Research paper

Wood biomass potentials for energy in northern Europe: Forest or plantations?

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Abstract

Wood biomass for energy can be largely produced in northern Europe from forest land resulting from silvicultural practices and from agricultural land in the form of fast-growing plantations. The present paper estimates and compares the current regional potentials for wood biomass production attending to these sources. The data are based on spatialized estimates from previous models, largely based on empirical records concerning forest and plantation’s productivity. The results show that 8.5 Mm³ of wood biomass can be produced annually from plantations when using 5% of the total available agricultural land, and 58.5 Mm³ from forest lands using current estimates of forest production. However, the results also show that a strategy for wood biomass resource management should be local rather than general: wood biomass potential from fast-growing plantations was larger in 19 regions than from forest resources (10 in Denmark, 6 in Norway and 3 in Lithuania) out of the 91 regions in the area included to this study. When considered together, northern Europe presents significant potential for wood biomass production for energy uses, and each country - and even region - should develop independent policy strategies of biomass generation in order to most efficiently realize their own potential for wood-based bioenergy.

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1. Introduction

Where lays the largest potential of wood biomass for energy in northern Europe? Wood biomass for energy can be largely produced from forests, resulting from silvicultural and management practices, as well as from agricultural lands in the form of fast-growing plantations.

In the case of forest biomass, it consists mainly of by-products of forest management. In other words, products that are felled during commercial and non-commercial operations but are not utilized for conventional forest industries such timber and pulp. Available biomass fractions for energy uses include small diameter stems, branches, tops, needles and even stumps and roots [1] and have been the focus of several studies aiming at estimating forest based potentials for wood biomass for energy, revealing large amounts of unused biomass resources (e.g. Refs. [1–4]).

Concerning fast-growing plantations, they consist of fast-growing tree species established on former agricultural land. In northern Europe, the tree species belong to genera Salix and Populus, in management regimes called short rotation forestry. These plantations are intensively managed, often including fertilization practices and harvests every 3–6 years [5] with a lifespan of 20–25 years and expected high annual yields.
Currently, the use of wood biomass in northern Europe varies among countries, as there are differences concerning the location and availability of forest resources, feasible sourcing distance, technology availability, power plants, national laws and other issues that affect the development of the bioenergy sector [1]. For example, Finland accounts for 25% of its total energy consumption from biomass (93 TWh) [6] and Sweden accounts for 23% of its total energy supply from biomass (129 TWh), and 49% of this figure is based directly on wood-derived fuels [7] (the rest being: black liquor, biodiesel, and other biomass-based products). In both cases, the wood originates mostly from forest resources, although Sweden moreover presents a well-established scheme for fast-growing plantations since the 1980s [8]. The combined harvest potential of forest fuels in the Nordic and Baltic countries have been recently estimated in 236–416 TWh [9]. Currently, the primary production of biomass and waste in the area is 313.8 TWh [10].

However, future trends in biomass utilization for energy pose a challenge to the existing resources, as well as other competing uses of these resources in biocomposites or chemicals manufacture [11–13]. In fact, it is expected that the wood demand will double in the following years, exceeding the material availability between 2015 and 2020 [14] and getting even broader by 2030 [15], resulting in a significant wood deficit if the current mobilization of wood biomass remains at the same levels. However, the gap between supply and demand of wood biomass can, to a certain extent, be compensated increasing the current mobilization of forest wood biomass in combination with the establishment of fast-growing plantations [14].

The combination of wood biomass resources from forest and plantations will certainly play an important role in the development of energy alternatives. However, regions may present individual profiles concerning the wood potentials available, which determines the efforts to develop them. The present study estimates and compares regional estimates of biomass potential for bioenergy in northern Europe from both forest and plantations on agricultural land and contributes to reflect on regional strategies to translate this potential into practice.

2. Material and methods

2.1. Data parameters

The area of study entailed northern Europe including Denmark, Estonia, Finland, Latvia, Lithuania, Norway and Sweden. Two alternate sources of wood biomass for energy were considered: forest biomass and fast-growing plantations on agricultural land.

The estimates of local wood production from forest land were based on Verkerk et al. (2015) [16]. The dataset consisted on estimates obtained at 1 × 1 km resolution, and were based on surrogate variables used for top-down disaggregation of public statistics related to growth conditions, growing stock forest cover and net annual increments, among others [17]. This resulted in a collection of 10 maps based on the annual estimates for wood production for the years 2000–2010. In addition, country based estimates of forest wood for energy were collected for different biomass fractions (Table 1).

The estimates for fast-growing plantations of agricultural land were based on [18]. The data were calculated at 1 × 1 km resolution, using empirical records from 1790 plantations using climatic variables and management assumptions as extrapolation proxies. This resulted in three scenarios of plantation performance (low, medium and high).

The disaggregation methods used in both studies (forest and plantation productivity) were based on boosted regression trees, which combines statistical and machine learning techniques. These aim at the improvement of the performance of a single model by recursively partitioning the explained variance into many individual consecutive models and combining them for prediction [21].

2.2. Methods to regionalize potential

Data concerning production potentials were harmonised to match the same units and spatial extent. The regional unit considered was the NUTS-3 level (Nomenclature of Territorial Units for Statistics) as defined by the European Commission [22] and the equivalent county level in the case of Norway. The spatial distribution of the data was visually examined, and metrics concerning their frequency distribution, mean and median were retrieved at country and regional levels. Calculations were based on the average of the 2000–2010 period covered in the original study [16], as the forest production is variable along time. Concerning plantation productivity, the calculations were based on the most productive of the three scenarios available.

In order to calculate the wood biomass available for energy from the data retrieved, two different parameters had to be estimated: 1) what fraction of forest biomass can be used for energy, and 2) what share of agricultural land can be considered for plantations.

In the case of forest biomass for energy use, there are expansion factors that consider additional biomass fractions other than the conventionally extracted biomass. These fractions include stumps, roots, needles, and branches, in addition to small diameter trees not fit for other industrial uses. At the same time, assumptions must be made to differentiate the theoretical potential (all biomass that can be used for energy) from the available potential (using availability reduction factors to estimate the total technical potential of harvestable biomass). Thus, in this study the available potential at country level for each of these fractions was extracted from previous studies and the final relationships were based on the estimated available potential for energy, considering felling residues and below-ground biomass based on Karjalainen et al. (2004) [1], Asikainen et al. (2008) [2] and Anttila et al. (2009) [3]. The retrieved estimates were based on assumptions that, in general lines, can be summarised in: grouping the forest species in main categories (spruce, pine and broadleaves), use of simple equations for the expansion factors, application of general restrictions for the use of wood available (e.g. assuming 75% of clear cut areas and 45% of

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thinnings as technically available for supply), for the recovery rates (e.g. assuming 65% in mechanized cutting and 50% in manual cutting) and land use restrictions entailing poor soils (due to nutrient loss), steep slopes endangered by erosion and avalanches and other sensitive sites (see the original studies for further details). These estimates were compared to the calculated wood production at country level, resulting in a country level parameter that was applied to each cell provided by Ref.[16], yielding a disaggregated estimation of wood biomass supply and allowing further aggregations at regional level. Finally, a sensitivity analysis of the estimates was performed, using systematically 10%, 20%, 30% and 40% of the wood biomass production as a fixed level (see Appendix Table A1).

In the case of plantations on agricultural land, alternative percentages and land qualities were explored (see Appendix Table A.2) and a threshold level of 5% of available agricultural land was fixed for the final calculations. The yield estimates in this case were based on Mg (oven dry) which were converted to m³ using a density of 0.450 t m⁻³ [23]. Since the original model only considered the first cutting cycle, the data was converted to a full rotation of 21 years (including one year for cut-back and five cycles of 4 years each) following Mola-Yudego and Aronsson (2008)[5] and Mola-Yudego and González-Olabarria (2010)[8].

3. Results

The yield estimates were arranged to match the same resolution and geographical extent (Fig. 1). The highest productivity of forest lands was located in areas of southern Sweden (Småland). Concerning fast-growing plantations, the highest yields were in Denmark and the southernmost Sweden (Skåne).

The average production of forest lands was 1.41 m³ ha⁻¹ year⁻¹ (Fig. 2), although large areas presented yields below 1 m³ ha⁻¹ year⁻¹. In the case of fast-growing plantations, the average was 15.48 m³ ha⁻¹ year⁻¹.

The yield of fast-growing plantations was higher in most of the Baltic countries and Denmark (Fig. 3), as well as the coastal areas of Finland, Sweden and to a lesser degree, Norway. The inland areas of these countries presented larger forest production levels, due to the scarcity of agricultural land, and the challenging climatic conditions for plantations, which resulted in substantial regional variation (Fig. 4) following a combination of the north-south and coastal-interior gradients.

There was some small variation concerning the ratios between forest-based wood biomass and the total available wood biomass for energy (aggregated by countries), but in general the estimates agreed (Fig. 5). When compared to each other, the estimates of the original studies showed a coefficient of variation ca 18% for Sweden, Finland and Lithuania, and higher for the rest (34% for Latvia, 39% for Estonia and 48% for Denmark). The average fraction, once included the expansion factors and availability parameters, ranged from 17.3% in Estonia to 49.7% in Norway, while most of the other countries were between 30 and 40%. It must be taken into account that only estimates from one source (i.e.[3]) could be considered for Norway. Using a fixed ratio for all the area (see Appendix Table A.2), the largest relative deviations (above 20% deviation from the trend) were found for all the regions of Estonia, as well as Finnmark, Troms (Norway), Copenhagen area, Bornholm (Denmark) and Riga (Latvia).

The percentages were locally fit for each country and then extrapolated to each region. The equivalent estimates for plantation

Fig. 1. Yield estimates of wood biomass production (m³ ha⁻¹ year⁻¹) at 1 x 1 km for northern Europe for forestlands (left) and fast-growing plantations on agricultural land (right) based on harvest records.
productivity were using 5% of the agricultural land. The combination of forests and plantations resulted in estimates of total wood biomass potential for energy for the whole area: 58.27 and 8.49 Mm$^3$ from forest and plantation sources, respectively, as well as for each region (Fig. 6): in Denmark, 80% of the wood biomass potential would rely on plantations, for 40% in Lithuania, 24% in Estonia, 18% in Norway, 11% in Latvia, 7% in Sweden and 4% in Finland (for the disaggregated data see Appendix Table A.3).

In most of the regions in Finland, Estonia and Latvia, the wood biomass potentials were mostly located in forest lands. However, in Denmark, Lithuania and Norway, a significant percentage of the locally available wood potential biomass was laid on agricultural lands. In fact, in 19 regions the percentage of total wood biomass potential from plantations clearly exceeded the estimates obtained for forest land biomass (Fig. 7), such as the regions of Vest-og Sydsjælland, Fyn and Sydjylland in Denmark, where 80% of the wood biomass potential would be based on plantations.

4. Discussion

The present paper deals with spatially explicit wood biomass estimates for northern Europe available from potential forest resources and plantations established on agricultural land. The geographical scale entails seven countries, the accuracy levels are $1 \times 1$ km, and the aggregation level is the region. The data used to feed the original models are based on harvested records, both from forest operations and from plantations, which assures the reliability of the estimates. This approach is thus a solid basis for providing realistic estimates at a detailed spatial level, which is necessary for a more accurate planning, and economic and policy approaches in bioenergy development.

The estimates concerning forest wood biomass refer to stemwood biomass based on harvest records [16]. However, wood biomass for energy include the use of branches, needles, tops and even stumps and roots that are not accounted for in these records, and therefore require the use of allometric equations and biomass expansion factors in order to derive these fractions from the stemwood estimates. In general, these factors are age and species dependent (such as the equations used in Karjalainen et al., 2004 [1], Verkerk, et al., 2011 [24], among others), and include some alternative reduction factors in order to consider actual availability. In this study, the estimates of available forest biomass for energy were based on different authors [1–3] and were directly spatialized using the estimates of forest wood biomass as a proxy. This allows having locally accurate figures of biomass potential that can be used for bioenergy uses of wood.

There were some discrepancies between the estimates resulting from the studies considered, which suggested a higher level of uncertainty for some of the countries (Latvia, Estonia and Denmark) than in the rest. It must be taken into account that the different assumptions used in the studies included have direct results on the estimates. For instance, concerning the expansion factors [11], and [2] made use of the same allometric models ([25] based in Sweden), which may increase the error in those regions.
differing significantly from Swedish conditions. Concerning the availability assumptions, the general assumptions taken in the original studies concerning mechanization rates may also result in the under-estimation of the potentials in Latvia and Lithuania. The use of generic percentages for steep slopes can particularly affect the estimates for Norway and the fact that there was a fixed conversion ratio between forest wood yield and wood fuel may result in underestimations of the forest potentials in the south-east of the country. Finally, the inclusion of stump biomass, despite being already limited following the availability criteria, may be controversial as stump removal has a significant negative impact upon forest biodiversity, and it has been suggested that the complete removal of stumps should be avoided [26]. Stump harvesting is also likely to favour invasive, pioneering vegetation and leads to a shift in the plant species composition on sites where it is carried out, potentially leading to additional herbicide requirements [26].

As these assumptions may vary among studies, there are expected discrepancies with other studies. As observed in Díaz-Yáñez et al., 2013 [4], the selection and application of the allocation or scenario based factors lead to divergent estimates of the potentials.
allocated to these fractions in the countries studied, and that may explain the lower parameters applied e.g. in Estonia, compared to Latvia and Lithuania. The forest based estimates compared to other studies based on alternative restrictions of wood biomass availability [44] showed large discrepancies for Finland (20 vs 58 Mm³, for this study and [44], respectively) whereas were in agreement in the case of Sweden (25 vs 27 Mm³). However, this has been reflected in several studies demonstrating the divergences between estimates of wood fuel potential (e.g. Refs. [34,24]) which underlines the inner difficulties of their accurate estimation. Finally, the use of estimates of available biomass potential, rather than theoretical potential, and the fact that current harvest records do not account for changes in the forest productivity due to future climate variation [27] or to improvements in the mechanization, among others, suggest that the estimates of this study should be considered as at the lower end of the spectrum of possible future scenarios.

Concerning the yields of fast-growing plantations on agricultural land are also based on harvest records, spatialized for each region using climatic variables, and extrapolated to the whole period. These yields are therefore more robust than rough national estimates used in previous studies (e.g. Ref. [28]). Yields from harvest records from commercially managed plantations incorporate harvesting losses, mortalities, and hazards affecting the plantations, providing more realism to the figures presented [18], and explain why the estimates are lower than those presented in other studies. However, it must be taken into account that, in the case of plantations, yields are subject to improvements due to better clonal varieties released as well as management methods that have an effect on the productivity [29]. Although the estimates aim at incorporate this trend into account by considering the highest productivity scenarios available, recent and future yield gains are not contemplated in the estimates, thus they can also be regarded as conservative.

In addition to yield levels, a critical factor to estimate total wood biomass deals with the percentage of the current agricultural land that can be expected to be available for plantations. Today, several countries in the area have areas planted with fast-growing plantations, especially willow and to a lower extent poplar and hybrid aspen. The areas so far established are, however, very limited: there are 11 574 ha established in Sweden, 5505 ha in Denmark, 2139 ha in Latvia, ca. 745 ha in Estonia, and 110 ha in Finland (own estimates based on the Swedish land register in 2014 [30], Tollus et al., 2012 [31], Heino and Hytönen 2012 [32]). The largest extend, in Sweden, entails ca. 0.45% of the arable land of the country [33], which is lower than the 5% considered in the figures. In this country, the threshold considered would translate in ca. 100 000 ha, which at the same time falls short of the plans suggested by Naturvårdsverket (1998) [34] entailing 14% of the Swedish arable land by 2021. In this sense, the threshold used in the figures is speculative, and aims at a compromise between the current situation of plantations established and some optimistic plans of future land use potentials. On the other hand, it goes in line with Aust et al. (2014) [35] who considered that 5.7% of cropland should be suitable for biomass production with fast-growing tree species in short rotation coppice in Germany, which is very close to the threshold considered.

The potentials are large from both forest and plantations, although the land use distribution shows that they are unevenly distributed spatially. This has direct consequences in their utilization. One of the key advantages of forest based biomass is that it is a by-product of existing forest operations, which has an evident economic appeal. However, a large part of the potential for energy is located in remote areas, with lower population and thus demand of energy. The logistic efforts to mobilize these resources are therefore linked to their profitability and, in fact, the accessibility and transport costs — rather than the availability of the resources — are frequently the limiting factors in biomass use [36]. In the case of tree plantations for energy, most of agricultural land is located in the more densely populated areas, and the nature of plantation management permits its establishment in optimal locations; being forest biomass spatially fixed to a given location. On the other hand, plantations make exclusive use of the land (i.e. are not a side stream of some established activity) and therefore may interfere with current land uses dedicated to food or feed.

It is clear that there should be different strategies at national level to combine effective valorisation of both forest and plantation resources. For instance, in the case of Finland, most of the forecasted wood biomass demand can be fulfilled integrating a more intensive forest management and higher mobilization [13], a conclusion also supported by the results of this study (although the recent developments in biorefinery installations may pose a challenge to these figures). In the case of Denmark, however, it will be necessary to establish large plantation schemes in order to fulfill the future biomass demand, as a higher mobilization of forest wood biomass reserve will not be enough. According to Mantau et al. (2010) [13], a European deficit of ca. 8 Mm³ of wood is expected by 2020 which has motivated several actions to valorize novel biomass sources, such as municipal wastes, animal manure and wastewater streams for energy [37,38]. This would require a larger quota of agricultural areas dedicated to wood biomass production schemes, important efforts to increase the yield productivity and possibly larger imports of wood as well. The other studied countries may develop mixed strategies. For instance, in Estonia it is estimated that achieving the targets of the Estonian Energy Sector...
Development Plan in the energy sector would require 1.14 Mm$^3$ of solid wood per year, in addition to current figures, which forms approximately 15% of total domestic timber consumption [39]. The results show that ca. 1.3 Mm$^3$ can be provided by forest biomass and 0.4 Mm$^3$ can be obtained from plantations, fulfilling the estimated wood deficit with a fair margin.

Often the policy-oriented incentives for the development of biomass production for energy have been proposed at country level. However, beyond the national level, geographically clustered areas may present different profiles when it comes to their bio-energy potentials. This is the case of e.g. Jönköping/Småland compared to Skåne in Sweden. In the first case, agricultural land is restricted and only 1.7% of the total region’s wood potential for energy, as 98% is based on forest biomass. In the case of Skåne 30% would rely on plantations, and in Gotland, over 38%. Despite these regional variations, incentives for the establishment of plantation schemes in Sweden were based on a national-based set of policy incentives oriented towards the adoption of the cultivation by farmers [40]. Other countries, however, have already presented to a certain extent different regional policies. In Germany, for instance, the policy incentives are regional (i.e. subsidies [41]), and in UK, there are different incentive schemes in England, Scotland, Wales and Northern Ireland [42].

The estimates of this study have a large level of uncertainty: the
estimates of forest biomass are subject to assumptions and simplifications in their calculations, and the estimates of short rotation plantations are especially sensitive to the shares of land available for their cultivation. In addition, to ecological restrictions and land availability there are socio-economic, technical, and political factors that will certainly influence the materialization of these potentials. Having into account the necessary cautions, the results show that a more rational strategy must adapt the promotion and goals of energy policy at a regional level, rather than at national scale, to better fit the local mobilization of wood resources.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2017.08.021.