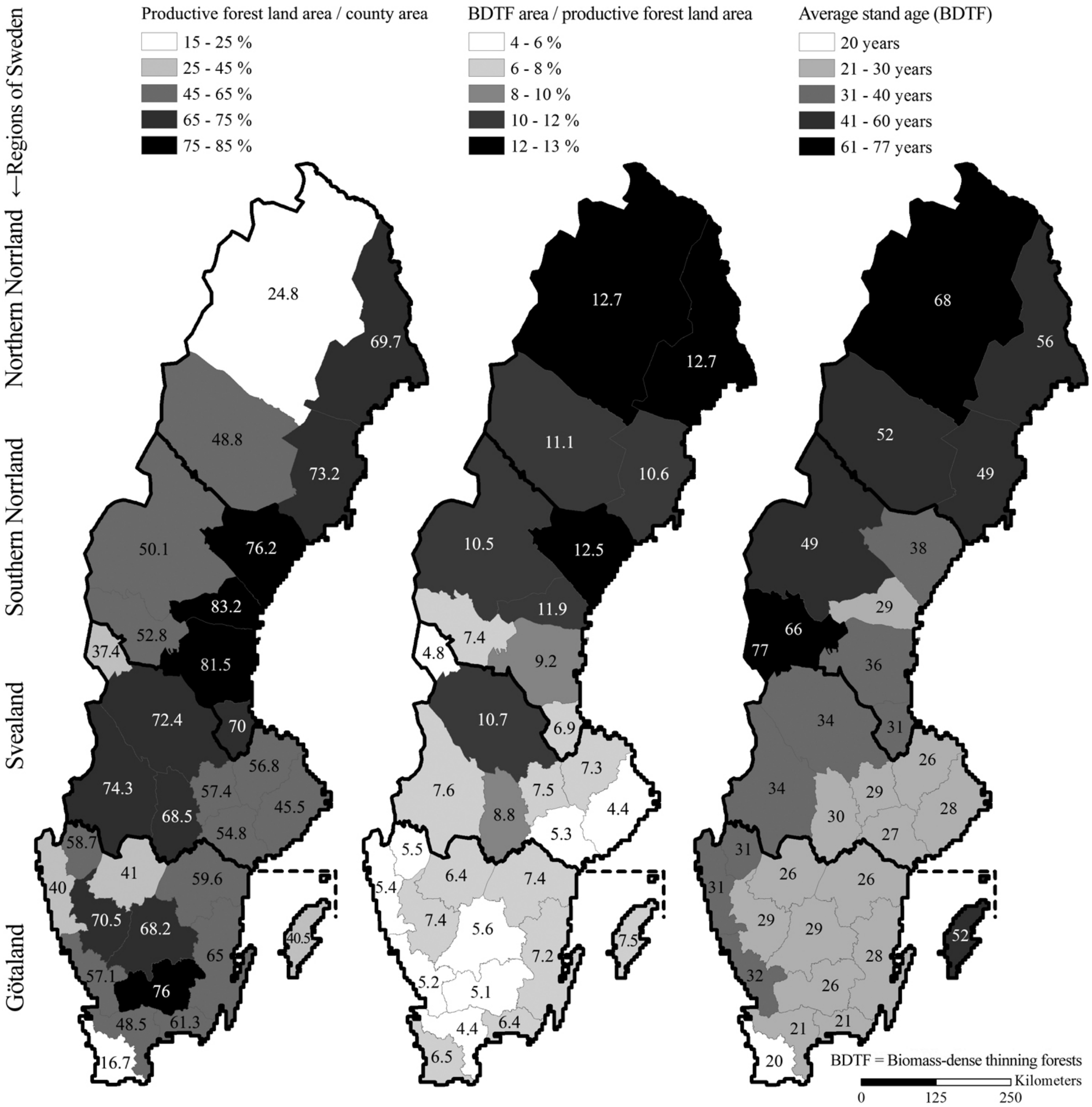

Fig. 1. The regions of Sweden (Northern Norrland, Southern Norrland, Svealand, Götaland), the areal proportion (%) of productive forest land by county (left), the areal proportion of BDTF within the productive forest land by county (middle) and the average stand age of BDTF by county (right). Results refer to BDTF of category D (i.e. applying all selection constraints to the overall NFI dataset). © Lantmäteriet, i2014/764.

3 Results

The estimated area occupied by BDTF decreased as the selection constraints were successively applied to the overall NFI dataset: from 9.8 M ha (44% of the total productive forest land in the country) when applying constraint A, to 2.1 M ha (9% of the total productive forest land) when applying all constraints (Tables 2 and 3). In general, both the absolute and relative areas of BDTF (of category D) increased from south to north (Fig. 1); from just 15% of the BDTF area in Götaland, and 20% in Svealand, to 65% in Norrland (representing 6% of Sweden's productive forest land). In general, across the counties in Norrland, the productive forest land contained the greatest proportion of BDTF and the coastal counties had high proportions of productive forest land (Fig. 1).

Table 2. The area of BDTF (defined using indicated constraints), the ratio of BDTF area to the total area of productive forest, the BDTF growing stock and the ratio of BDTF growing stock to the total growing stock on Sweden's productive forest land.

Category	BDTF area (M ha)	Ratio of BDTF/total productive forest areal (%)	BDTF growing stock (M OD t)	Ratio of BDTF/total growing stock (%)
A	9.77	43.5	564.07	34.2
B	6.94	30.9	518.25	31.4
C	2.97	13.2	160.81	9.7
D	2.11	9.4	119.26	7.2

Table 3. Regional distribution of BDTF area (ha), average biomass of growing stock (OD t ha^{-1}) and total standing biomass (M OD t), by average stem volume subclass (BDTF of category D).

Region	Subclass (average stem volume "x", dm^3)								
	$10 \le x < 20$			$20 \le x < 30$			$30 \le x < 40$		
	ha	OD t ha^{-1}	M OD t	ha	OD t ha^{-1}	M OD t	ha	OD t ha^{-1}	M OD t
1 N.Norrland	262 292	50.1	13.14	147 003	54.6	8.03	108 859	55.3	6.02
2 S.Norrland	195 624	58.8	11.51	128 204	61.0	7.83	79 770	57.3	4.57
3 Svealand	146 521	53.6	7.85	83 711	55.3	4.63	57 296	57.3	3.28
4 Götaland	93 846	54.4	5.10	53 124	59.7	3.17	49 465	63.6	3.15
Total	*698 282*	*53.8*	*37.60*	*412 042*	*57.4*	*23.65*	*295 390*	*57.6*	*17.02*
	$40 \le x < 60$			$60 \le x < 120$			Total		
	ha	OD t ha^{-1}	M OD t	ha	OD t ha^{-1}	M OD t	ha	OD t ha^{-1}	M OD t
1 N.Norrland	137 044	49.3	6.76	142 258	54.8	7.80	797 455	52.3	41.74
2 S.Norrland	76 397	61.1	4.67	97 930	60.3	5.90	577 924	59.7	34.48
3 Svealand	75 715	60.5	4.58	66 881	59.3	3.96	430 125	56.5	24.30
4 Götaland	64 683	67.1	4.34	44 556	66.7	2.97	305 673	61.3	18.73
Total	*353 839*	*57.5*	*20.34*	*351 624*	*58.7*	*20.64*	*2 111 177*	*56.5*	*119.26*

Table 4. Proportions (%) of BDTF dominated by indicated single species or pairs of co-dominants (accounting for at least 60% and at least 80% of stands' cover, respectively; BDTF of category D).

Dominant tree species in the stand	Proportion (%) of total BDTF area (2.11 M ha)	Proportion (%) of BDTF area on abandoned farmland (0.04 M ha)
Broadleaves (*≥60%*)	10.6	24.6
Spruce *(Picea abies) (≥60%)*	26.6	65.8
Scots pine *(Pinus sylvestris) (≥60%)*	52.0	5.7
Lodgepole pine *(Pinus contorta) (≥60%)*	7.4	-
Spruce and scots pine *(≥80%)*	0.8	1.1
Spruce and broadleaves *(≥80%)*	1.7	-
Scots pine and broadleaves *(≥80%)*	0.7	2.9
Scots pine and lodgepole pine *(≥80%)*	0.1	-
Total	*100*	*100*

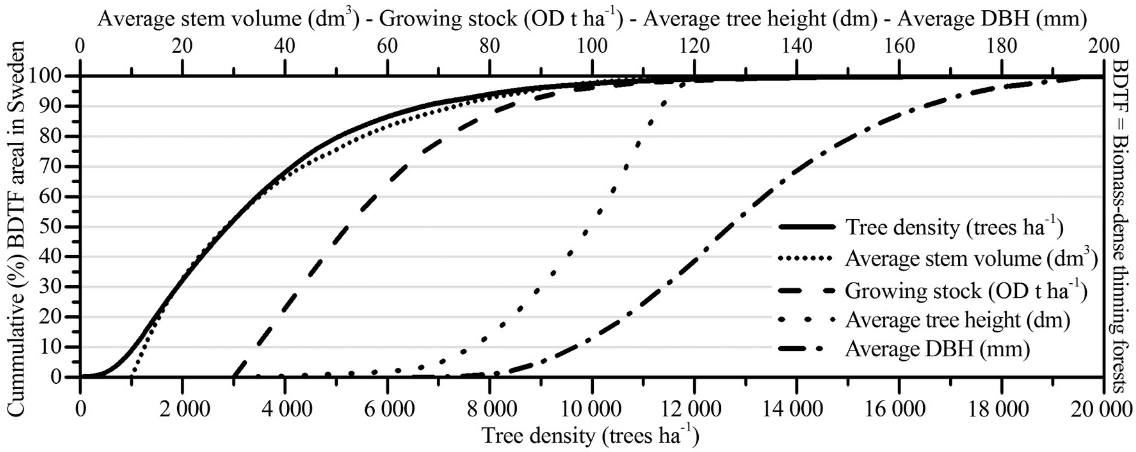

Fig. 2. Characteristics of the BDTF (of category D) across the whole of Sweden. The Y-axis shows the cumulative percentage of the area occupied by the forests characterized by the parameters represented on the upper and lower X-axes. The absolute BDTF areas are shown in Table 3.

Further analyses showed that most of the BDTF were pine-dominated (59% of the BDTF area), followed by spruce- (27%) and broadleaf-dominated stands (11%) (Table 4). BDTF on abandoned farmland accounted for 2% of the BDTF area (of category D), which equates to 41 517 ha (2.8 M OD t), of which 38% was found in Götaland, 39% in Svealand and 23% in Norrland. These stands were dominated by spruce (66%) and broadleaves (25%) (Table 4). About 451 000 ha (27 M OD t; 21%) of the BDTF area was on difficult terrain (classes 4 and 5 according to Berg 1992), of which peatlands accounted for 26%. The analyses showed that just 12% (or 251 247 ha) of the BDTF area (of category D) had been subjected to PCT.

The total growing stock of BDTF ranged from 564 M OD t (34% of the total stock on Swedish productive forest land) when applying only constraint A to 119 M OD t (7% of the total) when applying all of the selection constraints (Tables 2 and 3). Most the biomass was found in Norrland (64%), followed by Svealand (20%) and Götaland (16%). Detailed analyses of tree size (Table 3) showed that the stands situated in Norrland had similar biomass densities regardless of tree size, while in the southern areas the average biomass density increased with tree size. The differences in average values of these stand characteristics between regions seemed to be small and showed no particular trend. Therefore, only averages for the whole country are presented here (Fig. 2).

The average stand ages indicated that about 65% of the BDTF area fell within the age class 0–40 years (7% and 58% in the classes 0–20 and 21–40 years, respectively). Stands 41–60 years and > 60 years old accounted for 19% and the remaining 16% of the BDTF area, respectively. The average stand age (Fig. 1) increased from south to north and from east to west, being 28, 33, 42 and 57 years in Götaland, Svealand, Southern Norrland and Northern Norrland, respectively.

The technical harvesting potential of stemwood ranged from 3.0 to 6.1 M OD t yr^{-1} (7.5 to 15.1 M m^3 yr^{-1}) depending on the scenario considered (Table 5), while the potential for harvesting undelimbed whole trees ranged from 4.3 to 8.7 M OD t yr^{-1} (10.2 to 20.6 M m^3 yr^{-1}).

Table 5. Annual technical harvesting potential of delimbed stemwood and whole (undelimbed) trees from BDTF across regions of Sweden, applying selection constraints A-C and A-D.

	Constraints A–C (2.97 M ha)								Constraints A–D (2.11 M ha)							
	70% of the area				100% of the area				70% of the area				100% of the area			
	Stemwood		Whole trees		Stemwood		Whole trees		Stemwood		Whole trees		Stemwood		Whole trees	
Region	M OD t yr^{-1}	M m^3 yr^{-1}	M OD t yr^{-1}	M m^3 yr^{-1}	M OD t yr^{-1}	M m^3 yr^{-1}	M OD t yr^{-1}	M m^3 yr^{-1}	M OD t yr^{-1}	M m^3 yr^{-1}	M OD t yr^{-1}	M m^3 yr^{-1}	M OD t yr^{-1}	M m^3 yr^{-1}	M OD t yr^{-1}	M m^3 yr^{-1}
1 N. Norrland	1.07	2.67	1.53	3.63	1.53	3.81	2.19	5.19	0.78	1.93	1.11	2.62	1.11	2.76	1.58	3.75
2 S. Norrland	1.33	3.31	1.90	4.50	1.90	4.73	2.72	6.43	0.90	2.23	1.28	3.03	1.28	3.19	1.83	4.33
3 Svealand	1.03	2.56	1.47	3.49	1.47	3.66	2.10	4.98	0.74	1.85	1.06	2.51	1.06	2.64	1.52	3.59
4 Götaland	0.82	2.05	1.18	2.79	1.18	2.93	1.68	3.98	0.59	1.46	0.84	1.98	0.84	2.09	1.20	2.83
Total	*4.26*	*10.60*	*6.09*	*14.41*	*6.09*	*15.14*	*8.69*	*20.58*	*3.00*	*7.47*	*4.29*	*10.15*	*4.29*	*10.67*	*6.13*	*14.50*

4 Discussion

4.1 Main results

Analyses of the areal distribution and characteristics of BDTF within Sweden show that they represent a significant resource across the country (from 7 to 34% of the total growing stock on Sweden's productive forest land, depending on the category of BDTF considered), particularly in the northernmost regions. Comparison of the dataset used for the present study (2006–2010) and corresponding data used by Nordfjell et al. (2008) for the period 2001–2005 revealed that the area of BDTF had increased by 3.7% (about 102 000 ha) and the growing stock by 4.4% (about 6.56 M OD t) during the five years between the studies. To facilitate this comparison, plots in the 2006–2010 dataset were only selected if they fell within NFI maturity classes "B3" (young forest; average tree height > 3 m and DBH < 10 cm) and "C1" (thinning forest; unthinned stands with 10 cm ≤ DBH < 20 cm) and met constraints B and C. Although category A, as defined in our study, corresponds with the "B3" and "C1" definitions, the NFI determines maturity classes at a stand level rather than plot level, so the NFI class of some plots did not match the average DBH or tree height in those plots. The methodology used to choose the stands in our study enables comparison with other studies, even though similar analyses may not have been carried out previously and the definitions and methodologies of forest inventories between countries may differ significantly. Using data from the Swedish Forest Agency (2014a), the area within classes "B3" and "C1" in need of PCT increased on average by about 300 633 ha between 2001–2005 and 2006–2010, in line with the trend we observed. Analyses also revealed that only a small fraction (12% or 251 247 ha) of the BDTF area (of category D) had been subjected to PCT. Moreover, the area of forest in 0–40 years age classes has almost doubled since the mid-1950s, and the standing volume per hectare has increased, especially for the age class 21–40 years (cf. Kempe and Fridman 2011); corroborating the increases in forest land area and volumes in BDTF in Sweden we detected. Regional differences in mean annual increment in stem volume (6.9, 5.8, 4.7 and 3.0 m^3 ha^{-1} yr^{-1} in Götaland, Svealand, Southern Norrland and Northern Norrland, respectively) (Nilsson et al. 2011) appear to reflect the latitude and topography (increasingly mountainous from east-west) of the regions. This explains the spread in stand age across the BDTF (Fig. 1), and for this reason the term "young" has been avoided when referring to the BDTF, focusing instead on the stand characteristics from a harvesting perspective rather than their age. However, it should be noted that the stand age is highly important from the forest owner's perspective when calculating the profitability of silvicultural treatments and forests' present value.

Only a small proportion of BDTF (2% or 41 517 ha, BDTF of category D) was found on abandoned farmland (arable and grazing lands), with an average stand age of 23 years. This area is 3.4 times larger than the area of energy crops on arable land in Sweden. The abandoned farmland area covered by BDTF represented about 8% of the total abandoned farmland area (548 185 ha) classified as productive forest land in the overall NFI dataset. The NFI classifies land according to its current state and applies a 3-year period before reclassifying abandoned farmland as forest land (Lundström and Glimskär 2009) provided that the definition of forest land is met (Swedish Forest Agency 2014b). Agricultural land becomes a forest by spontaneous afforestation (natural) or reforestation (active planting) with forest species (e.g. spruce or pine) and, in the latter case, land and drainage ditches are cleared of overgrown vegetation and the soil is prepared. Active establishment of forest is a way of increasing production from this land (cf. Bergström et al. 2015).

4.2 Characteristics of BDTF from a harvesting perspective

Although the lower limit on tree height was set at 3 m, results (Fig. 2) revealed that most of the area of BDTF (90%) contained trees with an average height over 7.5 m and an average DBH more than 9 cm (74% of the BDTF area had a mean DBH between 9 and 14 cm). This implies that using current techniques it is possible to make some profit from energy thinnings across a large area of BDTF, as the break-even point is usually set at around 8–9 cm DBH (Di Fulvio et al. 2011a). Furthermore, it should be possible to use harvesters with AFHs for multi-tree handling or innovative feller-bundlers in combination with innovative working methods like boom-corridor thinning (Bergström and Di Fulvio 2014a). This is because average stem sizes are small (stem volumes are less than 45 dm^3 in about 72% of the stand areas) and tree densities sufficiently high (more than 67–47% of the chosen stands had a density exceeding 2000–3000 trees ha^{-1}, which is the target density of future crop trees after PCT in Sweden) (Claesson et al. 1999; Varmola and Salminen 2004). Harwarders could also be used to harvest BDTF (Di Fulvio and Bergström 2013).

Harvesting costs are strongly dependent on tree size and density of removal (Kärhä et al. 2005; Bergström et al. 2007), whether using conventional or multi-tree handling techniques. Therefore, the use of innovative technologies and geometric thinning methods, rather than single-grip harvesters and selective thinning, increases the productivity and cost efficiency of harvesting small-diameter trees in early thinnings (either as pulp or energy wood). In terms of average stem volumes (Table 3), the smallest subclass ($10 \leq v < 20$ dm^3) has the highest coverage, representing about 33% of the total BDTF area, followed by the $20 \leq v < 30$ dm^3 subclass (20% of the BDTF area). The average stem volume is an arithmetic average, so the value can be misleading for plots with many small stems and a few big trees. The average DBH can be regarded as a more robust value because it is weighted by basal area (i.e. thicker trees are better represented). However, more detailed inventory data are needed to assess the distribution across DBH classes rather than average values. A stem volume of 30–35 dm^3 (Di Fulvio et al. 2011a) is normally considered to be the lower limit for profitable energy thinnings, so to harvest very small trees profitably further developments of cutting technology are required, for example harvesters equipped with a double-crane system for use in geometric boom-corridor thinning (Jundén et al. 2013). As shown by Oikari et al. (2010), further training of machine operators will also be needed to allow them to work effectively with new harvesting technologies. Only a small proportion of the volume from a BDTF can be harvested as pulpwood (Di Fulvio et al. 2011b), which is why selection constraints A–D were applied, so that stands were chosen that could be harvested either as energy wood (only for energy and/or biorefinery production) or only pulpwood, or as pulpwood from larger trees and energy wood from smaller trees and tree tops (i.e. integrated harvests, Jylhä 2011; Pasanen et al. 2014; Petty 2014). As pointed out by Di Fulvio et al. (2011b), the suitability of harvesting pulp- or energy-wood depends on the harvestable volumes, market prices and distances to end-users. For example, if medium size trees (30–60 dm^3 or 9–11 cm DBH) are targeted, it could be more convenient to deliver whole trees and/or tree parts (eventually roughly delimbed or chipped) to energy plants rather than delimbed pulpwood logs to pulp mills (or future biorefineries) if the distances are much shorter, but integrated harvests could also be convenient.

4.3 BDTF harvesting potential

Analyses revealed a technical harvesting potential of at least 4.3 M OD t yr^{-1} (10.2 M m^3 yr^{-1}) of undelimbed whole trees and 3.0 M OD t yr^{-1} (7.5 M m^3 yr^{-1}) of delimbed stemwood (Table 5). No explicit economic restrictions (e.g. forwarding distance from the stand to roadside) were considered in the calculations, but the selection constraints (A–C and A–D) are implicitly based on techno-economic assumptions and limitations. The technical potential harvests presented by Nordfjell et al. (2008) and Routa et al. (2013) amounted to 5 M OD t yr^{-1} and 2.7 M OD t yr^{-1}, respectively, although the methodologies used for their calculations differed from ours. Räisanen and Athanassiadis (2013) have presented the potential distribution of small-diameter trees in Finland, which according to Anttila et al. (2013) amount to 8.3 M m^3 yr^{-1} of whole trees or 12.4 M m^3 for integrated harvest of energy wood and industrial roundwood.

4.4 Further work and conclusions

Further analyses of the biomass supply chain from BDTF must be performed (e.g. transportation distances to existing pulp mills, energy plants and future biorefineries) and they should consider the demand from each individual facility. The largest energy plants will rely on a combination of biomaterials, including energy wood, logging residues and stumps (Ranta and Korpinen 2011), and by-products from forest industries. Restrictions from the industry regarding tree species, dimensions and assortments should also be considered. Studies of the availability of logging residues for supplying energy plants in Finland have shown that GIS is a very useful tool for this type of analysis (Ranta 2005). Forest terminals (Kons et al. 2014) between stands and the end-users are additional nodes that should be included in future supply chain analyses. Analyses of biomass availability (logging residues and stumps) for terminals in Sweden have shown that about 95% of logging residues and stumps are available for current terminals within a procurement area of 75 km (Enström et al. 2013), but these calculations did not consider the potential of energy wood from BDTF because the required data were not available.

The demand for small-diameter trees is expected to increase with the development of a bio-based society, as the use of by-products from traditional forest industries and logging residues is close to maximal in relation to their availability. This study has shown that there is a large biomass potential from BDTF. It also showed that a large proportion of BDTF can be harvested effectively with current technologies and working methods, but further development is needed in order to utilize its full potential. The information presented here may provide foundations for more detailed studies on cost-efficiency of biomass supply systems, taking into account the availability of small-diameter trees, forest terminals and the demand from already established industries and future biorefineries.

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